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Hydrogeological conceptual model of the Spittal area - Project Groundwater Northumbria

Project Groundwater Northumbria

Commercial report CR/26/048

BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/26/048

Hydrogeological conceptual model of the Spittal area - Project Groundwater Northumbria

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Summary

This report has been produced by the British Geological Survey (BGS) on behalf of Project Groundwater Northumbria, the Flood and Coastal Innovation Programme (FCIP) project managed by Gateshead Council. It uses existing data and information to provide a conceptual understanding of the hydrogeology of the Spittal area, whilst discussing recent groundwater trends and groundwater flood susceptibility in the area. It also provides information on how historic coal mining may have impacted the groundwater system. The report shows two schematic cross-sectional diagrams to visually conceptualise groundwater across the area.

The geology is composed of interbedded Carboniferous age sedimentary rocks which have been folded, forming an asymmetrical anticline. Therefore, geological strata towards the east coast dip steeply to the east, whilst strata further west dip more gently to the south-southeast.

The Ballagan Formation and Fell Sandstone Formation located in the northwest of the area form a productive aquifer which supplies water to the local population. The Scremerston Coal Member which underlies the village of Spittal and village of Scremerston forms a complex, multi-layered aquifer system comprising sandstone aquifer units separated by low permeability rocks forming aquitards. The Tyne Limestone Formation and Alston Formation in the east and south of the area also form a series of aquifer units and aquitards. Groundwater flow is likely to broadly follow the dip of the geological strata, potentially creating a groundwater divide through the area.

Superficial deposits include till, morainic and glaciolacustrine deposits, alluvium in the River Tweed and Allerdeanmill Burn valleys, river terrace, estuarine and glaciofluvial deposits around the River Tweed, beach deposits (sand, silt, gravel) on the coast, including under parts of Spittal. Till and glaciolacustrine deposits are likely to reduce bedrock aquifer recharge, whilst permeable alluvium, river terrace deposits, morainic deposits and beach deposits are conducive to groundwater recharge (or discharge), potentially forming small, perched aquifers.

Mine workings throughout much of the Scremerston Coal Member are likely to increase aquifer storage and potentially provide flow pathways connecting separate sandstone aquifer units. Some mine adits drain mine water into the North Sea and some workings extend under parts of Spittal, potentially increasing groundwater flow towards the village.

Groundwater level trends vary, with levels in the Fell Sandstone Formation and Ballagan Formation lowered significantly by abstractions. Groundwater levels and trends in the Scremerston Coal Member, Tyne Limestone Formation and Alston Formation are poorly understood due to a lack of data.

Groundwater flood risk is greatest in lower parts of Spittal where water likely discharges from sandstone aquifer units of the Scremerston Coal Member. Localised groundwater flooding is also possible in higher elevation areas where it emerges from aquifer units, fractures or perched superficial deposit aquifers.

1 Introduction

1.1 BACKGROUND AND SCOPE

This report presents a conceptual hydrogeological understanding for the Spittal area as part of commissioned work for Project Groundwater Northumbria (PGN), part of the Flood and Coastal Resilience Innovation Programme (FCRIP) project led by Gateshead Council. This hydrogeological understanding incorporates and builds on previous work including groundwater flood risk susceptibility work undertaken by the Environment Agency (EA) and superficial deposit hydrogeological domains work undertaken by BGS (Burke et al., 2024).

The PGN workstreams are intended to help project partners including the Environment Agency and Gateshead Council understand spatial variations in recharge to bedrock aquifers and highlight areas where outflow from sandstone units or historic mine workings may increase risks of groundwater flooding and/or interact with surface water systems and shallow superficial aquifers.

This report compiles existing datasets to provide a conceptual understanding of regional groundwater recharge, flow and discharge for both bedrock and superficial deposit aquifers. It also highlights mining impacts on groundwater flow, aquifer connectivity and flood susceptibility in the Spittal area. Conceptual hydrogeological cross-sections have been produced to illustrate the various hydro(geo)logical processes and source(s) of groundwater flooding.

1.2 AREA OF INTEREST

The area of interest (AOI) is approximately 5 km by 5 km and comprises Spittal, East Ord, Tweedmouth and Scremerston (Figure 1). The study area matches that of the superficial hydro-domains work by Burke et al. (2024).

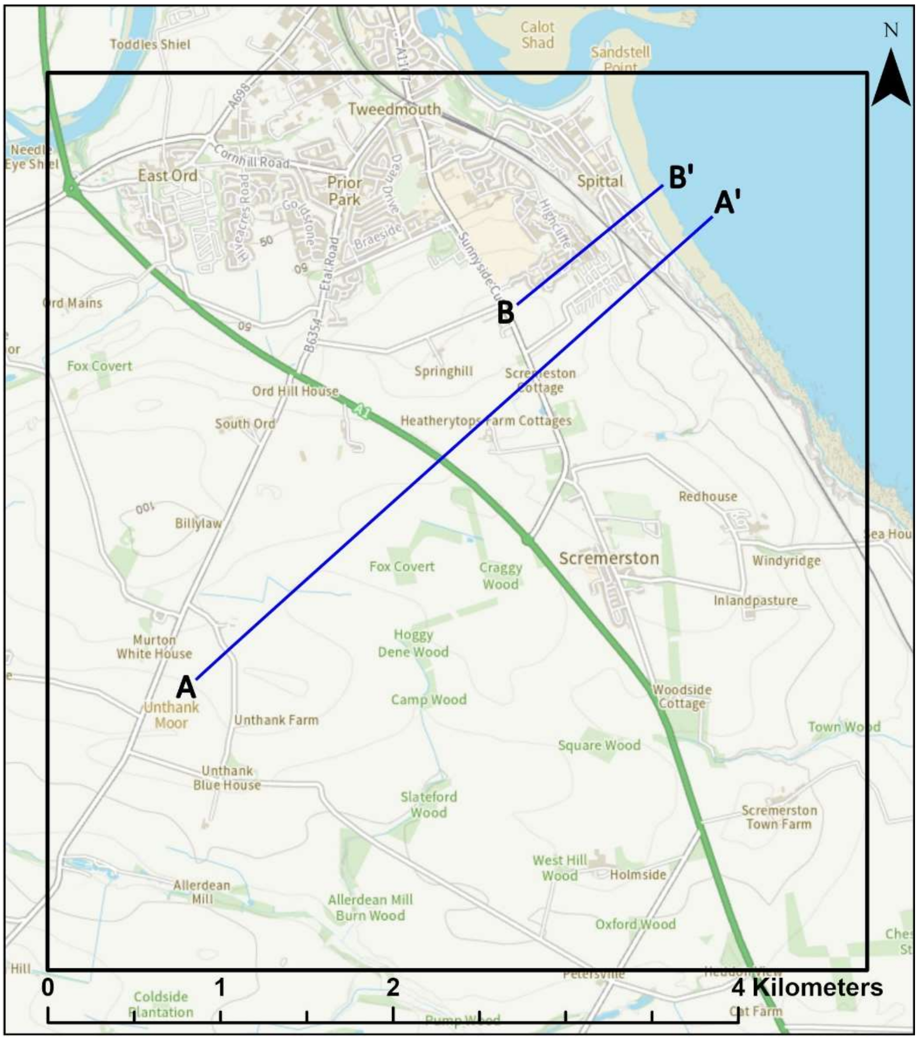

Figure 1: Area of interest used for the conceptual model, bounded by the black outline. The locations of cross-sections in Figure 10 and Figure 11 are shown. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

1.3 GEOGRAPHY AND CLIMATE

The AOI is located on the Northumberland coast immediately south of where the River Tweed flows into the North Sea. The villages of Spittal and East Ord and town of Tweedmouth are found in the north of the area, whilst the rest of the area comprises mostly arable land and the village of Scremerston. The Allerdeanmill Burn is in the south of the AOI, flowing southeast to the North Sea.

Land elevation varies from sea level to 108 Metres Above Ordnance Datum (mAOD) to the southwest of the A1 Road (Figure 2). There are coastal cliffs to the south of Spittal and the village itself is situated on moderately-steeply sloping land from around 75 mAOD to near sea level.

The area has a mild, temperate, maritime climate with precipitation occurring year-round, but peaking in the autumn and winter months. Mean annual rainfall is around 700 - 725 mm (Met Office, 2025) but can vary from around 500 - 900 mm (Bianchi et al., 2023b). Actual evaporation in the region is around 470 - 530 mm a^{-1} (Kay et al., 2013), indicating that approximately 170-255 mm a^{-1} is available for potential recharge or runoff. Bianchi et al. (2023b) who modelled the Fell Sandstone aquifer used recharge values generated by ZOODRM of 150 - 225 mm a^{-1}. Most aquifer recharge occurs during the winter months when precipitation is typically higher and evaporation is significantly lower.

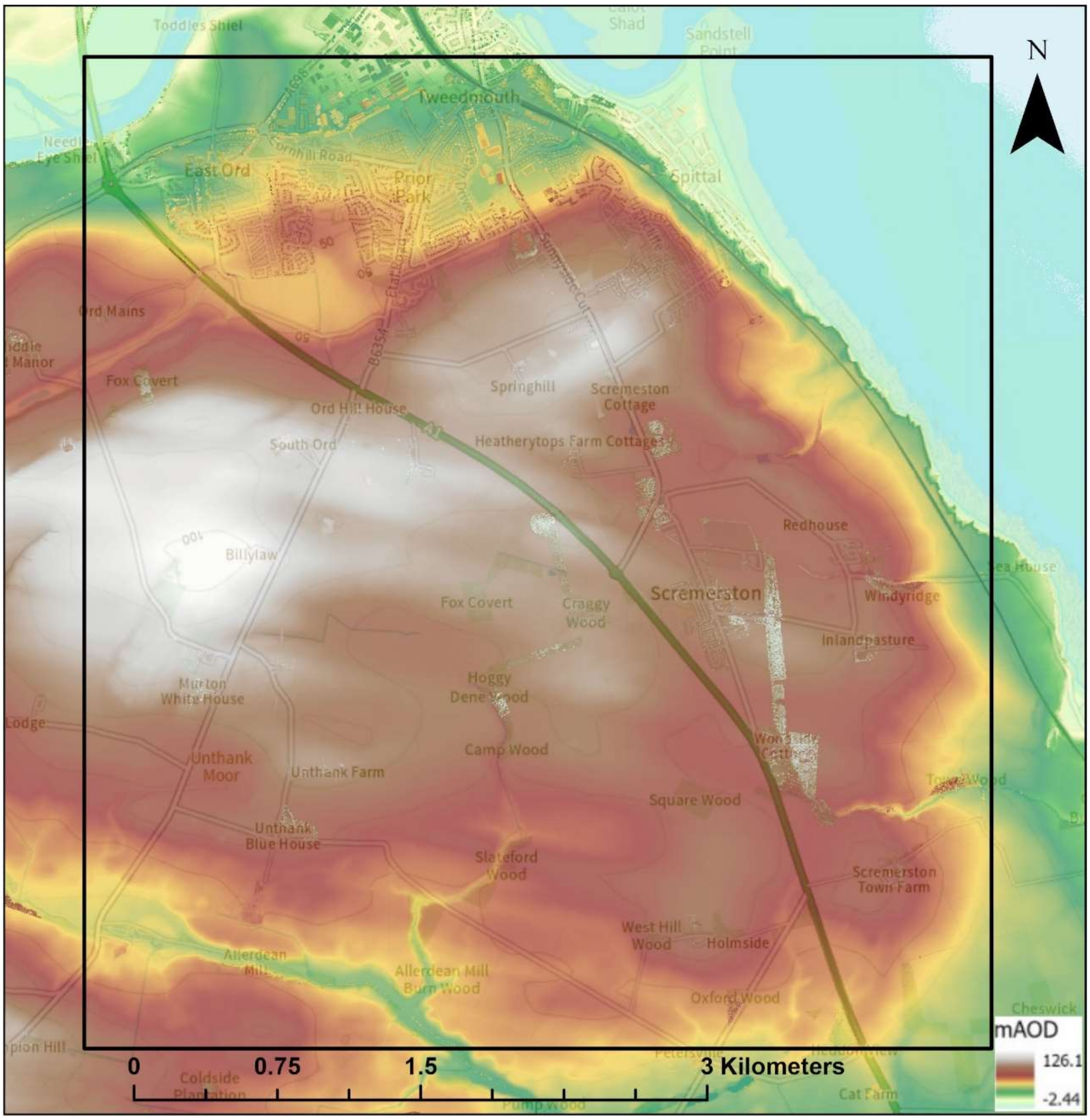

Figure 2: Topographic map of the AOI. LiDAR DTM 1m model © Environment Agency copyright and/or database rights 2022. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

1.4 BEDROCK GEOLOGY

The bedrock geology of the area comprises Carboniferous sedimentary rocks. The oldest bedrock unit in the area is the Ballagan Formation which is present around the River Tweed in the northwest. It is composed of siltstone, dolomitic limestone and sandstone.

