Effects of CO_2 injection on shallow groundwater resources: a hypothetical case study in the Sherwood Sandstone aquifer, UK

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Abstract

The far-field effects of CO_2 storage on onshore potable groundwater systems is examined for a hypothetical injection site within the Sherwood Sandstone Group (SSG) on the East Lincolnshire coastline, United Kingdom (UK). Using the quasi-three dimensional object-orientated groundwater flow model ZOOMQ3D, supported by conceptualisation and aquifer parameterisation of the wider hydrogeological setting, injection of 15 Mt/yr of CO_2 for 20 yrs (60 Ml/day groundwater equivalent) into the aquifer at depth is simulated. Model scenarios are carried out which test the dissipation of pressures up-dip within the storage formation. When applying typical vertical hydraulic conductivity of 10^{-6} m/day to the Mercia Mudstone Group (MMG) caprock groundwater pressure heads in the shallow confined SSG aquifer, 60 km up dip, where it is used for potable water supply, increase by 0.01-10 m. Groundwater levels within the unconfined aquifer, 80-100 km up-dip from the injection zone, increase by <0.01m to 1m with a corresponding increase in river flows of approximately 1.7%. Two important points are observed, firstly that the degree of impact on shallow groundwater systems is highly sensitive to the vertical leakage assigned to the caprock. When the leakage co-efficient is increased by one order of magnitude groundwater heads in the potable aquifer are reduced by two orders of magnitude. Secondly, that the response of groundwater pressure heads to injection is rapid, as is the subsequent recovery. Using a groundwater model, in addition to detailed reservoir modelling, provides a useful tool to assess the potential scale of impact of CO_2 storage on shallow groundwater systems and can be used to aid the regulation of such operations.

Keywords: Groundwater, CO_2, model, sandstone, pressure, permeability, Sherwood Sandstone Group, Lincolnshire

1. Introduction

Carbon Capture and Storage (CCS) presents new challenges to the regulator and licensing regime for the underground storage of CO_2. In particular, for onshore and nearshore sites the impact of CO_2 storage in geological formations on groundwater systems is potentially significant. The prediction of behaviour during the physical migration of CO_2 within groundwater systems (IPPC, 2005), and the propagation of increased groundwater pressure heads arising from injection pressures (Bergman and Winter 1995) requires the integration of an understanding of the geological framework, the multiphase flow of dense CO_2 and the hydrogeological regime. Compared with migration of CO_2, the influence of increased groundwater pressures is far-reaching with effects felt at distances of over 100 km compared with distances typically less than 5 km for the migration of CO_2 (Nicot, 2008; Birkholzer and Zhou, 2009; Yamamoto et al., 2009). Pressure perturbations within groundwater systems have implications for groundwater discharges, both natural and artificial, as well as the physical displacement of saline water into areas of fresh potable water. The impacts on groundwater systems are not necessarily restricted to the storage formation with the vulnerability of overlying and underlying aquifer systems dependent on the integrity of the caprock and the presence of leakage routes. Leakage via wells (e.g. Celia et al., 2011), along existing or induced faults and fractures, vertically through permeable caprock intervals and up-gradient through the storage formation are the most likely mechanisms for CO_2 escape and pressure dissipation (Figure 1)(Bricker et al., 2010; Koornneef et al., 2011).

Figure 1 Schematic of the hydrogeological system present within the study area. Hypothetical leakage pathways for pressure dissipation are shown.

Assessment of the impacts of CO_2 storage in deep saline formations (DSFs) on the wider groundwater environment are more limited than other CCS investigations. Those investigations that do consider impacts on the groundwater environment frequently omit an assessment of pressure effects, concentrating rather on the fate and transport of CO_2 leakages and the resultant acidification of water and ecosystem impacts. The Environmental Impact Assessment (EIA) for CO_2 storage in geological formations requires consideration of groundwater directives (Directives 2000/60/EC and 2006/118/EC) for the protection of groundwater against pollution and deterioration (EU, 2009) and should consider pressure effects as well as CO_2 leakage. Recent evaluation of EIAs for CCS operations in a UK setting identify the risk to groundwater systems from CO_2 leakages but pressure effects are not included in the list of potential impacts (Hill et al., 2009). First acknowledged by Bergman and Winter (1995), the impacts of injection pressures on groundwater systems were only considered in a qualitative manner until Nicot (2008) published the outcomes of a quantitative groundwater model looking at the effect of CO_2 storage on fresh-water aquifers in the Texas Gulf Coast basin. Further modelled outputs have been published subsequently (Birkholzer et al, 2009; Birkholzer and Zhou, 2009; Yamamoto, 2009; Person, 2010) but none consider a UK geological setting.

Research into the potential geological storage capacity for CO_2 within the UK offshore territory has identified several DSFs of the southern North Sea as suitable targets (Brook et al., 2002). In particular, faulted stratigraphical and structural traps in the Sherwood (Bunter) Sandstone Group (SSG) represent a key target. Onshore this stratigraphical horizon is a principal aquifer for groundwater resources in the East Midlands of England (WMC, 2005). Although storage of CO_2 in onshore geological formations is not currently being considered by the UK government (EA, 2011),it is recognised that a deep geological formation offshore may have a natural hydraulic onshore connection and that the impacts of CO_2 storage in the near-offshore may not be confined to offshore localities. An assessment of the wider hydrogeological setting is therefore required. Any evaluation of the impacts of CO_2 storage which does not include an assessment of increased pressure heads will significantly underestimate the radius of impact of injection and the risk to surrounding areas (Oruganti and Bryant, 2009).