Above the Ballagan Formation lies the Fell Sandstone Formation which comprises 225 - 350 m of sandstones interbedded with mudstones and siltstones (Bianchi et al., 2023b). It comprises seven main sandstone units which are up to 40 m thick and vary laterally (Ford et al., 2019). It is present at the surface around East Ord and Tweedmouth and dips to the southeast beneath the overlying Scremerston Coal Member. Water abstraction boreholes drilled into the Fell Sandstone Formation around Berwick-upon-Tweed revealed variable net sand contents of 40-80% (Howell et al., 2022). Sandstones were deposited in an unconfined braided-river system whilst silts and mudstones were deposited in lower energy terrestrial environments or possibly from sporadic marine incursions (Howell et al., 2022; Bianchi et al., 2023b).

Above the Fell Sandstone Formation lies the Scremerston Coal Member which forms the lower part of the Tyne Limestone Formation. The Scremerston Coal Member is approximately 310 m thick in the AOI (Jones et al., 2007) and comprises sedimentary cycles of mudstones, siltstones, sandstones, thin limestones and coal seams. Prominent coal seams within (oldest to youngest) include the Fell Coal, Wester Coal, Cooper Eye Coal, Bulman Main Coal, Blackhill Coal, Fawcett Coal and Robie's Coal. In 330 m of strata at Berwick, 14 sandstones between 3 - 15 m thick are recorded along with other thinner sandstones (Smith, 1967). The Scremerston Coal Member was deposited in a deltaic environment with marine incursions (Smith, 1967; Jones, 2007). Jones (2007) observed major channel sandstones up to 35 m thick and often stacked with a variable palaeoflow direction to the southwest - southeast around Berwick-Upon-Tweed. The Scremerston Coal Member is exposed along the coastline, including just south of Spittal where channel sandstones including the Red Shin, Maidenkirk Brae and Pier Quarry Sandstones are observed (Jones, 2007; Gardiner, 1983).

The Tyne Limestone Formation above the Scremerston Coal Member is composed of limestone, sandstone, siltstone, mudstone and coal. Around Spittal, the Dun Limestone signifies the base of the Tyne Limestone Formation. It includes the Dun and Woodend Limestone Members and the Little Howgate Coal.

The youngest bedrock in the area is the Alston Formation which is composed of limestone, sandstone, siltstone and mudstone. It includes the Oxford Limestone Member, the Eelwell Limestone Member and an unnamed coal. The base of the Alston Formation is associated with the Watchlaw Limestone Member.

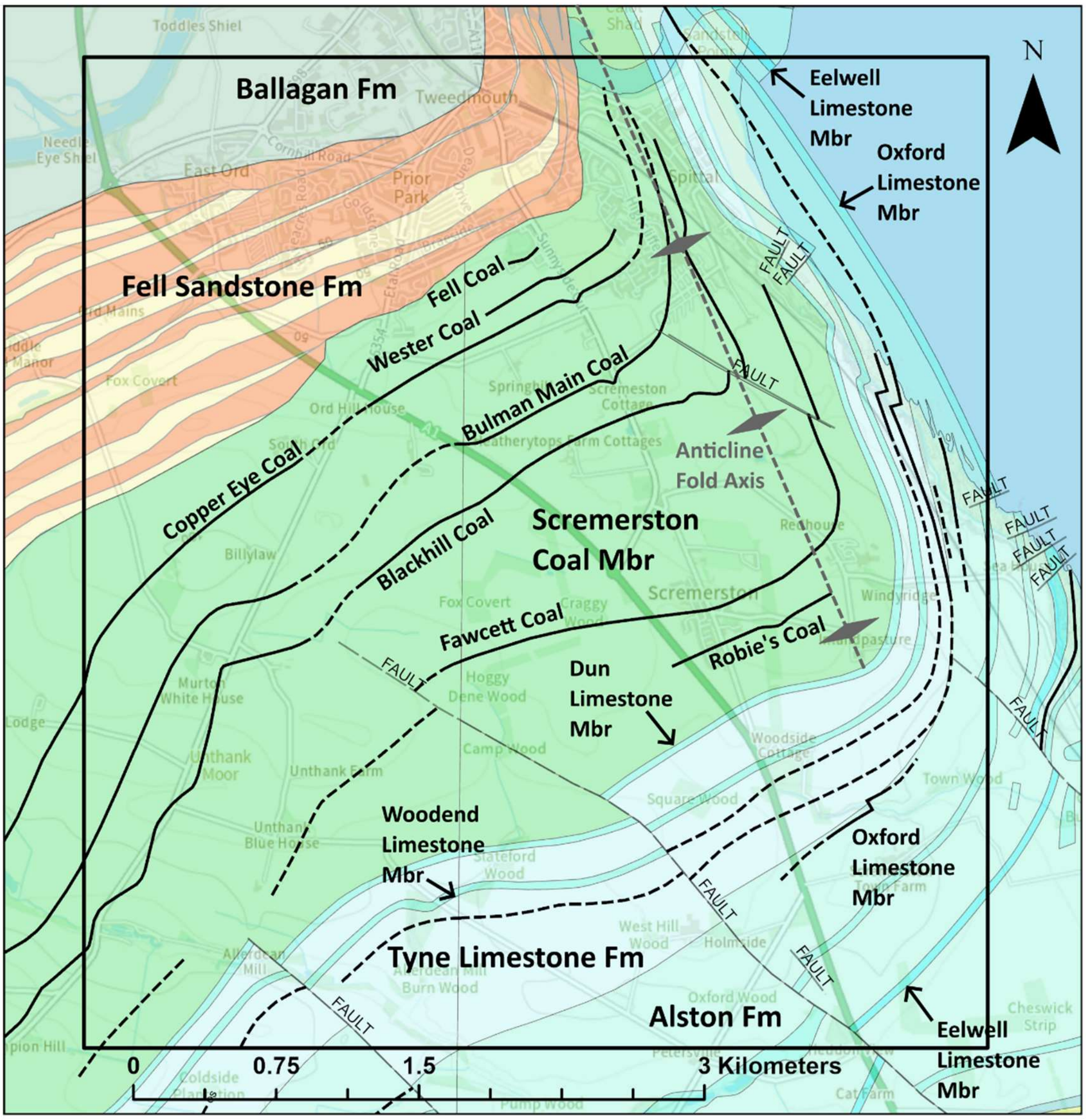

Figure 3: Bedrock (1:50 000 scale) geology showing the main formations (labelled) and mapped coal seams (black lines), the Berwick Monocline (anticline) fold axis and fault lines. Fm = Formation, Mbr =

Member. BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

1.4.1 Structural Geology

The geological structure of the Carboniferous rocks in the Spittal area comprises an asymmetrical plunging anticlinal fold known as the Berwick Monocline (Figure 3) (Shields, 1963). This structure changes the dip of the strata from 10-20 degrees to the southeast to 50 - 55 degrees to the east along the coast (Bianchi et al., 2023b). The Berwick Monocline has formed at the end of a major north-south orientated fault line which fades out immediately north of Berwick-Upon-Tweed (Bianchi et al., 2023b). The Berwick Monocline likely has a strong control on the hydrogeology of the area which is discussed in section 3.1.4. Two northwest-southeast orientated faults have been mapped in the south of the area, and there are small southwest – northeast orientated faults exposed in cliff sections in the east of the AOI.

1.4.2 Superficial Geology

The superficial geology of the area has recently been remapped by Whitbread & Dewald (2026) as the original maps dated back to 1920. Approximately 63% of the area of interest is covered by superficial deposits, with till comprising clay with variable proportions of silt, sand and gravel covering 57% of the area (Whitbread & Dewald, 2024) (Figure 4). The till is typically <10 m thick (Burke et al., 2024). River terrace sands and gravels, and marine-estuarine deposits comprising sands, gravels, silts and clays are found immediately along the eastern banks of the River Tweed (Whitbread & Dewald, 2026). Alluvium is also present around the River Tweed, and around Allerdeanmill Burn where it is 1-2 m thick (Burke et al., 2024). Morainic and glaciolacustrine deposits associated with deglaciation are also present, with a moraine ridge present to the south of Spittal (Figure 4). Coarse sand and gravel beach deposits are present along the coastline around Spittal and Berwick-upon-Tweed, with interbedded sands and gravels reaching thicknesses of around 20 m beneath Spittal (Whitbread & Dewald, 2026). Superficial deposits are absent or thin (<2 m thick till) across 37% of the area, particularly on the higher ground and where bedrock is exposed at the surface.

A superficial deposit thickness model for the area was developed by Burke et al. (2024) through analysis of borehole records. From this model, superficial hydrogeological domains were developed to help understand the influence of complex superficial deposit sequences on potential recharge to, and discharge from, underlying bedrock aquifers (Burke et al., 2024). Hydro-domains are discussed in section 3.2. along with the hydrogeological implications of the 2026 re-mapping of superficial deposits.

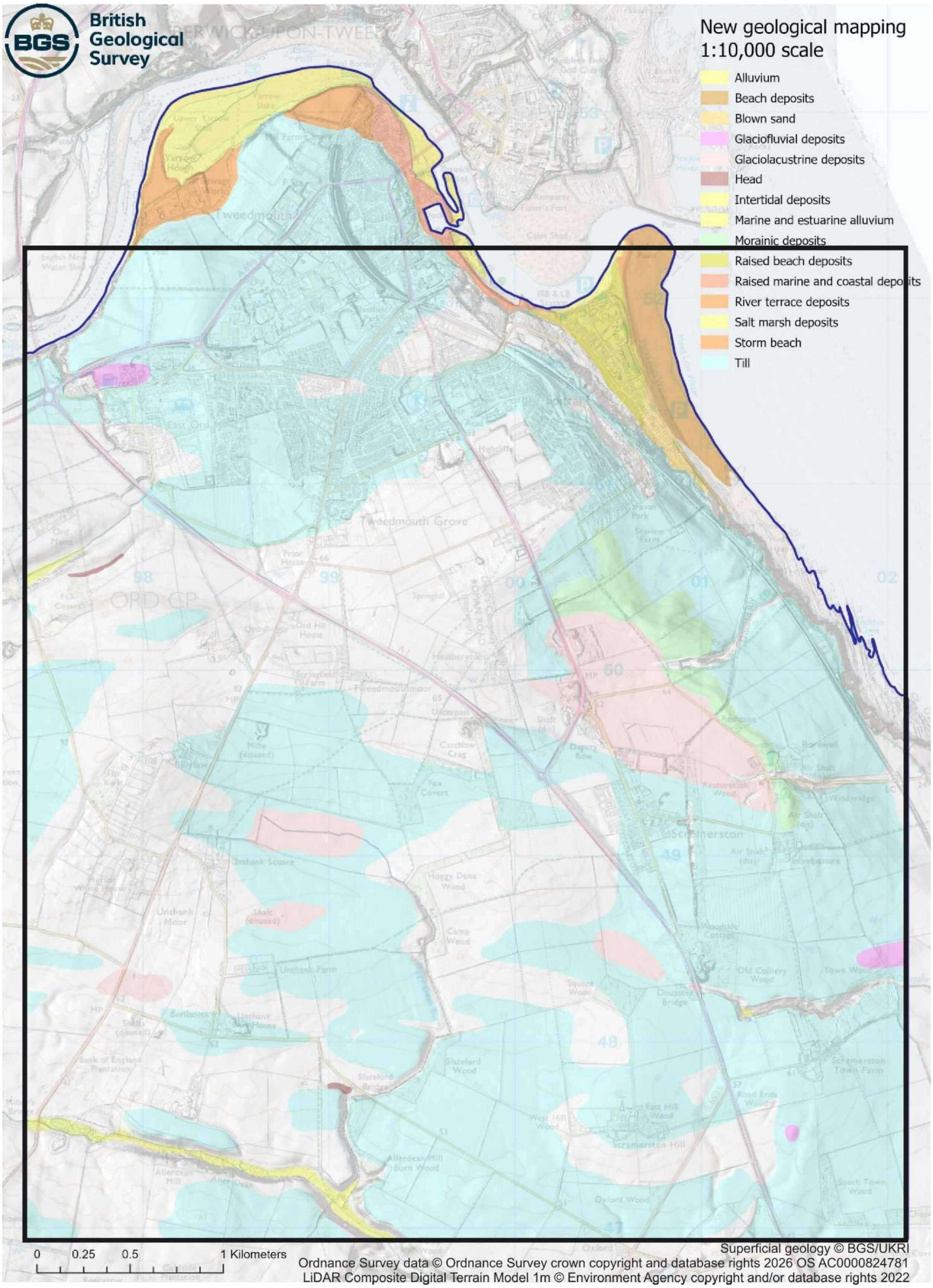

Figure 4: Superficial deposits recently remapped by Whitbread & Dewald (1:10 000 scale) in the AOI. BGS © UKRI 2026. LiDAR DTM 1m model © Environment Agency copyright and/or database rights 2022. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

1.5 SUMMARY OF MINING

Coal mining occurred within the Scremerston Coal Member, with numerous collieries operating in the area in the 19th and first part of the 20th century. The stratigraphically oldest worked coal seam is the Cooper Eye Coal, which was extensively mined around Scremerston with workings reaching Spittal (Figure 5). The next seam is the Bulman Main Coal which was only worked locally near Scremerston and in the southwest of the AOI. Above this, the Blackhill Coal was extensively worked around Scremerston in a southwest - northeast orientation. The highest worked seam in the Scremerston Coal Member is the Fawcett Coal which was worked around the village of Scremerston in a southwest – northeast orientation. Other minor coal seams may have been worked locally. Underground workings followed the dip of the coal seams, ranging from near-surface workings in the northwest of the Scremerston - Allerdean mine water block to deeper workings (>300 m below ground level) in the southeast. Workings were concentrated along the shallower dipping coal beds on the southwestern side - southern end of the Berwick Monocline, with few workings on the steeply dipping eastern side of the fold. Mineshafts shown in Figure 5 reveal the linearity of the coal workings in a southwest – northeast orientation. Five adits in the northeast of the AOI including in Spittal were excavated to drain mine water out into the sea.