The SSG aquifer system has been modelled previously at different spatial scales with varying degrees of complexity. Firstly in the early 1990s, covering the area around Nottingham (Bishop and Rushton, 1993) and then subsequently extended to include the Doncaster area (Shepley, 2000; Shepley and Soley, 2009). These groundwater models were commissioned by the environmental regulator with the purpose of assessing regional groundwater resources and cover the unconfined and potable confined SSG. As part of the CASSEM (CO_2 Aquifer Storage Site Evaluation and Monitoring) project (Smith et al., 2011) and using data from a real site in the North East of England we examine, using a ZOOMQ3D groundwater model (Jackson and Spink, 2004), the response of shallow groundwater systems to hypothetical injection pressures within the SSG. Particular attention is paid to preferential pressure displacement up-dip within the storage formation and vertically through overlying strata. In this way the scale of impact of CO_2 injection into a deep saline aquifer within relative proximity of important shallow groundwater systems can be analysed.

With the benefit of a basin-scale groundwater flow model, populated with site-specific hydraulic parameters, key questions about the impacts on ground and surface water systems at the interface of confined and unconfined flow and the interaction of groundwater with surface water systems may be examined. For example, will increased pressure heads propagate into fresh potable aquifer systems and what will the response in groundwater heads and groundwater-fed surface water systems be? Our study begins to address these concerns by investigating which data are required and demonstrating the validity of using a comparatively simple but cost-effective modelling approach to aid in the regulation of CO_2 storage operations.

2. Study area

2.1 Geology

A real site was selected on the East Lincolnshire coastline to model the hypothetical onshore injection of CO_2, with the SSG forming the storage formation and the overlying Mercia Mudstone Group (MMG) acting as the primary sealing formation (Figures 1 and 2). The geology of the study area was examined as part of the CASSEM project, an account of which is provided in (Monaghan et al., 2012). The geological sequence within the study area is summarised in table 1. Land between the SSG outcrop area in the west and the injection zone in the east is predominantly flat, falling off from 600 m in the Peak District to sea-level at the Humber Estuary and Lincolnshire coast some 80 Km away. Other than the chalk of the Lincolnshire Wolds, which form a local high, much of the land has an elevation of less than 100 m AOD.

Regionally the bedrock dips gently (1-2^{o}) to the east with progressively younger units cropping out in that direction. Defined by a north-south trending outcrop area approximately 80 km west of the injection zone, (Figure 2) the SSG comprises red-brown Triassic sandstone with calcareous mudstone and mud flake conglomerate and ranges in thickness from 90 m south of Nottingham to 400 m at the Humber estuary. The overlying MMG comprises mudstone, siltstone and sandstone with anhydrite and gypsum. The youngest bedrock deposits within the study area are the chalks of Cretaceous age which are present at surface along the East Lincolnshire coastline, separated from the injection zone by some 1,200 m of intervening bedrock.

The SSG and MMG deposits form part of the onshore section of the Eastern England Shelf where relatively undisturbed Permian deposits dip gently to the North Sea (Milodowski et al., 1987). Offshore the Eastern England Shelf extends beyond the Dowsing Fault Zone into the Southern North Sea Basin. Fault displacements in the region of 400 m are recorded within the Dowsing Fault Zone, which lies approximately 50-75 km offshore and for the purpose of our investigations marks the easterly extent of our study area.

Figure 2 – Geology of the study area with model boundaries and injection points shown. Geological cross-section through the study area annotated with hypothetical leakage routes.

2.2 Hydrogeology

The study area is hydrogeologically significant with three principal aquifers present within the geological sequence between the injection zone and the ground surface, these are, with increasing age, the Chalk Group, the Lincolnshire Limestone Formation and the SSG (Table 1), which support 370 Ml/d, 150 Ml/d and 450 Ml/d licensed groundwater abstraction respectively within the study area (Bricker et al., 2010 and refs therein). In the East of England over 45% of public water supply is derived from groundwater sources, largely supplied by the Chalk and the Lincolnshire Limestone, while the SSG provides for a quarter of all abstraction in the UK (Downing, 1998).

The Chalk Group forms the uppermost, or shallowest, bedrock aquifer unit of interest. In Lincolnshire the Chalk Group is characterised by a southeast-northwest escarpment which falls steeply to the west and dips gently to the east (1-2^{o}). It is approximately 60 m thick at the escarpment increasing to 100 m or more at the coast. The Chalk Group is a principal aquifer and supports high yielding supplies. Within the study area it forms a highly transmissive, dual porosity aquifer (median transmissivity (T) – 1,800 m^2/d; MacDonald et al., 2001) with fractures permitting significant groundwater flow. Artesian groundwater conditions are found within the study area along with wetland environments sensitive to groundwater level fluctuations. Whilst there is evidence of vertical leakage between the Chalk and the underlying Lower Cretaceous Deposits (Whitehead and Lawrence, 2006), there is no evidence of leakage through the Jurassic clays to deeper aquifer units. While fissures, from centimetre scale through to macro fault features occur within Mesozoic mudstones, such as the Jurassic clays, their strength may be insufficient to sustain open fissures at significant depths below ground surface (Tellam and Lloyd, 1981). Artificial (deep boreholes) and direct (faults) leakage routes aside, this implies that the Jurassic clays represent a hydraulic barrier separating the Chalk from the influence of CO_2 storage in the SSG.

Limestones of Jurassic age, of which the Lincolnshire Limestone Formation is the most significant aquifer unit, form an alternating sequence of thicker limestone or sandstone bands inter-bedded with thinner silt or clay horizons. The Lincolnshire Limestone Formation dips gently to the east; from thickness of 40 m in South Lincolnshire it pinches out to the north and south and down-dip (Allen et al., 1997). At Cleethorpes, to the north of the injection sites, 17.2 m of Lincolnshire Limestone was recorded (Downing et al., 1985). As an aquifer, the

Lincolnshire Limestone is highly transmissive due to significant fracturing along bedding planes and secondary permeability is provided by solution enhanced karstic features (Allen et al., 1997). Abstraction from the Lincolnshire Limestone comes largely from the confined aquifer where the saturated thickness is less fragmented by fractures and incised valleys (Allen et al., 1997). The Jurassic limestones are separated from the MMG caprock by the Lias Group which are predicted here to be in the region of 150 m thick above the injection zone. Though thick, the Lias Group has a highly varied lithological sequence at the bed-scale and as a result, formation permeability covers several orders of magnitude (Jones et al., 2001). Should the integrity of the MMG caprock be breached the capacity of the Lias Group to prevent the interference of injection-induced pressure heads with the overlying Lincolnshire Limestone Formation is uncertain.