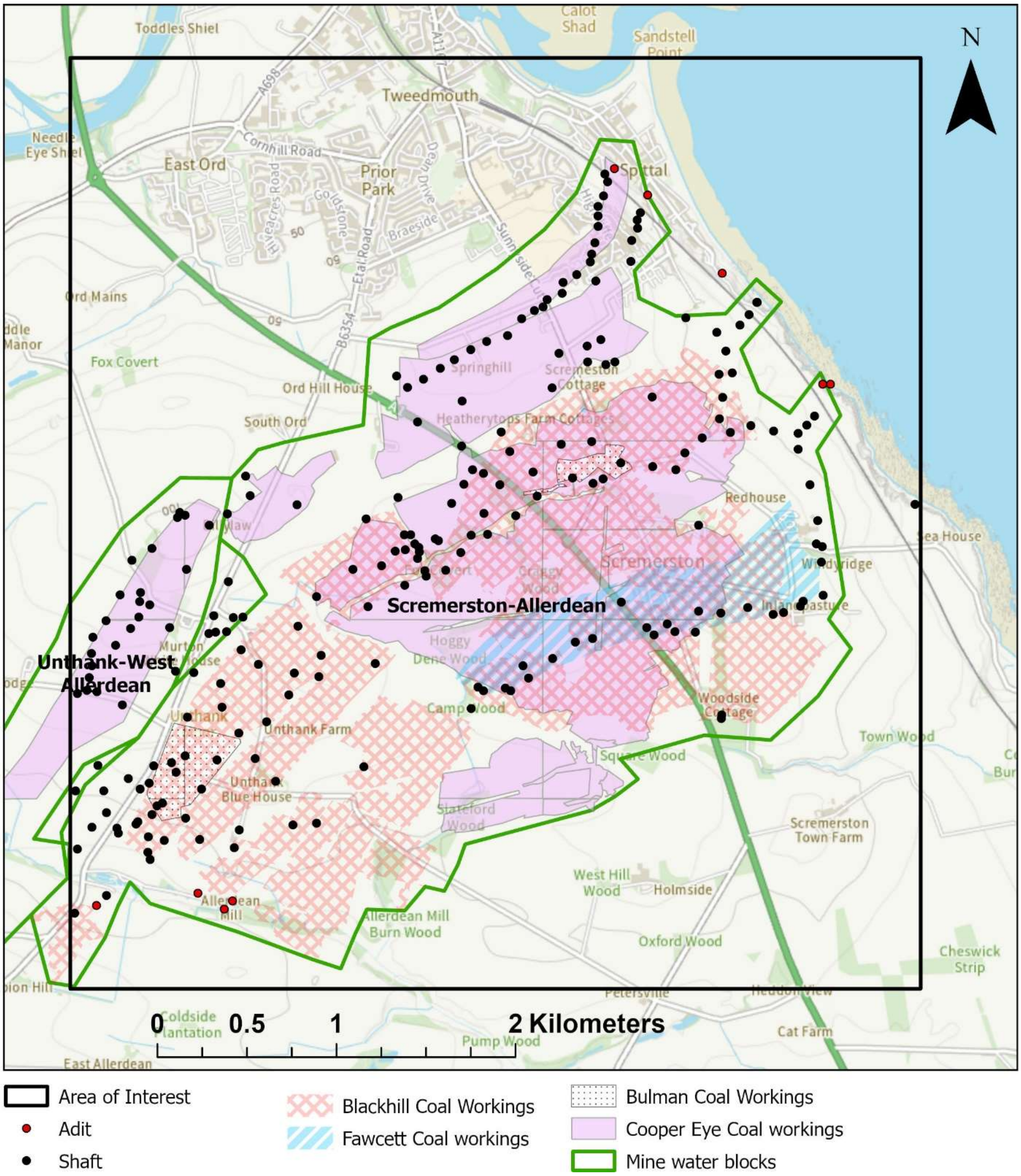

Figure 5: Map showing underground mine workings associated with four significant coal seams, adits, shafts and mine water blocks. Incorporates BGS and Mining Remediation Authority data. Reproduced with permission of © Mining Remediation Authority. All rights reserved. BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

The terms mine water and groundwater are both used in this report. The term mine water is used when specifically referring to water in mines, whilst the term groundwater is used more generally and when not specifically linked to mines. Mine water is essentially groundwater that has seeped into mine workings through fractures, joint and pore spaces in the surrounding rock.

Surface water (e.g. rainwater, stream water etc) may also enter mine workings through shafts, boreholes or other disturbed ground at the surface.

1.6 GROUNDWATER FLOODING

Groundwater flooding is the emergence of groundwater at the ground surface away from perennial river channels or the rising of groundwater into man-made ground, under conditions where the 'normal' ranges of groundwater level and groundwater flow are exceeded.

Unlike surface water flooding (e.g. rivers or surface runoff) which is highly responsive to rainfall events, groundwater flooding occurs following long periods (months or sometimes years) of above average rainfall. Groundwater flooding most commonly occurs in the late winter and spring following high winter rainfall combined with low evapotranspiration resulting in significant aquifer recharge. Groundwater flooding may happen slowly and often less frequently than river flooding, but when it does occur, it can last for weeks or even months.

2 Datasets and methods

Numerous data sets have been used to develop a hydrogeological conceptual understanding of the Gateshead area. Key datasets are listed below.

BGS datasets and reports

- Bedrock (1:50 000) geology, superficial (1:50 000) geology, and structural geology maps
- Depth to groundwater (gwlevel_v4) raster dataset
- Groundwater Flooding susceptibility map (50 m resolution, v6.1)
- Groundwater recharge and discharge model raster dataset
- SOBI borehole logs
- Permeability dataset (1:50 000)
- Aquifer properties data (Jones et al., 2000)
- Spring locations dataset
- Superficial geology of the Berwick-Spittal area, Northumberland (Whitbread & Dewald, 2026)

Project Groundwater datasets (including BGS and EA)

- Project Groundwater Northumbria - Geological Cross-sections (Kearsey et al., 2023) Project Groundwater Northumbria - Superficial hydrogeological domains for the Spittal area (Burke et al., 2024)

Environment Agency (EA) datasets

- Groundwater level data at six monitoring boreholes (Hydrology explorer)
- Rainfall data (Hydrology Explorer)
- Spring locations (hydronodes – springs and outflows)
- Flood susceptibility spatial data and methodology report
- Shallow mine workings

Mining Remediation Authority (MRA) datasets

- Mine Water block areas (2022)
- Underground workings spatial datasets
- Mine entry location data

3 Hydrogeology

3.1 BEDROCK HYDROGEOLOGY

According to the BGS bedrock aquifer designation, the Fell Sandstone Formation forms a principal aquifer whilst the Ballagan Formation, Scremerston Coal Member, Tyne Limestone and Alston formation are categorised as secondary A aquifers.

The Ballagan Formation comprises water bearing sandstone beds, particularly towards the top of the formation where it forms a productive aquifer (Jones, 2007).

The base of the Fell Sandstone Formation was recently re-mapped by the BGS and is defined as the first coarse sandstone above the last cementstone in the Ballagan Formation (Bianchi et al., 2023b). The Fell Sandstone Formation forms a locally important aquifer, supplying drinking water and water for industries and businesses in and around Berwick-Upon-Tweed. There remains uncertainty regarding the connectivity between the Fell Sandstone Formation aquifer and the aquifer unit in the upper Ballagan Formation, however, it is likely that the Fell Sandstone Formation aquifer leaks into the Ballagan Formation aquifer unit.

The seven main sandstone units observed in the Fell Sandstone Formation form the productive aquifer; these being separated by low permeability mudstones and siltstones which can be tens of metres thick. It is therefore highly likely that the aquifer is compartmentalised into separate aquifer units.

The Scremerston Coal Member overlying the Fell Sandstone Formation contains a greater proportion of mudstone and siltstone, with fewer laterally continuous channel sandstones compared to the Fell Sandstone Formation (Jones, 2007). The Scremerston Coal Member also contains coal seams and thin limestone beds. Despite being categorised as a secondary A aquifer, channel sandstones in the Scremerston Coal Member can reach 35 m thick (Jones, 2007), potentially forming productive aquifer units. Limestones within the Scremerston Coal Member may also form minor aquifer units where they are highly joined and fractured.

The Tyne Limestone Formation above the Scremerston Coal Member comprises similar sequences to the Scremerston Coal Member but with thicker limestone beds (Jones, 2007). Major stacked channel sandstones such as the Dun Sandstone form aquifer units which are separated by low permeability mudstones and coals. Limestone beds including the Dun and Woodend Limestone may also form aquifer units where fractured and jointed.

The overlying Alston Formation also contains channel sandstone and limestone aquifer units separated by low permeability siltstones, mudstones and thin coals.

Although the Fell Sandstone Formation comprises the most productive aquifer units, the entire succession from the upper Ballagan Formation, the Fell Sandstone Formation, Scremerston Coal Member, Tyne Limestone and Alston formations form a sequence of aquifers and aquitards. Naturally, most of these aquifer units are likely to be disconnected from one another, although there may be connectivity between aquifer units where mudstones and siltstones are thin or discontinuous and where faults exist. However, historic mining and boreholes in the AOI are likely to create flow pathways between aquifer units, resulting in greater connectivity of the system.

3.1.1 Aquifer extent and properties

Laterally extensive and continuous Fell Sandstone Formation aquifer units outcrop in the far northwest of the AOI. Fell Sandstone aquifer units dip to the southeast, whilst generally thickening to the southwest (Bianchi et al., 2023a). Aquifer units in the Ballagan Formation beneath the Fell Sandstone Formation similarly dip to the southeast. Aquifer units are likely to be present across the rest of the AOI, however, these aquifer units are separated by layers of low permeability mudstones, siltstones and coal seams. The villages of Spittal and Scremerston are situated on the Scremerston Coal Member.

Sandstone channel subsurface mapping by Jones (2007) within the Scremerston Coal Member and Tyne Limestone Formation has improved understanding of the lateral extent, size and orientation of channel sandstones. Jones (2007) inferred that the largest channel sandstones exceeded 8.5 km width, with palaeoflow directions to the south, southwest and southeast. The length of these channels is likely to be many times greater than channel width (Jones, 2007), therefore, some aquifer units in the Scremerston Coal Member could be quite extensive.

3.1.2 Sandstone aquifer units

Various facies (distinct sedimentary bodies / features) have been identified in the Scremerston Coal Member; this section describes two channel facies described by Jones (2007), which based on their geological properties, are likely to form aquifers. Other, non-channel sandstone facies may also produce aquifers, i.e. poorly cemented and friable medium grained sandstone layers.

Major single storey channel

This facies, present in outcrop at Spittal cliffs, is typically composed of fine - medium grained sandstone with an erosive base and a palaeoflow direction to the south or southeast. These channel sandstones are likely to form low-moderately productive aquifer units depending on the proportion of silt, level of cementation and fracture density.

Major stacked channels

This facies probably has the greatest aquifer potential. Deposits are composed of medium - coarse grained sandstone, with a pebbly base. Channel bases are often erosive, therefore interbedded low permeability mudstones and siltstones are thinner and laterally discontinuous and sometimes missing. This combined with channel stacking is likely to increase groundwater connectivity between channels.

As sandstones are typically harder and more brittle compared to surrounding mudstones and siltstones, they preferentially fracture (Aydin et al., 2023). Consequently, groundwater flow may occur through fractures within the sandstones, even when the primary porosity and permeability is low. Fractured bedding planes in the Scremerston sandstones would likely increase aquifer productivity.

3.1.3 Aquifer properties data

There is aquifer properties data for the Fell Sandstone Formation but there is less data for the Ballagan Formation, Scremerston Coal Member, Tyne Limestone and Alston formations.

Ballagan Formation

Aquifer properties data for the Ballagan Formation were estimated by Bianchi et al. (2023a,b) when modelling the sustainability of abstractions in the area. The model used a horizontal transmissivity value of 50 m^2/d and a storage coefficient value of 0.1. Values were estimated using trial and error calibration to minimise the error between observed and simulated groundwater levels (Bianchi et al., 2023b). Simulations reproduced borehole levels and trends (associated with variable abstraction rates) with satisfactory accuracy (Bianchi et al., 2023b).

Fell Sandstone Formation

Seven sandstone units in the Fell Sandstone Formation were mapped by Turner et al. (1993). Turner et al. (1993) stated that these sandstone units ranged from 10 - 70 m thick (thickest being the Peel Knowe Sandstone) and were separated by laterally continuous 10 - 50 m thick, low permeability mudstones (Jones et al., 2000; Turner et al., 1993). Recent remapping by BGS (Ford et al., 2019) generally correlated findings with that of Turner et al. (1993), although they found that the Peel Knowe Sandstone Member could generally be divided into three layers separated by two variable and sometimes discontinuous mudstone layers. This explains the lower reported maximum thickness value of ~40 m (for the Middle Leaf Peel Knowe Sandstone Member) for sandstone units in the formation by Ford et al. (2019).

Pumping tests have indicated negligible leakage through mudstones from surrounding sandstones (Turner et al., 1993), suggesting that the Fell Sandstone Formation aquifer is compartmentalised into individual units. The Peel Knowe and Murton Crags sandstones are the most important for water supply, and within the sandstone units there are specific flow horizons associated with fractures (Jones et al., 2000). Porosity and permeability values determined from thin sections and mini-permeameter measurements on core plugs from three boreholes show significant variability, with coarser grained sandstone generally exhibiting the highest porosity and permeability (Fordham 1989; Turner, 1993). Measured effective porosity values ranged from 7.5 - 25.5% and permeability values varied from 9.87 x 10^{-16} to 4.9 x 10^{-12} m^2 (Turner, 1993). Jones et al. (2000) noted a strong linear relationship exists between porosity and hydraulic conductivity.

Geometric mean matrix permeability was around 730 mm a^{-1}, which over a thickness of 100 m would give a transmissivity of 0.2 m^2/d. However, reported transmissivity values from pumping tests were commonly 100 m^2/d, therefore most groundwater flow must be through fractures or along thin, poorly cemented, coarse sandy layers (Jones et al., 2000). Laboratory measurements of porosity in the offshore Fell Sandstone Formation ranged from 1.4 - 23%, but were typically 6-12% (Jones et al., 2000).

Pumping tests (total 28) within the Fell Sandstone Formation aquifer revealed transmissivity values of 9 – 692 m^2/d, with a geometric mean of 119 m^2/d (Jones et al., 2000). One field calculation of storage coefficient from a pumping test at Thornton Bog (outside of the AOI) was 4 x 10^{-4}, meanwhile specific yields have been calculated from thin sections from three cores had a specific yield of ~0.1 (Younger, 1992). Other transmissivity values were calculated for the Fell Sandstone Formation in 2016 and 2021 - 2022 as part of a WINEP investigation into the sustainability of Northumbria Water (NW) abstractions (Dearlove & Swartz, 2022). Transmissivity values ranged from 21.7 - 145 m^2/d with estimated hydraulic conductivities of 3.3 to 5.3 m/d (see Dearlove & Swartz (2022) for methods). These values are significantly higher than laboratory measurements of hydraulic conductivity which were generally between 2 x 10^{-5} and 5 x 10^{-2} m/d with a geometric mean of 0.0016 m/d (Jones et al., 2000).

Scremerston Coal Member

The major single storey channel sandstones in offshore wells have been described as well-cemented with porosity values of 4 - 14%, meanwhile, major stacked channel sandstones have been noted for visible porosity (Jones, 2007). In offshore cores, porosity values in stacked channel sandstones range from 9 - 19% with horizontal permeabilities of < 9.9 x 10^{-16} to 4.9 x 10^{-13} m^2 (Jones, 2007). Other sediments had permeability values of < 9.9 x 10^{-18} m^2, and UK coals typically have permeability values of < 9.9 x 10^{-19} m^2 (Jones, 2007). The matrix porosity is important, but fracture density including bedding plane fractures are also controlling factors affecting aquifer yields.

Limestones within the Tyne Limestone & Alston formations

The thickest limestones in the AOI are found in the Tyne Limestone and Alston formations and are 1 - 3 m thick (Jones et al., 2007). The limestone matrix has low porosity and permeability but may form aquifers where a secondary network of solution enlarged fractures and joints have developed, forming complex flow paths. Yields from these limestones vary from virtually no yield to high yields depending on whether a borehole intersects large conduits and fractures.

3.1.4 Structural controls

The Berwick Monocline forms a high relief area with steep slopes on its eastern edge and gentle slopes to the north, south and west. This structure probably exerts a strong influence on groundwater flow direction in the Spittal area as groundwater is likely to broadly follow the dip of the strata. Therefore, the fold axis (Figure 3) probably forms a groundwater divide. This would indicate that to the east of the A1 and Scremerston, groundwater would flow to the east or east-northeast, potentially with a steep gradient given the 50-55 degree bedding incline. To the south of Scremerston and southwest of the A1, groundwater flow is likely to be towards the south-southeast through strata that dips at 10-20 degrees. Bianchi et al. (2023a,b) inferred a groundwater flow direction to the east or northeast (along bedding strike) within the Ballagan and Fell Sandstone formations in the north of the AOI.

Only 11 faults have been mapped, and only four have been inferred to extend over a distance of 1 km. However, it is likely that there are many unmapped radial faults and fractures associated with tensional stresses during formation of the Berwick Monocline (see schematic in Figure 11). Small faults and fractures may provide focussed zones of recharge and preferential groundwater flow pathways, potentially connecting separated sandstone aquifer units. However, this depends on fracture frequency, extent, and whether secondary processes such as mineralisation have occurred. It is difficult to ascertain the distribution and frequency of these fractures due to limited outcrop exposure, however, cliff section exposures are likely to reveal more information on the fracture network and whether groundwater is discharging from fractures.

3.1.5 Mining impacts

Mining of coal seams within the Scremerston Coal Member has likely impacted the natural groundwater system. Mining has probably affected groundwater recharge (see section 3.3), but the mined seams have also likely created preferential groundwater flow paths and significant voids for groundwater storage. The presence of shafts and adits combined with removal of low permeability coals is likely to increase connectivity between aquifer units and increase volumes of water reaching channel sandstone units that were naturally isolated from the main aquifer units.

In some areas, mining has occurred directly beneath aquifer units. This could result in groundwater draining from the aquifer into the shafts, lowering groundwater levels.

3.1.6 Abstractions

Large private and public groundwater abstractions occur from the Fell Sandstone and Ballagan formations around Tweedmouth and East Ord.

Sandstones in the upper Ballagan Formation form a productive aquifer unit which is abstracted from by a private company who, as of 2026, have a licenced abstraction rate of 2100 m^3/d (Bianchi et al., 2023a). A southwest - northeast orientated elliptical cone of depression, 700 m long, 200 m wide and 25 m deep, has developed from abstractions. Evidence suggests that the current abstraction rates in the Ballagan Formation aquifer may not be sustainable (Bianchi et al., 2023a,b).

There are also groundwater abstractions of up to 8400 m^3 day from six Northumbrian Water (NW) boreholes at Murton Water Works located ~4.5 km southwest of Spittal. These abstraction boreholes target the Fell Sandstone aquifer units though one borehole also intercepts part of the Scremerston Formation.

3.1.7 Groundwater quality

Systematic baseline groundwater sampling of the Fell Sandstone has not been undertaken by the BGS. However, historic groundwater sampling described the Fell Sandstone Formation has having generally a neutral pH, moderately hard and of satisfactory water quality (Hodgson & Gardiner, 1971). The EA monitor water quality in boreholes in the Fell Sandstone Formation, with a summary of averaged monthly results shown in Table 1 (see Figure 8 for borehole locations). Bianchi et al. (2023a) used this data and data from other boreholes intercepting the Ballagan and Fell Sandstone formations to try and determine whether groundwater chemistry between the Ballagan and Fell Sandstone aquifers were distinguishable. Although they found no general trend between the aquifers, some boreholes exhibited different chemistries which may relate to different recharge pathways associated with different sources. A lack of distinct differences between aquifer chemistries may indicate that aquifer units in the Fell Sandstone and Ballagan formations are in hydraulic continuity.

Table 1: Averaged monthly EA groundwater chemistry measurements for boreholes in the AOI, extracted from Bianchi et al. (2023a). Values reported as dissolved (filtered) unless marked with an asterisk = total (unfiltered).

EA Borehole	**Calcium mg/l**	**Chloride mg/l**	**Conductivity uS/cm**	**Fluoride mg/l**	**Iron ug/l**	**Lead (ug/l**	**Magnesium mg/l**	**pH**	**Potassium mg/l**	**Sodium mg/l**	**Sulphate mg/l**
The Kells	78.1	43.6	663.5	0.2	121.4	0.1	38.1	7.2	5	17.7	27.1
Cornhill Road	66.4	66.3	815.5	0.2	68.1	0.8	46.7	7.3	6.4	28.7	20.2
Ord Road	91.8	63	811.8	0.2	121.5	1.0	42.5	7.3	2.9	37	50.5
Osborne Road	144.9	60.4	1388.4	0.2	389.2	0.9	67.1	7	4.8	36.9	213.2
Fox Covert	39.7*	60.7	528.8	0.1	35	1.0	21.7*	6.2	7.2*	25.1*	43.4*
Middle Ord	44.8*	42.3	412.8		66*		19.2*	7.9	2.2*	15.4*	25.7*

Dearlove & Swartz (2022) investigated nitrate levels in the Fell Sandstone aquifer using data collected from NW and EA boreholes. From this, they developed a conceptual model of nitrate transport through aquifer. They found increasing trends in nitrate levels in 13 of 14 boreholes, and nitrate levels had already exceeded the 50 mg l^{-1} (drinking water limit) in all EA observation boreholes targeting the Fell Sandstone Formation. The only EA borehole which had not yet exceeded 50 mg l^{-1} was situated in the Ballagan Formation. Nitrate increases were attributed to changing land-use practices such as nitrate application through mineral fertilizers in groundwater recharge areas (Dearlove & Swartz, 2022).

Seasonal variations were also observed, with increased nitrate levels in spring attributed to winter recharge; and a reduction in nitrate over the summer attributed to lower recharge and higher nitrate uptake by plants/crops (Dearlove & Swartz, 2022). Based on groundwater recharge rates in the Fell Sandstone Formation, they predicted that changes to groundwater nitrate levels from future catchment management techniques may not be observed for at least 450 days. Based on current trends, it is predicted that nitrate concentrations will exceed drinking water limits in five out of six NW boreholes by the end of the 21st century (Dearlove & Swartz, 2022).

Two boreholes in the Fell Sandstone Formation exhibited higher chloride concentrations, particularly at greater depths (Dearlove & Swartz, 2022). One NW borehole showed a significant increase in conductivity from 470 - 5500 uS / cm at the base of the borehole, which was interpreted as ‘old’ groundwater by Dearlove & Swartz (2022). There is limited evidence of saline intrusion in the Berwick area (Hodgson & Gardiner, 1971; Bianchi et al., 2023b).

There is less information on groundwater quality in the Scremerston, although one NW borehole with an open screen section through the Scremerston and Fell Sandstone shows increasing nitrate trends (Dearlove & Swartz, 2022). Coal mining in the Scremerston is likely to have impacted water quality in aquifer units intercepted by or near to mine workings. Ochreous mine water is observed discharging out at the coast immediately south of Spittal, signalling the presence of polluted, acidic mine water within the strata.

Permeable units of the Scremerston Coal Member and Tyne Limestone and Alston formations exposed in the littoral (nearshore) zone are likely to be saline where regularly submerged by seawater. However, the steeply dipping strata of these formations and separation of aquifer units by low permeability strata suggest that aquifer units immediately inland, such as in Spittal, may not be affected by saline intrusion.