The SSG is the second most important aquifer in the UK, supplying around 25% of all licensed groundwater abstraction in England and Wales (Allen et al., 1997). The large storage potential of the SSG, a geometric mean storage coefficient of 10^{-3} and a porosity of approximately 30%, is the primary reason why it is such an important unit for groundwater resources and equally why it is being considered for the storage of CO_2. The hypothetical point of CO_2 injection into the SSG near the coastline at Mablethorpe occurs at a depth of 1,200 m and is some 80 km downdip of the unconfined SSG and 60 km downdip of the nearest licensed abstraction. While there is a notable transition in aquifer properties from outcrop to the deep saline aquifer there is no evidence to suggest the presence of a geological structure that physically separates the deep saline aquifer from potable groundwater resources. Relatively minor faulting, compared with parts of the UK, does occur within the study area and is associated with the reactivation of Caledonaian and Variscan fault structures within the Palaeozoic basement (Ford et al., 2009). The faults are not identified at surface and are likely to terminate within the Jurassic or Cretaceous succession. There may be some local influence on groundwater flow patterns and the migration of CO_2 associated with the presence of these faults but regionally they are less significant.

3. Hydraulic properties of the deep saline formations

3.1 Sherwood Sandstone Group (SSG)

Understanding the hydraulic properties of the storage formation and the overlying caprock from their deep saline extent through to outcrop is important as these parameters will determine not only the spatial extent of pressure impacts and vertical leakage but also the timing of these impacts.

The SSG at the injection zone is expected to be in the region of 275 – 330 m thick (Gale et al., 1983; Ford et al., 2009) and lies at a depth of approximately 1,200 m below ground level (bgl). Aquifer properties information for the shallow SSG and MMG, up to depths of approximately 150 – 200 m bgl, is obtained from hydraulic well testing and core samples (Downing and Gray, 1986 Allen et al., 1997). Information about hydraulic properties for the deep saline aquifer, at depths of approximately 1,000 m bgl and over are obtained primarily from geothermal investigation boreholes drilled in the early 1980s (Gale et al., 1983; Rollin et al., 1993) and subsequently re-analysed by Milodowski and Rushton (2009). Information for the SSG or MMG between depths of 200 m – 1,000 m is generally more limited.

The SSG where it is unconfined is highly transmissive (mean T of 200 m^2/day), porous (mean 30%) and has a large storage potential (specific yield 10^{-2} – 0.1) (Allen et al., 1997). The high intergranular porosity is derived from the preservation of primary pore space and the removal of anhydrite and halite cements and primary grains by dissolution and weathering enhancing secondary porosity (Milodowski and Rushton, 2009). Dissolution by fresh meteoric groundwater diminishes down-gradient and there is a corresponding reduction in porosity (15-18%, Gale et al., 1983; Milodowski and Rushton, 2009) observed at depths greater than 1,000 m where anhydrite and halite are intact.

The transition in hydraulic conductivity of the SSG with depth is considered in detail as its distribution forms a primary input to the ZOOMQ3D groundwater model. Intrinsic permeability data derived from SSG core samples for all sites within the UK held within the BGS aquifer properties database were examined (Figure 3). At depths greater than 200 m bgl permeability values cover five orders of magnitude (1 – 10,000 millidarcies (mD)) though typically in the range of 700 – 5000 mD (0.45 – 3.25 m/d) this is consistent with other permeability results obtained for the SSG at depth (Downing et al., 1985). While the minimum permeability appears to decrease with depth there is no corresponding reduction in maximum permeability. Thus maximum permeability values recorded for the deep saline SSG are in line with permeability results recorded for the SSG where it is unconfined (Allen et al., 1997; Downing and Gray, 1986). The layered heterogeneity of the SSG at the bed-scale exerts a greater control on observed permeability than depth, a conclusion that is shared with other investigations of SSG permeability (Bloomfield et al., 2006). Therefore, while the proportion of lower permeability beds may be greater at depth, the presence of high permeability horizons in the deep saline SSG should be anticipated.

Figure 3 – Box and whisker plots of SSG permeability at different depth intervals.

3.2 Mercia Mudstone Group (MMG)

The MMG is traditionally considered to be relatively impermeable and non-water bearing, though the abundance of thin inter-bedded, cemented sandstones, sulphate deposits and fracturing throughout the sequence serves to increase permeability locally such that small quantities of groundwater, suitable for domestic or small-scale agricultural use, may be obtained at shallow (<100 m) depths (Jones et al., 2000). The Tarporley Siltstone Formation the lowermost formation in the MMG, which directly overlies the SSG, has an equal abundance of sandstones and mudstones and can be considered as an extension to the SSG (Jones et al., 2000). The presence of dolomite and sulphate cements within the MMG series also exerts a control on formation porosity and by association permeability. Hydration of anhydrite to gypsum causes expansive disruption and is accompanied by fracturing, dissolution and collapse which enhance macroporosity (Monaghan et al., 2012). Permeability values in the range of 10^{-6} to 10^{-1} m/d (1.5 micro darcies (μD) - 150 mD) are observed for the MMG at shallow depths (Tellam and Lloyd, 1981; Hobbs et al., 2002; Jones et al., 2000), dependent on the weathered state of the MMG, the presence of sandstone horizons and the nature of the permeability test. Vertical hydraulic conductivity of the MMG at shallow depths derived from laboratory testing is in the range of 10^{-4} – 10^{-6} m/d (Tellam and Lloyd, 1981). At greater depths (>400 mbgl), where groundwater is saline and temperature and pressure are higher, gypsification is less significant and interconnected macroporosity is low (Monaghan et al., 2012). In consideration of these geochemical processes and the permeability data available for the MMG at depths greater than 1,000 m (Jones et al., 2000) the vertical permeability of the MMG in the vicinity of the injection zone is likely to be in the range 10^{-7} – 10^{-6} m/d (1 – 10 μD), though sandstone units and local faulting may provide local permeable conduits.