3.2 HYDROGEOLOGY OF SUPERFICIAL DEPOSITS

Superficial hydro-domains developed by Burke et al. (2024) are shown in Figure 6. They were categorised based on different sedimentological and hydrogeological properties. Superficial deposits <2 m thick were classified as permeable (Hydro-domain 1), whilst superficial deposits >2 m thick were classified as aquifers or aquitards based on the sequence of permeable and impermeable deposits and the thickest aquitard (Burke et al., 2024). Hydro-domain 2 was considered an aquifer, whilst hydro-domains 3b and 3c formed sequences of aquitards and aquifers. Hydro-domains 3a and 4 were classified as aquitards, consisting of low permeability clay-dominated deposits (Burke et al., 2024). Around Spittal and Tweedmouth, beach and storm deposits may form aquifers in the flat land below the break in slope; typically land <10 metres above ordnance data (mAOD). It is likely that bedrock-derived groundwater discharges into these sand and gravel aquifers.

There are also patches of locally sandy and / or gravelly till around Highcliffe, Eastcliffe, Tweedbank Retail Park and Old Shielfield Park which are estimated to reach thicknesses of 5 - 7 m. These deposits may form small, perched aquifers, in which case, groundwater flow would likely follow topography and could discharge at the lower elevation margins of the deposits. However, these deposits may be unsaturated if water is able to infiltrate into underlying bedrock aquifer units.

Recently mapped morainic deposits to the south of Spittal are likely to be permeable and may form perched aquifers, whilst recently mapped glaciolacustrine deposits would probably form low permeability aquitards (see Figure 6).

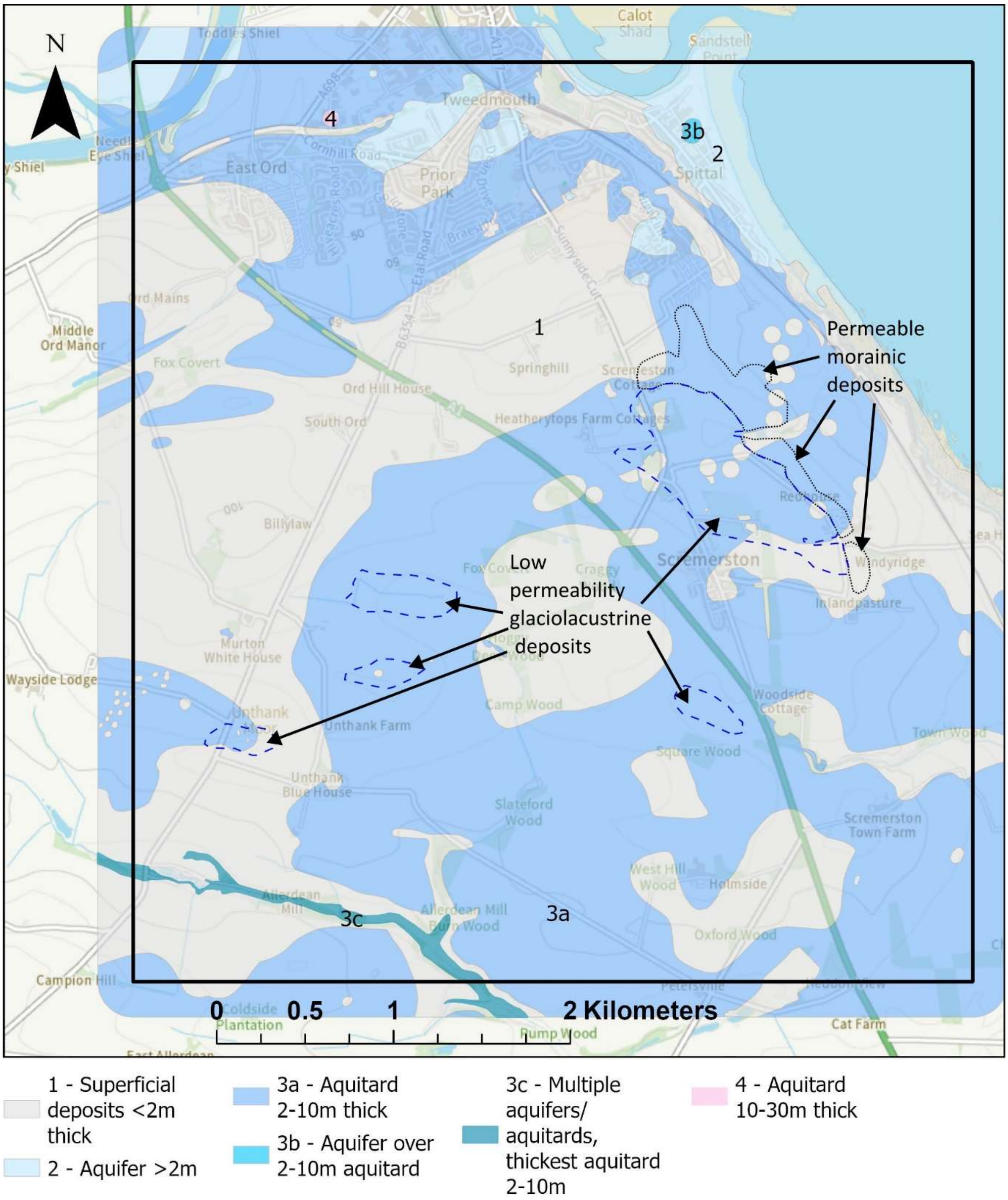

Figure 6: Map showing superficial hydrogeological domains categorised as identified by Burke et al. (2024), and containing recently mapped morainic and glaciolacustrine deposits (Whitbread & Dewald, 2026). BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

3.3 RECHARGE

Recharge to bedrock aquifer units is likely to predominantly occur where sandstones and jointed, fractured limestones outcrop at the surface (e.g. dotted areas showing sandstones within the Fell Sandstone Formation on Figure 7). Features which are likely to enable bedrock groundwater recharge to occur include permeable superficial hydro-domains 1 and 2 (Figure 6) and historic surface workings associated with mining and quarrying (Figure 7).

Sandstones have only been mapped for the Fell Sandstone Formation (Figure 7). Therefore, outcropping sandstones of the Ballagan, Tyne Limestone and Alston formations and Scremerston Coal Member which are not shown, are also likely to form important zones for groundwater recharge. Groundwater recharge is also likely to be focused on the higher ground associated with the top of the Berwick Monocline, particularly if bedrock strata have become more fractured or jointed in that area.

A conceptual hydrogeological model of recharge to the Fell Sandstone Formation developed by Dearlove & Schwartz (2022) similarly suggests preferential groundwater recharge occurring where sandstones outcrop. Groundwater level responses to significant rainfall events in the Murton Crags Sandstone of the Fell Sandstone Formation indicated that infiltrating groundwater took ~450 days to reach the water table, suggesting a vertical groundwater recharge rate of 0.04 m/day and an inclined recharge rate of 0.2 m/day (Dearlove & Swartz, 2022). Monitoring groundwater chemistry would help validate that monitored groundwater level responses are water level responses and not pressure responses. Recharge rates are likely to be slower in deeper and increasingly confined aquifer units and where the unsaturated zone is thicker (e.g. at higher elevations).

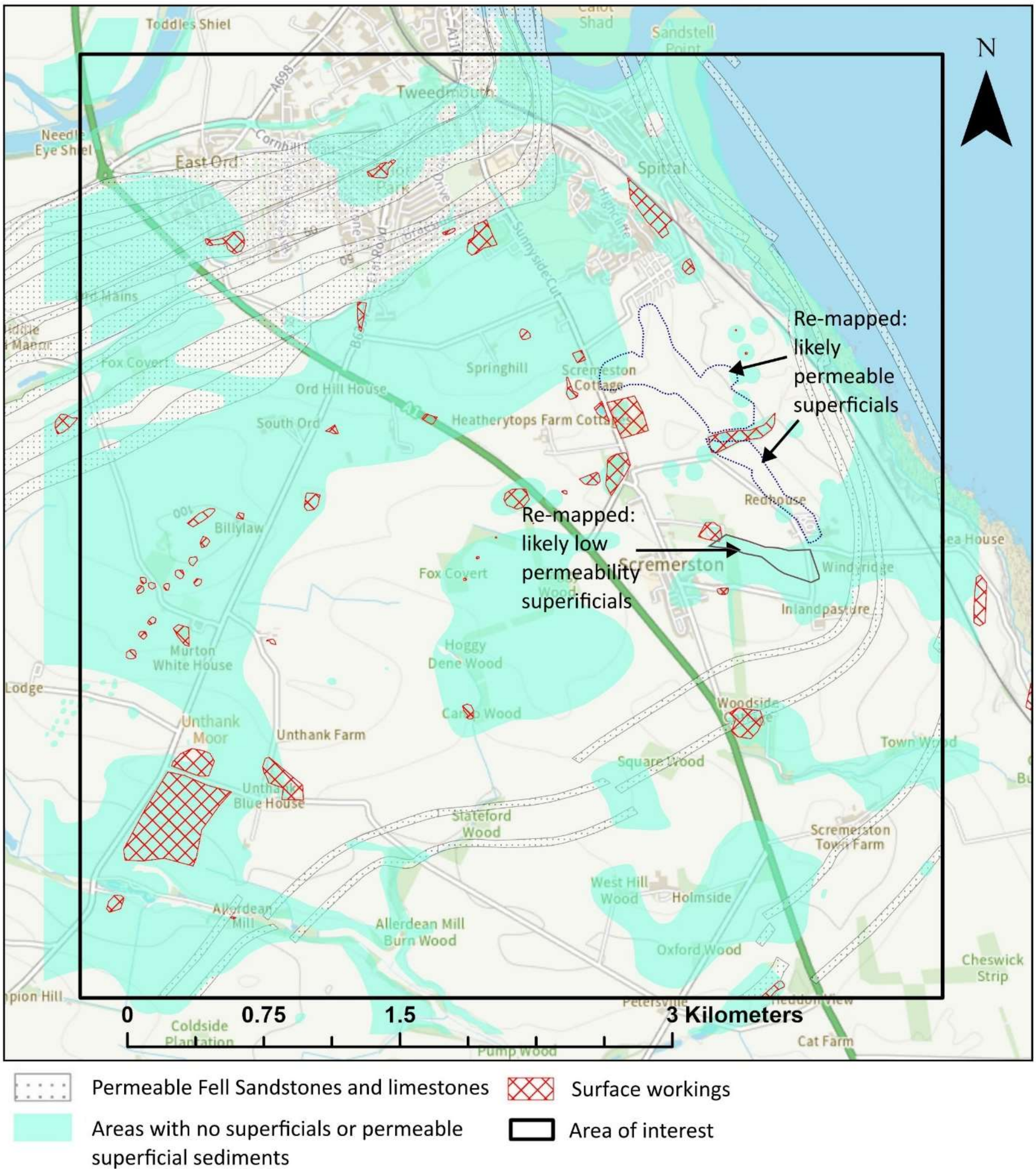

Figure 7: Map showing mapped Fell Sandstones and limestone beds, areas with no or thin (<2 m thick) and therefore permeable superficial cover and shallow mine/quarry workings derived from 1892-1914 OS maps (National Library of Scotland, 2026). Adjustments to recharge areas following superficial re-mapping are also shown. Recharge may occur elsewhere; e.g. where till deposits are locally less clayey and sandier. BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

Abandoned mine entrances (over 190 mapped shafts and adits in the AOI) and surface workings in the area are likely to provide artificial preferential recharge pathways (Figure 5 & Figure 7). Coal seams including the Cooper Eye Coal, Blackhill Coal and Fawcett Coal were extensively mined, and the remaining underground cavities now form man-made aquifers, whilst potentially also increasing connectivity between natural aquifer units. Mining is also known to create fracturing and collapses in the surrounding unmined strata, which could also create recharge and groundwater flow paths (Quiros et al., 2024). The extent to which recharge occurs through mine entrances depends on whether and how well mines and their entrances have been sealed / infilled. Mine entrances situated on the higher ground are likely to form areas of focussed recharge; meanwhile, mine entrances in low relief areas such as along the coastline are more likely to form preferential discharge pathways.

3.4 GROUNDWATER LEVELS AND TRENDS

Groundwater levels are monitored by the EA at six locations in the Fell Sandstone Formation and Ballagan Formation in the northwest of the area (Figure 8, Table 2). One EA borehole (The Kells) has been drilled through the base of the Scremerston Coal Member and into the Fell Sandstone Formation below, with the screened section being entirely within the Fell Sandstone Formation. One NW abstraction borehole intercepts both the Fell Sandstone Formation and Scremerston Coal Member but there are no known groundwater level observations for the Scremerston Coal Member, Tyne Limestone or Alston Formation in the area. All EA boreholes appear to target similar depths (-17 to -29 mAOD) except for the Kells OBH which terminates at +11 mAOD.

Groundwater levels vary significantly across the area, as do trends and fluctuations. Groundwater abstractions from the Fell Sandstone Formation and Ballagan Formation for the town of Berwick-Upon-Tweed and for private companies, locally depress groundwater levels as seen in observation boreholes (OBH), around Tweedmouth and East Ord. Three EA boreholes (EA, 2026) described below are situated within the Ballagan Formation and lowermost Fell Sandstone Formation (Figure 8).