Table 1 – Summary hydrogeological sequence within the study area. Observed and modelled permeability values are provided for each of the geological units.

4. Single phase vs multi-phase models

Simulation of multiphase flow (with CO_2 and brine as the two main fluid phases) or full compositional flow (CO_2-brine-oil phases) is required in the immediate vicinity of the injection point for the assessment of geological storage of CO_2. A multi-phase or full compositional simulator can model density-driven flow, resulting in a more accurate representation of the pressure field. By undertaking this approach the physics of multi-phase flow are represented properly and the governing equations are generalised to allow for any fluid to be modelled by using its equations of state. This method is important for the proper simulation of injection, especially in oil and gas reservoirs and saline aquifers. However, the models used to undertake these simulations are designed for use in oil reservoirs which are typically isolated from the surface and take significant computational run time, especially for large areas.

Single phase models are designed for simulated the shallow sub-surface and the interaction between groundwater and surface features. These include recharge to the water table, springs, rivers as well as water abstraction boreholes. Shallow confined aquifer conditions and the interaction with overlying, low permeability, strata can also be modelled. They also offer the advantage of faster computational run time, fewer input parameters and less specialised technical knowledge which may make them more attractive to operational and regulatory authorities (Nicot et al., 2011) A balance needs to be struck between the complexity of the physics represented, fast runtimes and interaction with the surface and shallow sub-surface environment such that objective of the modelling is met. Simplified modelling approaches such as single phase models can be thought of as a reconnaissance approach to understand the far-field effects, especially where interaction with the surface is important. By making small adjustments to permeability fields and injection rates to account for density, compressibility and viscosity variations between brine and CO_2, previous work (Nicot et al., 2011) also successfully demonstrates that single-phase flow codes can reproduce reasonable pressure heads in far-field localities. A single-phase method has been adopted for the study and is described in this paper.

4.1 Use of ZOOM

The ZOOM suite of models has been developed by the British Geological Survey (BGS) in collaboration with the University of Birmingham and the Environment Agency (Jackson and Spink, 2004). The ZOOM models consist of a recharge model ZOODRM, a groundwater flow model ZOOMQ3D and an advective particle tracking model ZOOPT. The main advantage of ZOOM is that grid refinement techniques are employed which enable more accurate representation of groundwater flow by nesting grids of different sizes.

These models have been used for a number of groundwater studies. ZOODRM has been applied to calculating recharge to the aquifers underlying the West Bank (Hughes et al. 2008), in northern China (O Dochartaigh et al. 2010) and to sub-catchments within the River Thames (Mansour et al. 2011). ZOOMQ3D has been used to investigate the potential impact of climate change on groundwater systems in the UK (Jackson et al. 2011) and Spain (Guardiola-Albert and Jackson, 2011) as well as to investigate groundwater flow in shallow superficial deposits in Glasgow (Campbell et al. 2010). The particle tracking model has been applied to examining the transport of pesticides in the Permo-Triassic Sandstone in the UK (Stuart et al. 2006).

ZOOM was used in this study as grid refinement allows significant pressure head gradients around the injection wells to be simulated appropriately.

5. Model Set-up and Boundary Conditions

Initially a steady-state model was created by using a three layer model run for a 20 year period, with 4 time-steps per stress period (month). The time-variant model was subsequently run using a 20 year constant injection pulse and 100 year recovery period. The three layers within the model all represent the SSG, however the inclusion of multiple layers allows the leakage of water from the SSG into the overlying MMG to be represented. A grid-spacing of 1,000 m was used for the coarsest grid with a finer spacing in the central section of the model (250 m). No significant flow is assumed to cross the model boundaries and therefore all are specified using a no-flow condition.

The model covers an area of 125 km in length, from the SSG outcrop to some 20 km off the East Lincolnshire coastline and is 70 km in width, from Nottingham in the south to Doncaster in the north. The unconfined SSG is represented in the model up to a distance of 20 km east, the potable confined SSG is represented up to a distance of 40 km east and the deep saline aquifer lies between 40 – 120km east (Figure 2). The thickness of the SSG has been inferred from an isopach map created by Gale et al. (1983), and a subsequent three dimensional geological model produced by Ford et al., 2009. Each of the three layers in the model equal a third of the total SSG thickness, which ranges between 50 and 450 m.

Input parameters for the groundwater model were informed by a review of field and laboratory test results and values presented in the peer-reviewed literature. Transmissivity varies from 40m^2/d (28 Darcy metres (Dm)) in the deep saline aquifer through to 500 m^2/d (352 Dm) in parts of the unconfined aquifer where fracture flow is well-developed (Allen et al., 1997). Hydraulic conductivity within ZOOMQ3D is specified by the transmissivity values divided by aquifer thickness. This being so, hydraulic conductivity varies from 0.1 m/d (154 mD) within parts of the deep saline aquifer up to 10 m/d (15400 mD) for sections of the unconfined SSG; these values are marginally higher than those observed from core samples (Allen et al., 1997; Downing and Gray, 1986; Downing et al., 1985) but allowing for scale dependency where secondary permeability is under-estimated in core samples the hydraulic conductivity values derived in conjunction with observed transmissivity values are considered more appropriate. Specific yield for the unconfined SSG was set to 0.1, while the storage co-efficient for the confined potable aquifer and the deep saline aquifer were set to $10^{-2} – 10^{-3}$ and $10^{-3} – 10^{-5}$ respectively. Aquifer recharge of 0.5 mm/d was assigned to nodes within the unconfined SSG in keeping with values used within regional groundwater flow models (Bishop and Rushton, 1993; Trowsdale and Lerner, 2003), while no recharge is received to the confined portion of the model.