Osborne Road OBH situated in Tweedmouth showed a rising trend in the early 1990s before steadying. A decrease of 34 m was observed between 2005 - 2018. Between 2018 and 2023 groundwater levels were stable. A steep rise has occurred since 2023 (Figure 8). The sharp decrease between 2005-2018 is likely to result from nearby abstractions, and the recent recovery suggests abstractions may have reduced or ceased. Given that groundwater levels are far below sea level, and the sites proximity to the estuary, there could be a risk of saline intrusion at this location, although there is no evidence to suggest that this is happening.

The Ord OBH is close to the Osborne Road OBH and shows similar trends. However, groundwater levels have remained very stable at around -15 mAOD since 2010. This borehole has most likely also been impacted by abstractions, which may explain its flat lining. Groundwater levels are not near the base of the screened-section, therefore the borehole may have intercepted a high permeability layer with significant groundwater storage.

Cornhill Road OBH shows a broadly similar trend to The Ord and Osborne Road, however, the decreasing trend since 2010 has been less pronounced, and seasonal trends are visible. There has also been a small recent recovery (Figure 8). This borehole is further inland and is perhaps less impacted by nearby abstractions, therefore, groundwater levels remain above sea level.

Three other EA observation boreholes, Fox Covert, Middle Ord and The Kells, (EA, 2026) situated a few kilometres inland to the southwest, exhibit different groundwater level trends and characteristics to Osborne Road, The Ord and Cornhill Road OBHs. Fox Covert and Middle Ord OBHs are situated approximately 65 mAOD and show similar trends. Fox Covert OBH showed a decreasing trend between 1993 - 1998, followed by a stable - steadily rising trend since. Groundwater levels are between 23 - 29 mAOD, and there appears little variation and no obvious seasonal trends.

The Kells OBH situated at 95 mAOD, exhibits a different pattern to the other boreholes (Figure 8). Levels rose sharply from 1991 - 2000 before stabilising. It is possible that the increase in water levels since the 1990s represents groundwater recovery following cessation of dewatering following mine closures. The Kells also exhibits strong seasonal fluctuations of 10 - 15 m per year, with groundwater levels typically peaking in late winter or early spring and being lowest in early autumn.

Overall, a historically decreasing but now stable-rising groundwater trend is observed in the Fell Sandstone Formation and Ballagan Formation around Tweedmouth and East Ord. Meanwhile, further southwest in the Fell Sandstone Formation away from large abstractions, groundwater trends are relatively stable. The variability observed in groundwater levels and trends across the six observation boreholes highlight aquifer complexities and indicate a multi-layer aquifer system. Boreholes showing relatively stable groundwater levels with small fluctuations may represent deeper, possibly confined aquifers, whilst boreholes showing higher magnitude responses and distinct seasonal fluctuations indicate unconfined, shallow aquifers which are rapidly recharged by rainfall.

Groundwater levels and trends in the village of Spittal may differ from levels and trends observed in the EA boreholes described in Figure 8 and Table 2. This is because Spittal is situated on the Scremerston Coal Member bedrock on the eastern side of the Berwick Monocline, whereas all borehole observations are from the Fell Sandstone Formation and Ballagan Formation situated west of the Berwick Monocline. There is no available groundwater level data from the Scremerston, however, seasonal groundwater flooding in the Spittal area is perhaps indicative of unconfined, shallow and responsive aquifer units. Groundwater levels in the Scremerston Coal Member are unlikely to be affected by abstractions as abstractions tend to target the Fell Sandstone Formation, however, groundwater levels may be affected by historic mining which affects aquifer recharge, groundwater flow and discharge.

An observation borehole is planned to be installed in the Scremerston Coal Member around the top of the Berwick Monocline by the EA in 2026. This should provide insights into where and how thick the aquifer units are, groundwater levels, and whether aquifer units are confined or unconfined.

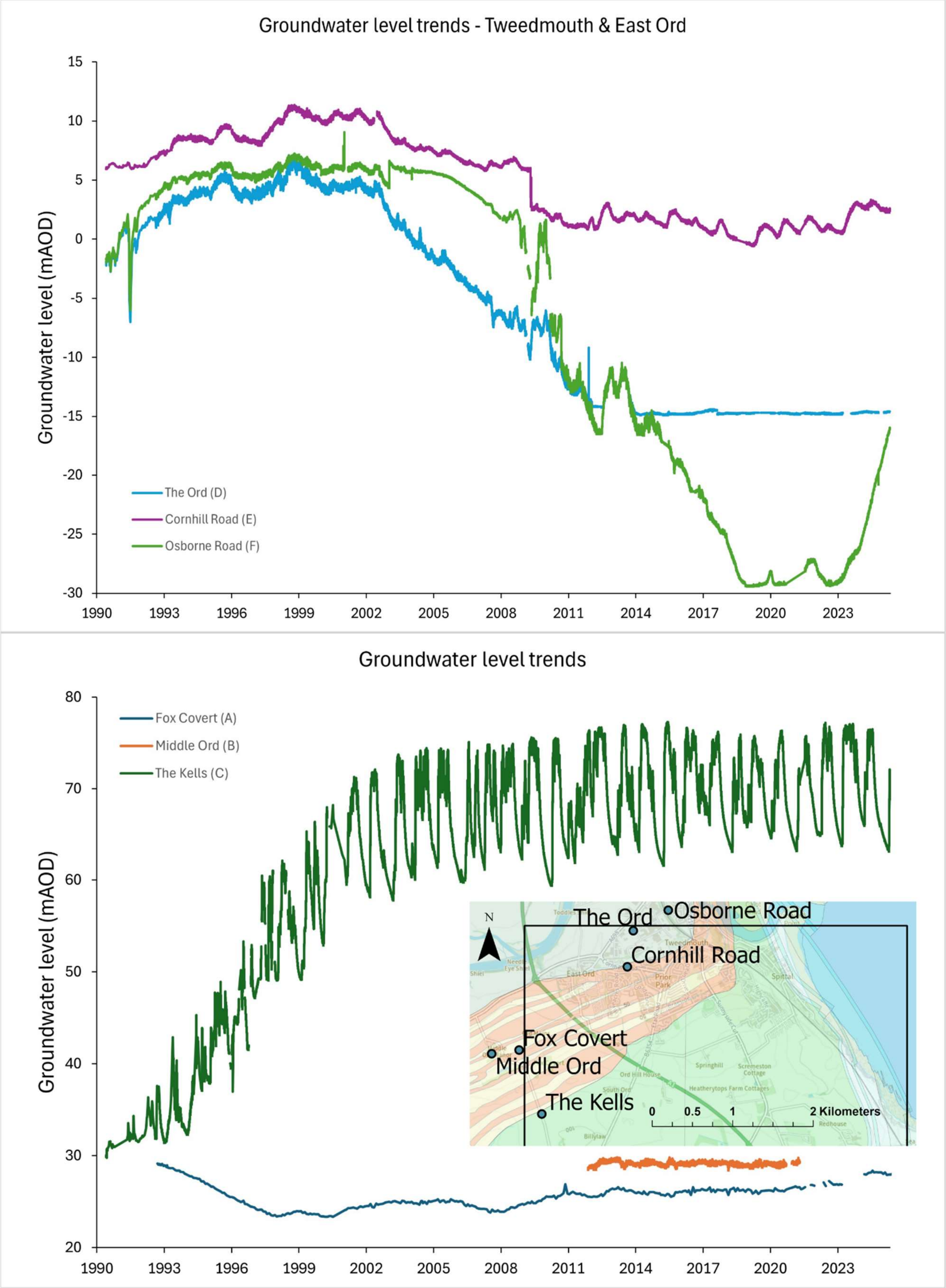

Figure 8: Groundwater level data from six boreholes in the AOI, with data ranging from 1991-2025 (EA, 2026). Contains public sector information licensed under the Open Government Licence v3.0. Inset shows borehole locations in relation to the AOI. BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

Table 2: Summary of groundwater level monitoring data in the area (EA, 2026). Contains public sector information licensed under the Open Government Licence v3.0.

Site	Grid reference (X Y)	Ground level (mAOD)	Borehole depth	Geology intercepted	Maximum water level (mAOD)
Osborne Road	399146 652328	17.2	39	Ballagan	7.3
The Ord	398710 652075	18.2	36	Ballagan	6.8
Cornhill Road	398636 651627	35.6	57	Ballagan	11.4
Fox Covert	397294 650597	64.5	90.9	Fell Sandstone	29.2
Middle Ord	396953 650549	65.3	94.5	Fell Sandstone	29.8
The Kells	397574 649804	95	84	Fell Sandstone	77.3

3.5 GROUNDWATER FLOW AND DISCHARGE

The groundwater flow regime is complex across the area due to the multi-layered aquifer system and presence of the Berwick Monocline. It is further complicated by large groundwater abstractions, and the heavily modified subsurface of the Scremerston Coal Member from mining and mine water drainage.

The groundwater flow regime within the Fell Sandstone and Ballagan formations in the northwest of the AOI is reasonably well constrained from observations and groundwater modelling. Osborne Road, The Ord and Cornhill Road boreholes (see Figure 8 inset) suggest a groundwater flow direction to the north or northeast towards the River Tweed, roughly following topography. Aquifers within the Fell Sandstone and Ballagan Formation appear to be under anthropogenic stress, therefore groundwater locally flows towards abstraction boreholes (Figure 9). Groundwater modelling of the Fell Sandstone - Ballagan aquifer undertaken by Bianchi et al. (2023b), similarly indicated regional groundwater flow to the east or northeast except around Ord and Tweedmouth due to abstractions.

Groundwater level data is lacking for aquifer units within the Scremerston Coal Member, Tyne Limestone and Alston formations. The model by Bianchi et al. (2023b) incorporated part of the Scremerston Coal Member within its boundary and indicated groundwater flow to the east towards Spittal. However, as observational data was not available for the Scremerston, this part of the model was not well constrained. Probable groundwater flow directions based on the known dip of the strata, topographic variations and spring locations are shown in Figure 9.

A northwest - southeast groundwater divide is likely to exist through the AOI, associated with the fold axis of the Berwick Monocline (Figure 9). This divide is situated along the A1 in the south, through Scremerston, and along the A1167 north of Scremerston to the west side of Spittal. To the east of this divide, groundwater broadly flows to the east (Figure 9). To the west of the divide, groundwater probably flows south-southeast in the south towards Allerdeanmill Burn, except in the north, where groundwater likely flows northeast towards the River Tweed (Figure 9). There is a high level of uncertainty regarding groundwater flow direction in the west of the AOI to the west of the B6354.

Mining activities within the Scremerston Coal Member are likely to have resulted in alterations to the natural groundwater flow direction described above. As coal mines extend along strike in a southwest – northeast orientation (as well as down dip to the southeast), groundwater flow paths in the Scremerston may exhibit a southwest or southeast flow direction to the west of the fold axis. To the east of the fold axis, groundwater flows northeast along adits towards the coast, although mining was less extensive this side of the fold.

Groundwater discharge occurs where groundwater reaches the surface. It naturally occurs in the form of springs but also occurs because of human interference. Groundwater can discharge from old mine drainage adits and unsealed shafts, the sewerage network, and potentially via boreholes which penetrate through the subsurface into confined aquifers. As groundwater flow is likely to be focussed along specific layers and fractures, the location where groundwater emerges may vary depending on which fractures and layers are saturated, based on groundwater levels at the time.

Groundwater springs in the area have been identified by the EA and BGS (Figure 9). Springs are perhaps not abundant because of the downward dip of the aquifer units associated with the Berwick Monocline. Borehole data in the area also shows that there is a significant unsaturated zone with groundwater often being >30 m below the surface in the Fell Sandstone Formation.

Springs are found along the coastline, probably where these aquifer units outcrop, and one spring is likely associated with a small, mapped fault. It is likely that there are other unmapped springs situated along the coastal cliffs, including in Spittal around the break-in-slope where groundwater is likely to discharge. Most other springs in the AOI either occur around the River Tweed and Allerdeanmill Burn. A few isolated springs occur elsewhere, perhaps associated with thin, perched superficial and / or bedrock aquifer units overlying low permeability strata.

A notable example of groundwater discharge located on the slope in the village of Spittal is from the Spa Well, which is a natural spring that had an ornate well head constructed around it during the 18th Century. This spring is likely to be associated with a permeable sandstone aquifer unit in the Scremerston Coal Member. There have recently been groundwater flooding issues associated with this spring, and it is possible that groundwater from nearby flooded mine workings of the Cooper Eye Coal could be contributing to increased discharge at the Spa Well. Water sampling could help determine the provenance of this discharging groundwater.