Salinity in the deep saline SSG is expected to be in the region of 45 g/l while temperature is likely to vary between 44 – 55^{o}C (Downing et al., 1985). ZOOMQ3D simulates baseflow within river basins using a series of linked river nodes and has the ability to replicate the interactions between rivers and the SSG aquifer system. It was used in preference to multiphase codes, which are better suited to deep reservoir models, to characterise impacts on the shallow groundwater system. Five rivers, orientated in an east-west direction, were positioned on the unconfined aquifer to simulate groundwater-surface water interactions. The river bed level was set such that groundwater heads remained above the base of the river bed. If this were not the case, the perched conditions would result in a different calculation of river bed leakage for different model scenarios. Whilst the river simulation adopted within the ZOOM model is not an exact representation of the true river network it does allow an assessment of groundwater-surface water interaction such that the effect of CO_2 storage on river flows may be investigated.

Abstraction of groundwater from specific nodes was incorporated within the model, using licensed quantities obtained from Environment Agency records. Due to the quality of groundwater, and ease of abstraction, the majority (~85%) of groundwater from the SSG is abstracted from the unconfined aquifer with the remainder abstracted from the shallow confined SSG aquifer. The location of individual boreholes in the model were set by their grid reference, with the top 29 (by volume) annual licensed abstractions from the SSG within the model boundaries included. Temporal abstraction data and borehole depth are not readily available, therefore abstraction within the model is constant with time and occurs in the second layer of the model.

Vertical leakage through the caprock is dependent on the pressure variation, permeability and thickness of caprock. In the model this was represented by: the vertical conductance of the leakage nodes (C_z), the area of the grid node, the aquifer head and the elevation of the leakage (for further detail see Jackson and Spink, 2004). Vertical conductance is equivalent to the vertical hydraulic conductivity of the overlying strata and the distance between the aquifer and the leakage node. The groundwater heads output by the steady-state model were used to define elevation level of the leakage nodes. A range of leakage scenarios were tested by varying the co-efficient of vertical conductance (C_z = 0, 10^{-8} 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} and 1) with the model run to steady-state. Subsequent time-variant model runs, which represent the life cycle of the CO_2 storage scheme and which better represent observed vertical hydraulic conductivity of the MMG were completed for a selection of leakage scenarios (C_z= 10^{-6}, C_z=10^{-7} and C_z=10^{-8}). See table two for a description of the four leakage scenarios for which results are presented.

5.1 Injection Representation

Onshore injection of CO_2 into the SSG aquifer system must be at depths suitable to maintain the critical state of the fluid. CO_2 is generally injected in a supercritical phase at pressures above 6.9 MPa to minimise the injected volume. Therefore, a depth of 800 m or greater must be used to keep the CO_2 in a supercritical state (Sminchak and Gupta, 2003). A real site, for hypothetical injection, was selected within the UK as part of the CASSEM project where the criteria for assessing the impacts of CO_2 storage were satisfied (Smith et al., 2011). While other aspects of the CASSEM project were concerned with multiphase reservoir modelling (Smith et al., 2011) the aim of this study was to assess the far-field impact on shallow potable water resources (within the SSG) using a groundwater flow model (ZOOMQ3D). CO_2 injection cannot be represented explicitly in ZOOMQ3D, as it does not simulate multiphase flow. The model is able to simulate the abstraction of water from individual, or a series of interlinked nodes. Through application of a negative abstraction it is possible to simulate the injection of water (for an equivalent CO_2 injection rate) into the system.

To align with injection scenarios run within the multiphase reservoir modelling exercise an injection rate of 15 Mt/yr for 20 years is assumed (p94 Smith et al., 2011). Sminchak and Gupta (2003) suggest a supercritical CO_2 density of between 0.6 and 0.75 g/cm^2, which, using the specified injection rate, equates to a volume of between 55,000 and 68,000 m^3/d. For the groundwater model an injection rate of 60,000 m^3/d was used. In the early phases of this study a number of injection scenarios were considered to ascertain the effects of pumping CO_2 into the system. It concluded that the spreading of injection over several sites would have the least impact on the groundwater system. Use of a single well at each site is also discounted, as the pressures on the injection pumping equipment would be too great. In this study injection has been spread over eight wells at four injection locations, each injecting 7,500 m^3/d (1.88 Mt/y) throughout the total thickness of the SSG at each well location.

6. Results

Results from the groundwater model are presented for the four leakage scenarios $C_z = 0$, $C_z = 10^{-6}$, $C_z = 10^{-7}$ and $C_z = 10^{-8}$ (table 2).

Table 2 – Description of the four leakage scenarios run within the groundwater model

6.1 Scenario 1 – zero leakage

Under steady state *zero leakage* conditions, the MMG is considered to behave as a perfect seal, groundwater pressure heads around the injection wells increase by more than 700 m and increases of up to 50 m are observed some 70 km up-dip within the potable confined aquifer. Groundwater levels in the unconfined SSG were raised by up to 10 m and river flows increased by between 11 – 18%. The disparity in river flow increases is due to the non-uniform increase in groundwater heads across the unconfined and shallow confined SSG aquifer. The largest increases in groundwater heads and therefore river flows are observed to the north of the study area near River Humber.