Groundwater discharge in the area also occurs via mine adits which were created to drain water out of the mines. Several mine adits to the south of Spittal continue to discharge mine water into the sea. Mine workings extending under parts of Spittal may induce groundwater flow towards the village, which could potentially discharge via adits (Figure 9), particularly if they are not fully sealed, whilst also increasing flows from natural springs.

Antecedent hydrological conditions play an important role in groundwater discharge from springs and adits. Many springs are seasonal, only activating during the winter and spring months when groundwater levels are at their highest. Other springs only activate during extreme conditions following months of above average rainfall (and subsequent recharge). It is therefore important to identify areas of outcropping aquifer units and faults which could be susceptible to groundwater discharge, even if there are no known records of groundwater flooding.

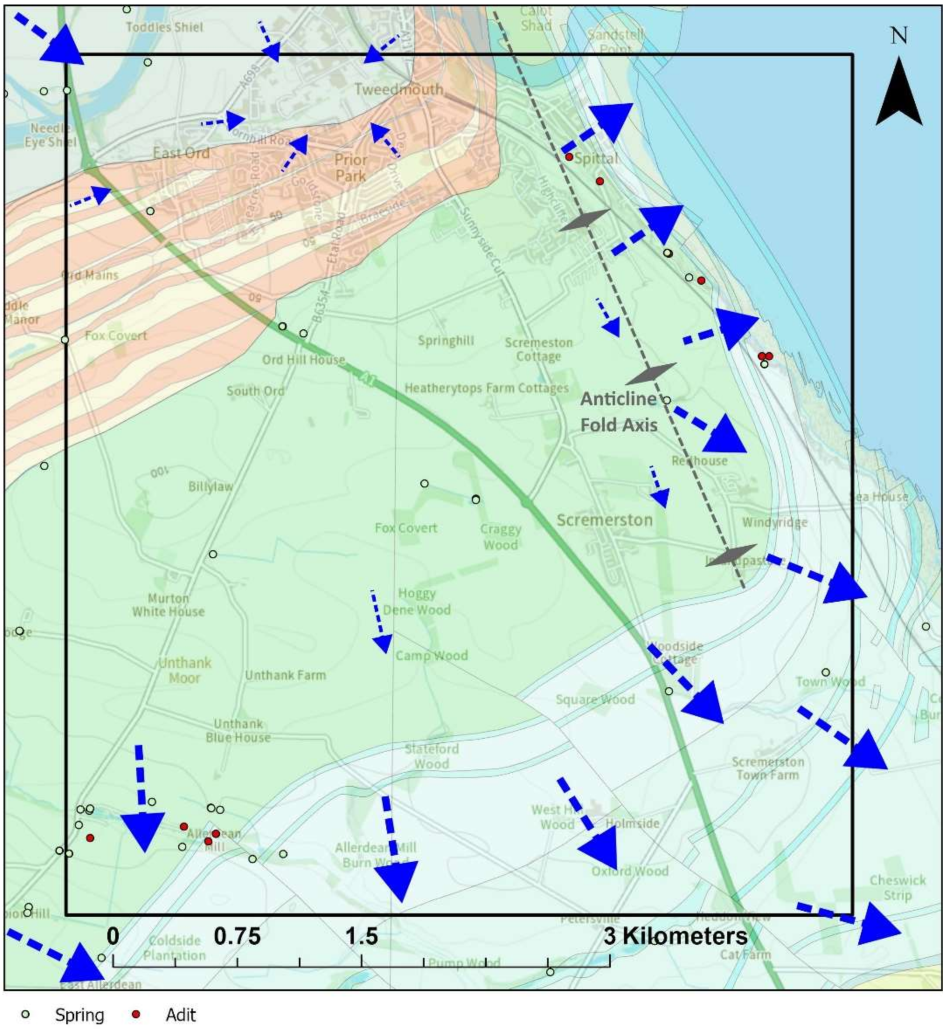

Figure 9: Inferred groundwater flow direction (blue arrows), mapped springs and adits from the BGS and the Environment Agency (Marchi-Smith & Hallam, 2025). 1:25000 OS maps. 50k geological map: BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

3.5.1 River Tweed and North Sea

In the River Tweed valley, it is likely that the river is hydraulically connected to sandstone aquifer units within the Ballagan Formation, Fell Sandstone Formation and the Scremerston Coal Member, particularly where the bedrock is exposed in the riverbed. However, given that nearby abstractions with significant drawdown are ongoing, it appears that the exploited aquifer units are disconnected from the river and sea, otherwise saline intrusion would have occurred. Aquifer units within the Tyne Limestone Formation and Alston Formation are likely to be hydraulically connected to the River Tweed estuary and North Sea. As the geology dips to the southeast or east, any aquifer units affected by saline intrusion are going to be encountered at increasing depths the further south in the AOI.

3.6 CONCEPTUAL CROSS-SECTIONS

The following figures conceptualise the hydrogeological understanding and processes in the Spittal area, highlighting areas of groundwater discharge and flood susceptibility. The first schematic cross-section depicts a greater level of geological detail to highlight the complex succession of permeable aquifer units separated by low permeability aquitards (Figure 10). Cross-section locations are shown in Figure 1.

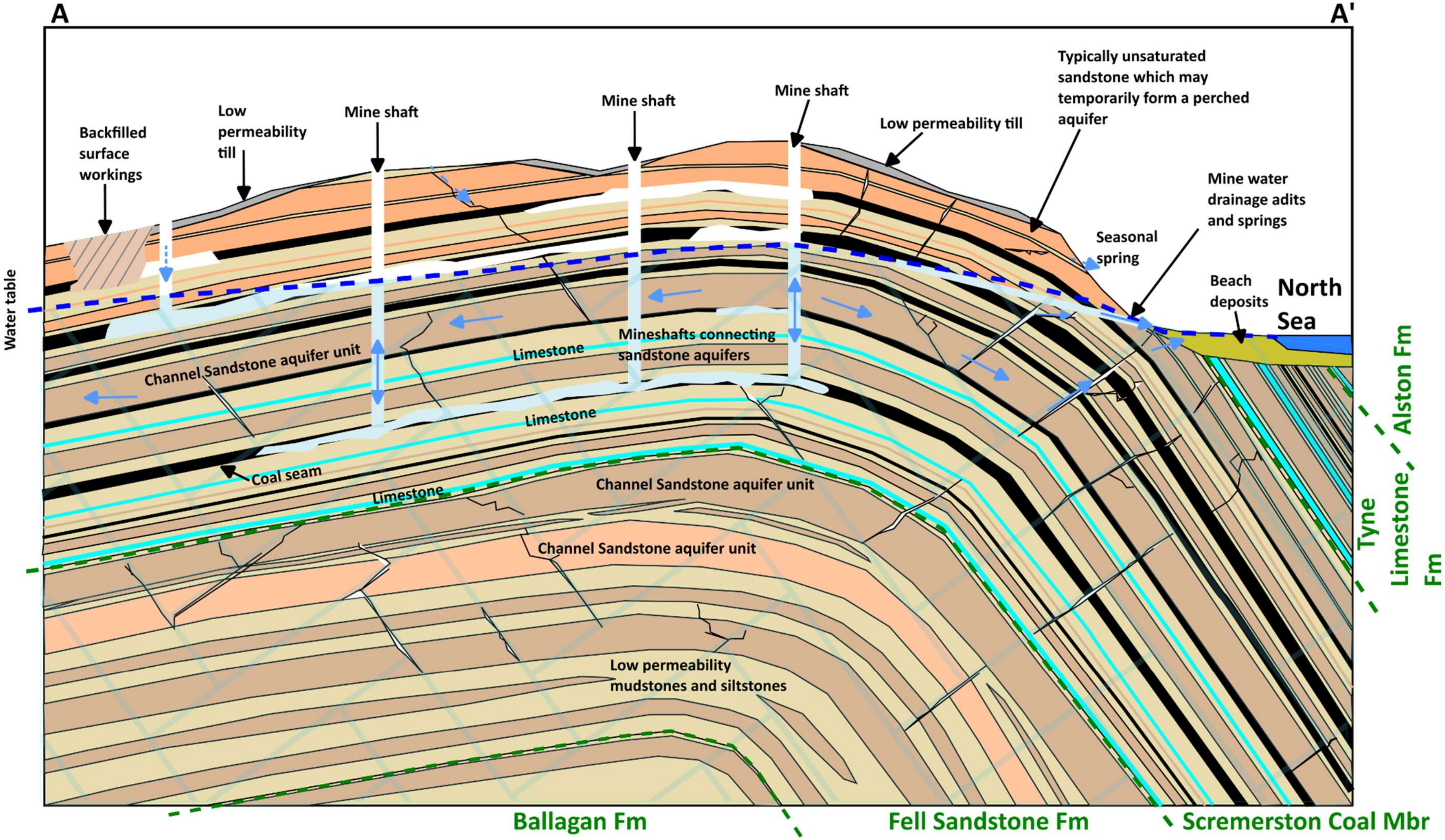

Figure 10: Schematic cross-section depicting the Spittal area in a southwest - northeast orientation. It shows hydrological and hydrogeological processes and interactions between historic mining activities and groundwater. The blue dashed line indicates the water table across the area, blue arrows depict groundwater movement. Sandstone = sandy orange, siltstone and mudstone = beige, coal = black, limestone = blue. Cross-section shows approximately 500 m of stratigraphy. Structural geology is broadly based on cross-sections by Kearsey et al. (2023), and stratigraphy roughly correlates to the stratigraphic log in Jones (2007). BGS © UKRI 2026.

Aquifer recharge occurs readily where sandstones outcrop and where low permeability till is thin or absent. Historic surface workings and mine shafts likely form areas of preferential recharge (Figure 10).

Thicker, coarse grained sandstone units (Figure 10: sandy orange layers) represent the main aquifer units which exhibit flow through fractures and the porous matrix, whilst groundwater flow through thinner, fine grained sandstone units is mostly limited to fracture flow. Groundwater flow may also occur along / through limestone units, especially where they are fractured or jointed.

There is little intergranular groundwater movement through the low permeability mudstones, siltstones and coals, however, groundwater may be able to pass through these deposits through fractures and voids created through coal mining. Mine workings also increase groundwater connectivity between sandstone aquifer units which otherwise may exhibit no or little connectivity. The fold axis is likely to form a groundwater divide, as shown in Figure 9. At depth, aquifer units may be confined and slow to recharge, potentially containing old groundwater. Deep groundwater flow may be vertically upwards due to increased pressure. Groundwater discharges along the east coast via adits and natural springs (Figure 10 & Figure 11).

In the Spittal area, groundwater is likely to discharge from permeable channel sandstone aquifer units of the Scremerston Coal Member, particularly from unconfined coarse units that are regularly recharged. Groundwater discharge in the village of Spittal is particularly likely along the steep slope where aquifer units are likely to outcrop, and along the base of the slope where the water table is likely to be shallow. Areas of Spittal around the base of the slope are situated on the more sandstone-dominated upper Scremerston Coal Member which probably comprises a higher proportion of aquifer units with fewer aquitards (Figure 11). Groundwater could potentially upwell through the superficial sands and gravels underlying the spur of land upon which parts of Spittal are built on.

Given that much of the bedrock in the AOI is of low permeability, groundwater storage and flow may be predominantly controlled by the fracture network. Radial fractures associated with the Berwick Monocline are likely prevalent through the Scremerston Coal Member, potentially forming important and rapid flow pathways (Figure 11). Groundwater discharge from such fracture networks could be significant, potentially resulting in localised flooding following periods of above average rainfall (Figure 11). Bedrock fractures associated with mining may create new groundwater flow paths and increase connectivity between aquifer units (Figure 11). Understanding the characteristics of the fractured bedrock and groundwater flow regime could be achieved using geochemical analysis and isotope studies, active tracer tests, hydrograph analysis and borehole well testing (Ofterdinger et al., 2019).

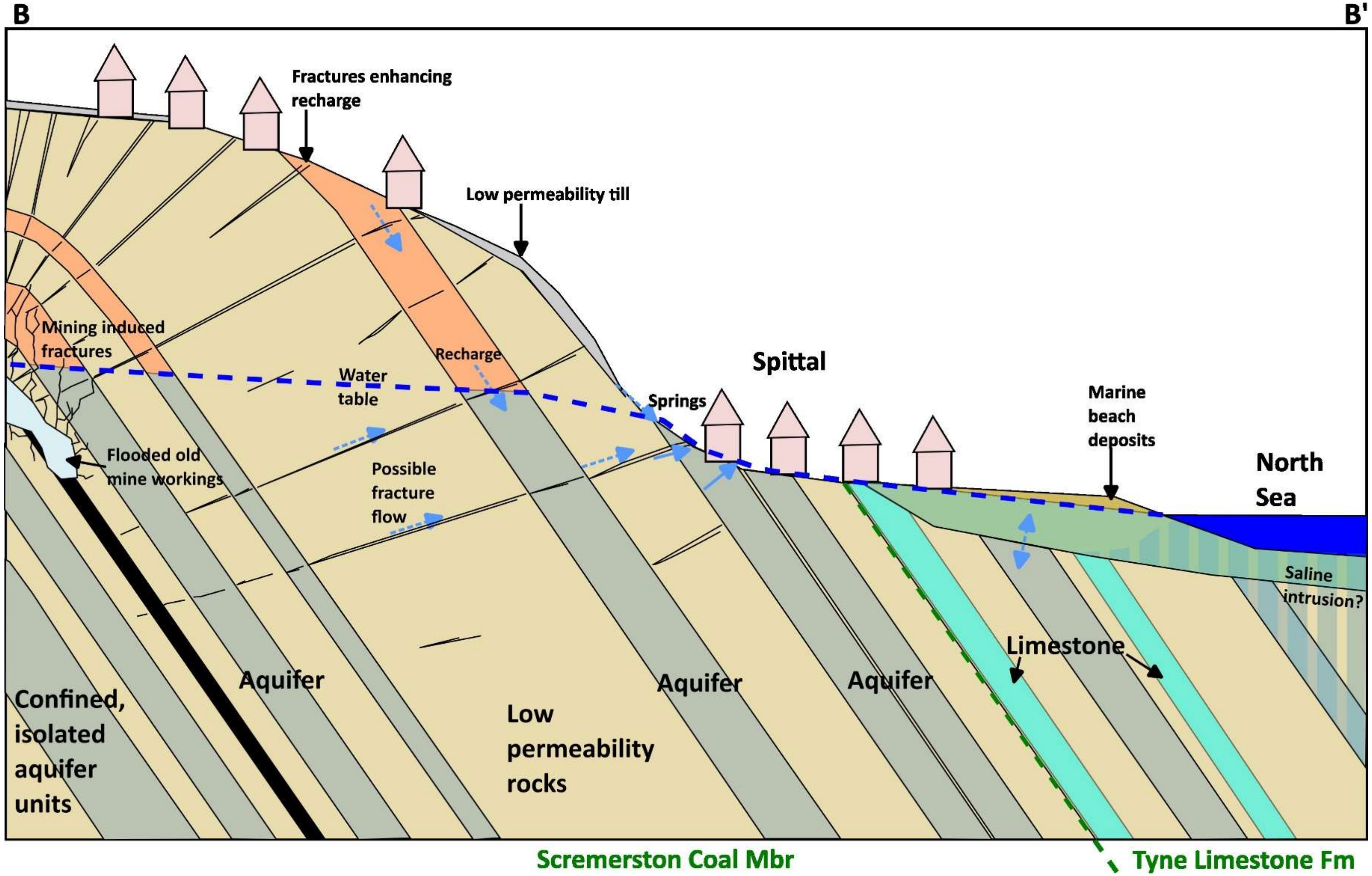

Figure 11: Schematic southwest - northeast orientated cross-section focussed on the coast around Spittal. It depicts channel sandstone aquifer units and shows hydrological and hydrogeological processes and historic mining associated with a major coal seam. Possible significant radial fractures associated with folding are also shown. The blue dashed line indicates the water table across the area whilst blue arrows depict groundwater movement. Cross-section shows 150-200 m of stratigraphy. Geological structure is broadly based on cross-sections by Kearsey et al. (2023), and stratigraphy roughly correlates to the stratigraphic log in Jones (2007). BGS © UKRI 2026.

4 Groundwater Flood Susceptibility

4.1 CURRENT GROUNDWATER FLOOD SUSCEPTIBILITY

Groundwater flood potential maps developed by the BGS and by the EA are both shown in Figure 12. The BGS groundwater flood potential dataset indicates that there is a risk of groundwater flooding in Spittal, particularly for the low relief areas immediately adjacent to the coastline including Main Street, Middle Street and Albert Road (Figure 12). EA flood susceptibility data does not appear to cover the village of Spittal.

BGS maps also indicate groundwater flooding potential along Allerdeanmill Burn in the south of the AOI, as do EA groundwater flood susceptibility maps (Marchi-Smith & Hallam, 2025). Other areas of groundwater flooding potential indicated by the BGS dataset include areas around Scremerston where the Scremerston Coal Member is not overlain by low permeability superficial deposits. This study finds little evidence to suggest that the land surface around Scremerston is prone to groundwater flooding, although groundwater may emerge from perched aquifers within the morainic deposits on the farmland situated between Spittal and Scremerston.

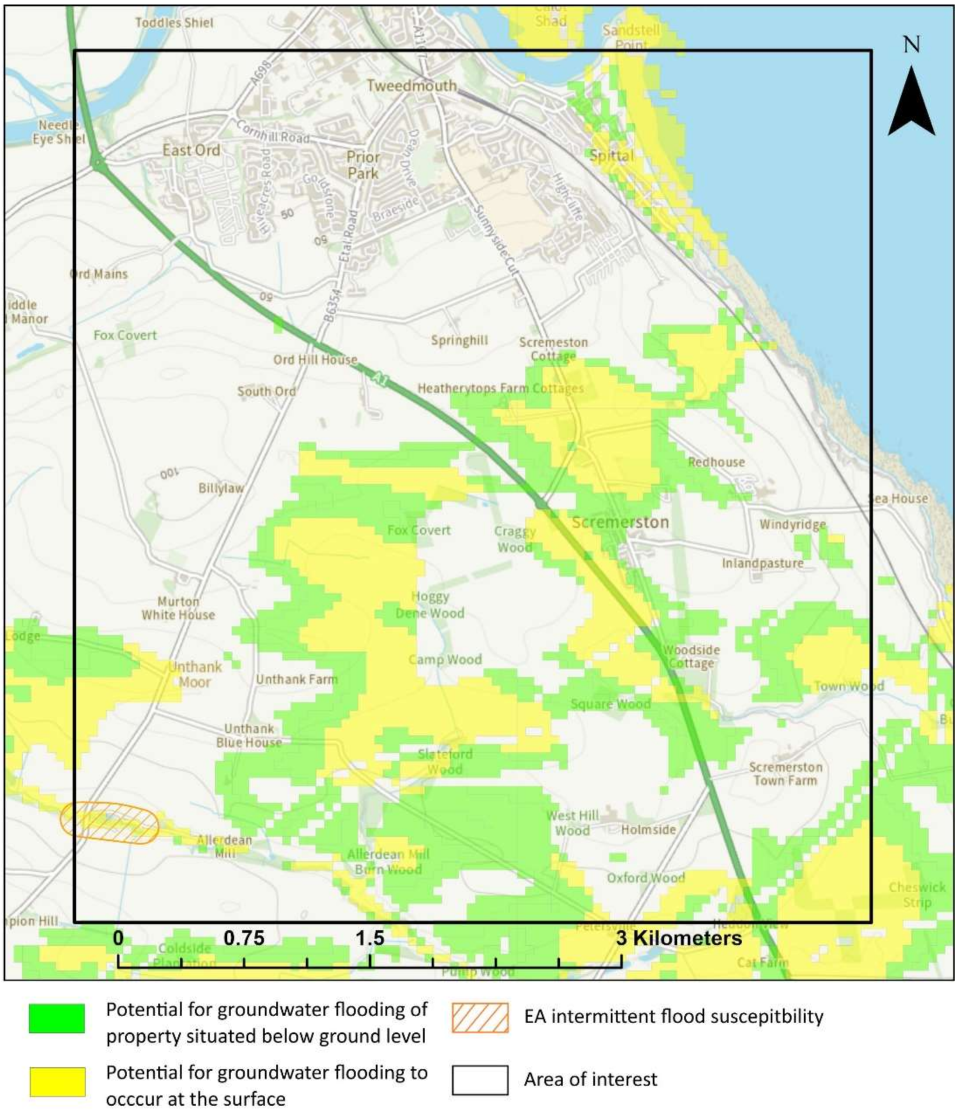

Figure 12: Mapped BGS groundwater flood risk areas (green and yellow) and flood susceptibility mapped by the Environment Agency (orange area) for Project Groundwater (Marchi-Smith & Hallam, 2025). Contains data from © Environment Agency copyright and/or database right 2025. All rights reserved. BGS © UKRI 2026. Contains OS data © Crown Copyright and database right 2026. OS AC0000824781.

Due to the complex hydrogeology, there may be areas not covered in Figure 12 that are susceptible to groundwater flooding. These areas include other parts of Spittal around the base of the slope and perhaps in seaward facing parts of the village with steep gradients, due to groundwater discharge from higher elevation outcropping sandstone aquifer units and fractures. Small volumes of groundwater could also emerge around Highcliffe and Eastcliffe from minor perched superficial aquifers. A recent flood risk report around the Berwick Academy in Spittal by JBA consulting (Thompson, 2024) indicated a groundwater flood risk at the surface around the Berwick Academy. This was based on JBA consulting's 5 m groundwater flood maps; but there was no information regarding how the map was produced. This study does not find evidence of a groundwater flood risk to the Berwick Academy.

4.2 LIMITATIONS AND UNCERTAINTY

Flood susceptibility maps provide a useful insight as to where groundwater flooding is possible, however, there remain uncertainties regarding the likelihood, extent and severity of flooding which may occur in and around Spittal. This is due to the complex spatial distribution of outcropping aquifer units, uncertainties regarding how mine workings interact with groundwater, and a lack of groundwater level and aquifer properties data for the Scremerston Coal Member.

4.3 FUTURE GROUNDWATER FLOODING

Future groundwater flooding is likely to become more frequent and severe as winter rainfall is expected to increase due to climate change (Bednar-Friedl et al., 2022; Met Office, 2022). Therefore, areas in Spittal that are already vulnerable to groundwater flooding may experience more frequent and more severe flooding in the future. Future groundwater flooding may also occur in at-risk areas that have not yet flooded.

5 Recommendations

Installing a shallow groundwater level monitoring network in the Scremerston Coal Member would help better understand aquifer properties, groundwater levels and trends, flow directions and responses to recharge events. A network should include monitoring within a groundwater discharge area in Spittal; including within the superficial deposits, monitoring in a higher elevation recharge area above Spittal and monitoring in a worked coal seam.

A detailed groundwater chemistry survey could be undertaken to examine the provenance of groundwaters, the mixing between different aquifer units and / or mine waters, and to identify where groundwaters are likely to emerge. This should include sampling from groundwater monitoring boreholes, springs, and mine water discharging from adits. Tracer tests could also be carried out to determine groundwater movement and flow rates through the mines to determine when and where mine water discharges (e.g. via adits along the coast).

Groundwater emergence observations during groundwater flooding events (images, location, duration, flows) could better constrain which sedimentological units form the highest yielding aquifers and the extent to which fracture flow occurs. This would require fieldwork focussed along the coastline, particularly in late winter - spring when groundwater levels are typically at their highest.

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Glossary

Aquifer: a rock formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be 'unconfined' beneath a standing water table, or 'confined' by an impermeable or weakly permeable horizon.

Confined aquifer: an aquifer whose upper and lower boundaries are low-permeability layers that confine the groundwater under greater than atmospheric pressure. These aquifers are sometimes called artesian aquifers, the term first being used where the pressure surface was above ground level resulting in overflow under artesian pressure.

Groundwater recharge: the inflow of water to a groundwater body from the surface. Infiltration of precipitation and its movement to the water table is one form of natural recharge. Many methods have been devised to increase natural recharge to utilise aquifer storage, termed artificial or managed aquifer recharge. Measured in mm/d or mm/yr.

Permeability (K): the term permeability, used in a general sense, refers to the capacity of a rock to transmit water. Such water may move through the rock matrix (intergranular permeability) or through joints, faults, cleavage or other partings (fracture or secondary permeability). A stricter definition is a measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient. It is the property of the medium only and is independent of the fluid. Commonly, but imprecisely, taken to be synonymous with the term hydraulic conductivity, which implies the fluid is water. Measured in m^2.

Porosity: The ratio of the volume of the interstices to the total volume of rock expressed as a fraction. Effective porosity includes only the interconnected pore spaces available for groundwater transmission; measurements of porosity in the laboratory usually exclude any void spaces caused by cracks or joints (secondary porosity).

Recharge: the quantity of water that is added to a groundwater reservoir from aerially distributed sources, such as the direct infiltration of rainfall or leakage from an adjacent formation or from a watercourse crossing the aquifer.

SuDS: sustainable drainage systems (sometimes sustainable urban drainage systems).

Unconfined aquifer: a partially saturated aquifer containing a water table that is free to fluctuate vertically under atmospheric pressure in response to discharge or recharge.

Water table: the surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere; the static water level in a well in an unconfined aquifer.

Yield (Q): the volume of water pumped or discharged from a borehole, well or spring. Measured in l/s or m^3/d.