6.2 Scenario 2 - Leakage C_z 10^{-7} (vertical hydraulic conductivity 10^{-6} m/d)

The outputs from the *zero leakage*, steady-state scenario represent the worst possible impacts on shallow groundwater systems, however they are not representative of the likely hydrogeological setting. With a vertical hydraulic conductivity of 10^{-7} – 10^{-6} m/d (1 – 10 µD), it is expected that the MMG does not behave as a prefect seal, such that the potential for vertical leakage out of the SSG storage formation exists. A coefficient of vertical conductance of 10^{-7} was used to represent the hydrogeological conditions of the MMG in this scenario (2). This value better represents the expected leakage through the MMG caprock. The difference in groundwater heads between baseline and injection conditions for this second scenario are shown in Figure 4. Groundwater heads within the injection zone are increased by approximately 300 m, while an increase in head of 50 m is observed up to 30 km up-dip within the SSG. An increase in groundwater head within the potable confined aquifer of between 1 m to 13 m is observed. Steady-state groundwater levels in the unconfined aquifer are increased by 0 – 1 m with a corresponding increase in river flows of between 1.5 – 2.3%.

Figure 4 – Difference in groundwater heads (m) between baseline and steady-state injection scenarios using a vertical leakage co-efficient (10^{-7}). The vertical red lines

represent the transition from unconfined, to shallow confined and deep confined (left to right).

Using the coefficient of vertical conductance of 10^{-7} (which represents a vertical hydraulic conductivity (K_v) of 10^{-6}m/day), a more realistic leakage condition of the MMG caprock, time variant outputs were also produced to investigate the propagation of groundwater pressure heads with time. For the time variant scenario a 20 year injection period was used with a 100 year recovery period.

The difference in groundwater heads from the baseline condition are presented (Figures 5 and 6). The system responds rapidly to injection pressures with notable increases in groundwater heads occurring within the first year of injection. The deep saline aquifer reaches steady conditions within three years of injection, with groundwater head increases of over 200 m close to the injection point. The potable confined aquifer is slower to respond; from initial groundwater head increase of up to 1 m during the first year of injection it takes a further 5-10 years for groundwater heads to stabilise, reaching a maximum of 10 m above the baseline condition. A similar delay in response is observed within the unconfined SSG aquifer where groundwater levels appear to stabilise 10-15 years into the injection period. Groundwater level increases within the unconfined aquifer approach 1 m in the north of the model area with a resultant increase in river flows of up to 0.6% locally.

The recovery of groundwater heads in the deep saline aquifer, near the injection point, is initially rapid with levels recovering to within 90 m of the baseline within the first year. Thereafter there is a halving of groundwater heads for every subsequent year recovery such that after 10 years recovery (t=30 yrs) groundwater heads in the deep saline aquifer return to baseline. In marked contrast recovery of groundwater heads in both the potable confined aquifer and the unconfined aquifer is initially slow with little or no recovery observed during the first year. After 10 years recovery (t=30 yrs) groundwater heads recover to within 1m of the baseline across most of the potable confined aquifer, while groundwater levels in the unconfined aquifer show no recovery. After 100 years of recovery (t = 120 years), groundwater heads in the confined aquifer are generally within 0.1 m of the original baseline setting. The contrast in response of groundwater heads and river flows to injection and recovery between the aquifer sections is shown in Figures 5 and 6.

Figure 5 – Yearly time-variant groundwater head differences (from baseline (m)) for leakage scenario 2 (C_z = 10^{-7}) for a 20 year injection period. The vertical red lines

represent the transition from unconfined to shallow confined and deep confined (left to right).

Figure 6 – Five-yearly time-variant groundwater head differences (from baseline (m)) for leakage scenario 2 (C_z = 10^{-7}) for a 20 year injection period. The vertical red lines represent the transition from unconfined to shallow confined and deep confined (left to right).

The spatial distribution of vertical leakage through the MMG, assuming a leakage co-efficient of 10^{-7}, is shown in Figure 7. At 20 years, the maximum vertical nodal leakage is 29.3 m^3/d around the injection wells, with leakage occurring up to 50 km from the injection site. Leakage into the potable confined SSG from overlying strata (negative) continues throughout the injection period occurring at a maximum rate of 4.5 m^3/d per node however the extent of this leakage into the deep confined is spatially constrained. After 20 years of recovery (t = 40 years), leakage within the system returns to pre-injection levels.

Figure 7 – Time variant vertical leakage plots for leakage scenario 2 (C_z = 10^{-7}) taken at baseline (zero years), 20 years (end of injection) and 40 years (after 20 years recovery). The vertical red lines represent the transition from unconfined to shallow confined and deep confined (left to right). Contours represent the rate of vertical nodal leakage with units of cubic metres per day (m^3/d).

6.3 Scenario 3 and 4 – Sensitivity of the model to the leakage coefficient of the MMG

The co-efficient of vertical conductance (C_z) of the MMG was varied to demonstrate the extent to which the vertical leakage of the caprock affects the pressure response within the storage formation and within overlying formations. C_z for the MMG was initially increased by one order of magnitude to 10^{-6}, corresponding to a vertical hydraulic conductivity of 10^{-5} m/day. Under this more leaky scenario groundwater head increases are less pronounced but still respond rapidly to injection. After 5 years injection groundwater heads are largely stabilised across the entire model area, though small increases in groundwater heads (<0.01 m) are observed in the unconfined aquifer throughout the injection period (20 yrs). Under this leakage scenario (C_z = 10^{-6}) groundwater heads increase by 0.01 – 0.1 m in the potable confined aquifer and by <0.01m in the unconfined aquifer with negligible increases in river flow. Increasing the vertical conductance of the caprock by one order of magnitude serves to reduce groundwater heads in the potable confined aquifer and the unconfined aquifer by two orders of magnitude. Recovery of groundwater heads under this scenario is rapid with the whole system returning to within 0.01 m of the baseline condition within 5 years.

The vertical conductance (C_z) of the MMG was subsequently reduced by one order of magnitude to 10^{-8} (K_v equivalent 10^{-7} m/day). The effect of this change on groundwater heads is marked. After 20 years of injection groundwater heads in the potable confined aquifer are up to 50 m above baseline conditions without reaching steady-state. Though approaching steady state, groundwater levels in the unconfined aquifer fail to stabilise either with levels up to 1 m above the baseline after 20 years. River flows at the end of this injection period increase by between 7.8 – 12.3%. A summary of injection pressure effects on groundwater systems under the different caprock leakage scenarios is provided in table 3.

6.4 The effect of abstraction

Groundwater heads in the unconfined and potable confined SSG aquifer are affected by abstraction such that vertical leakage into the SSG storage formation from overlying strata is induced. The effect of this is most noticeable when a lower permeability is assigned to the MMG caprock (leakage scenario 4 $C_z = 10^{-8}$, $K_v = 10^{-7}$ m/day). By reducing the permeability of the MMG vertical leakage into the SSG is significantly reduced. Therefore in areas where abstraction is high (i.e. the south-west sections of the model area) but vertical leakage through the MMG is low, groundwater heads in the SSG after injection remain low despite significant increases in groundwater heads in other parts of the potable aquifer. Such is the strength of this effect that groundwater heads in the southern parts of the potable confined and unconfined aquifer are lower when applying a C_z of 10^{-8} despite massive (5-fold) increases in groundwater heads elsewhere in the model area. It may be inferred from these results that if the caprock is of a sufficiently low permeability groundwater abstraction whether it be coincidental or as part of a planned pressure-relief exercise may be successful in keeping groundwater pressure heads low.

Table 3 – Summary of injection pressure effects on groundwater systems under different caprock leakage scenarios.

6.5 Limitations of the model results

While it is appropriate to adopt a simplified modelling approach for the determination of the scale of impact or risk calculation of geological storage of CO_2 on shallow groundwater systems, it does introduce limitations to the interpretation of the modelling results. These limitations relate either to simplification of the conceptual model within the groundwater flow model or the implementation of a single-phase flow code to represent multiphase flow.

Simplification of the conceptual model:

- Only the SSG storage formation and the overlying MMG primary sealing formation are represented within the groundwater flow model. While vertical leakage through the MMG is assessed the effect of the overburden, i.e. the hydraulic functioning of the geological units overlying the MMG is not accounted for.
- A no-flow condition has been applied to all model boundaries meaning they act as a barrier to the propagation of groundwater pressure head increases generated as a result of injection. The intersection of the cone of pressure increase with the eastern model boundary is evident in the modelling results. A no-flow boundary condition was assumed for the eastern model boundary given the close proximity of the Dowsing Fault zone where fault displacements of up to 400m are recorded. In reality a small amount of flow is likely to occur across this zone. The net effect of this assumed boundary condition is the prediction of artificially higher pressure heads up-dip within the system.
- The river drainage network is simplified to five rivers orientated in an east-west direction to represent an aquifer unit with a low drainage density as may be expected for the SSG. While the model results provide an indication of the volume increase in baseflow contribution to groundwater dependent surface water systems, model refinement would be required to identify (i) where the increased baseflow would be discharged and (ii) the mechanism of discharge e.g. via the river network or springs or by the reactivation of dry valleys.

Single phase model approach:

Nicot (2008) describes the limitations of single phase models and how these can be overcome. This author also states that the variance in the results is around 10% and less than 20%. Nicot et al., (2011) compare a single phase model with multiphase version and show that with simple modifications to permeability fields and injection rates overestimates in the pressure effects within single-phase models may be corrected. Following on from this work, Hosseini and Nicot, (2012) suggest how two phase models can be modified to represent the injection of supercritical CO_2 as an oil phase again by changing permeability and factoring the injection rate. This approach can be modified for supercritical CO_2 injection into single phase models. In light of these investigations, it is suggested that the groundwater head in our modelling results is over estimated by of the order of 10-20 % as outlined by Nicot (2008), and is acceptable for the risk estimation approach adopted for our work.

7. Discussion

Simulation of CO_2 injection into the SSG aquifer in its deep saline extent demonstrates that impacts on shallow groundwater systems are potentially significant despite their relatively distant position some 60-100km up dip of the injection zone. Using the most likely hydraulic parameters, modelled results show an increase in groundwater heads of up to 10m in the potable confined aquifer and up to 1 m in parts of the unconfined aquifer. Head increases of this proportion would be readily detected by routine groundwater monitoring of boreholes and could result in groundwater flooding in areas where groundwater levels are already close to surface such as near the Humber Estuary. It is unlikely given natural variability in river flows whether the expected increase in river baseflow of 1.7% (average) would be detected at gauging stations.

Since the MMG caprock is not a perfect seal, saline water would leak from the SSG to overlying formations as a consequence of injection. Applying the most likely vertical hydraulic conductivity of 10^{-6} m/day to the MMG approximately 40 Ml/d of saline water would be displaced as a result of injection and leak out of the storage formation. A similar volume (44 Ml/d) would be lost from the storage formation when the leakage co-efficient of the MMG is increased by one order of magnitude. Even when the leakage co-efficient is reduced by one order of magnitude (C_z 10^{-8}) approximately 20 Ml/d would be lost from the storage formation. The vulnerability of overlying strata under these leakage scenarios needs to be assessed. In the study area there are two principal aquifers and numerous secondary aquifers present within the geological sequence overlying the storage formation. Further investigation of these leakage effects is therefore warranted, in particular the layered hydrogeological heterogeneity within the MMG needs to be better characterised.

While the SSG is traditionally thought of as a high storage aquifer this is less true within its deep saline extent where porosity is half that of the SSG at outcrop (18%) and permeability is typically 700 - 5000 mD. The response of the deep saline aquifer to injection pressures is both great and rapid. As the pressure effect propagates through the storage formation into zones of higher storage and permeability within the potable confined aquifer and the unconfined aquifer the response to injection pressures becomes dampened and delayed with maximum impact occurring 5-15 years after injection.

Sensitivity analysis shows the importance of good characterisation of the caprock, the MMG, to understand the dissipation of injection pressures. When the leakage co-efficient is increased by one order of magnitude groundwater heads in the potable confined aquifer and the unconfined aquifer are reduced by two orders of magnitude. When the leakage co-efficient is reduced by one order of magnitude there is a five-fold increase in groundwater heads in parts of the potable confined aquifer. The buffering of the propagation of injection pressure heads induced by the reduced vertical leakage into the storage formation within the potable confined aquifer is unexpected. The combination of reduced vertical leakage and large volumes of groundwater abstraction apparently being sufficient to restrict the propagation of injection pressures and keep groundwater heads low in parts of the potable aquifer. There is a suggestion from these results therefore that if the caprock is of sufficiently low permeability the use of pressure relief abstraction boreholes to limit the effect of injection pressure may be an effective management tool and more detailed investigation may prove useful.

Modelling shows that groundwater heads will not stabilise during the 20 year injection period when the vertical leakage through the caprock is reduced by one order of magnitude from $C_z = 10^{-7}$ to $C_z = 10^{-8}$. In the event therefore that the injection period is extended the groundwater heads under this scenario are expected to exceed those currently observed within the modelling exercise. The time taken for the maximum impact to occur on the potable aquifer and the subsequent recovery of groundwater levels to baseline condition upon cessation of injection is largely controlled by vertical leakage through the caprock with the delay being anywhere between 5 and >20 years.

It is recognised that our existing groundwater model does not assess leakage via wells or along existing or induced faults and fractures, nor does it model the physical migration of CO_2. While it would be preferable to have full representation of both the physical and geochemical environment and better representation of our conceptual model, our simplified groundwater flow model is capable of establishing the scale of likely impact on shallow groundwater systems, to inform both more detailed environmental impact assessments and smaller-scale reservoir modelling. Moreover we identify areas of greatest concern and uncertainty such that further investigations can be undertaken and management questions can begin to be answered.

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Captions

Figure 1 – Schematic of the hydrogeological system present within the study area. Hypothetical leakage pathways for pressure dissipation are shown; through cap rocks, along faults and through existing wells within the storage reservoir and within the aquifer.

Figure 2 – Geology of the study area with model boundaries and injection points shown. The Dowsing Fault Zone lies approximately 20-40 km east of the eastern model boundary. Geological cross-section through the study area annotated with hypothetical leakage routes.

Figure 3 – Box and whisker plots of SSG permeability at different depth intervals.

Figure 4 – Difference in groundwater heads (m) between baseline and steady-state injection scenarios using a vertical leakage co-efficient (10^{-7}). The vertical red lines represent the transition from unconfined, to shallow confined and deep confined (left to right).

Figure 5 – Yearly time-variant groundwater head differences (from baseline (m)) for leakage scenario 2 ($Cz = 10^{-7}$). The vertical red lines represent the transition from unconfined to shallow confined and deep confined (left to right).

Figure 6 – Five-yearly time-variant groundwater head differences (from baseline (m)) for leakage scenario 2 ($Cz = 10^{-7}$). The vertical red lines represent the transition from unconfined to shallow confined and deep confined (left to right).

Figure 7 – Time variant vertical leakage plots for leakage scenario 2 ($Cz = 10^{-7}$) taken at baseline (zero years), 20 years (end of injection) and 40 years. The vertical red lines represent the transition from unconfined to shallow confined and deep confined (left to right). Contours represent the rate of vertical nodal leakage with units of cubic metres per day (m^3/d).

Tables

Geological sequence and relative thickness	Age	Hydrogeological classification	Approximate thickness at injection site (m)	Observed transmissivity/ hydraulic conductivity	Modelled Hydraulic Conductivity
Chalk Group	Cretaceous	Aquifer	180	Transmissivity 1800 m²/d	Not modelled
Jurassic Clays	Upper Jurassic	Non-aquifer	350	Hydraulic conductivity 10^{-6} m/d	Not modelled
Jurassic Limestones	Middle Jurassic	Aquifer	40	Transmissivity 650 m²/d	Not modelled
Lias Group	Lower Jurassic	Mixed permeability deposit	270	Hydraulic conductivity 5×10^{-4} m/d	Not modelled
Mercia Mudstone Group	Triassic	Non-aquifer	300	Hydraulic conductivity: Shallow: 10^{-5} m/d Deep: 10^{-5} - 10^{-7} m/d	Vertical hydraulic conductivity 10^{-5} - 10^{-7} m/d
Sherwood Sandstone Group	Permo-Triassic	Aquifer	300	Hydraulic conductivity: Shallow: 0.65 - 1.6 m/d Deep: 0.18 m/d	Hydraulic conductivity: Shallow: 1.3-10 m/d Deep: 0.1-1.8 m/d

Table 1 - Summary hydrogeological sequence within the study area. Observed and modelled permeability values are provided for each of the geological units.

Scenario	Leakage coefficient	Vertical hydraulic conductivity (m/day)	Condition
1	Zero $C_z = 0$	0	MMG behaves as a perfect seal
2	$C_z = 10^{-7}$	10^{-6}	Preferred MMG leakage value
3	$C_z = 10^{-6}$	10^{-5}	MMG leakage is increased by one order of magnitude
4	$C_z = 10^{-8}$	10^{-7}	MMG leakage is reduced by one order of magnitude

Table 2 - Description of the four leakage scenarios run within the groundwater model.

Leakage scenario (C_z)	**Caprock vertical hydraulic conductivity (K_v) m/d**	**Increase in heads in the unconfined aquifer (m)**	**Increase in heads in the potable confined aquifer (m)**	**Increase in river baseflow (%)**	**Time to maximum impact in potable aquifer (yrs)**	**Recovery time (yrs)**
10^{-6}	**10^{-5}**	<0.001	0.01 – 0.1	Negligible	> 5	<5
10^{-7}	**10^{-6}**	< 1	0.01 – 10	1.46 – 2.32	10-15	15
10^{-8}	**10^{-7}**	< 1	0.001 - 50	7.8 – 12.3	> 20	>20

Table 3 - Summary of injection pressure effects on groundwater systems under different caprock leakage scenarios.