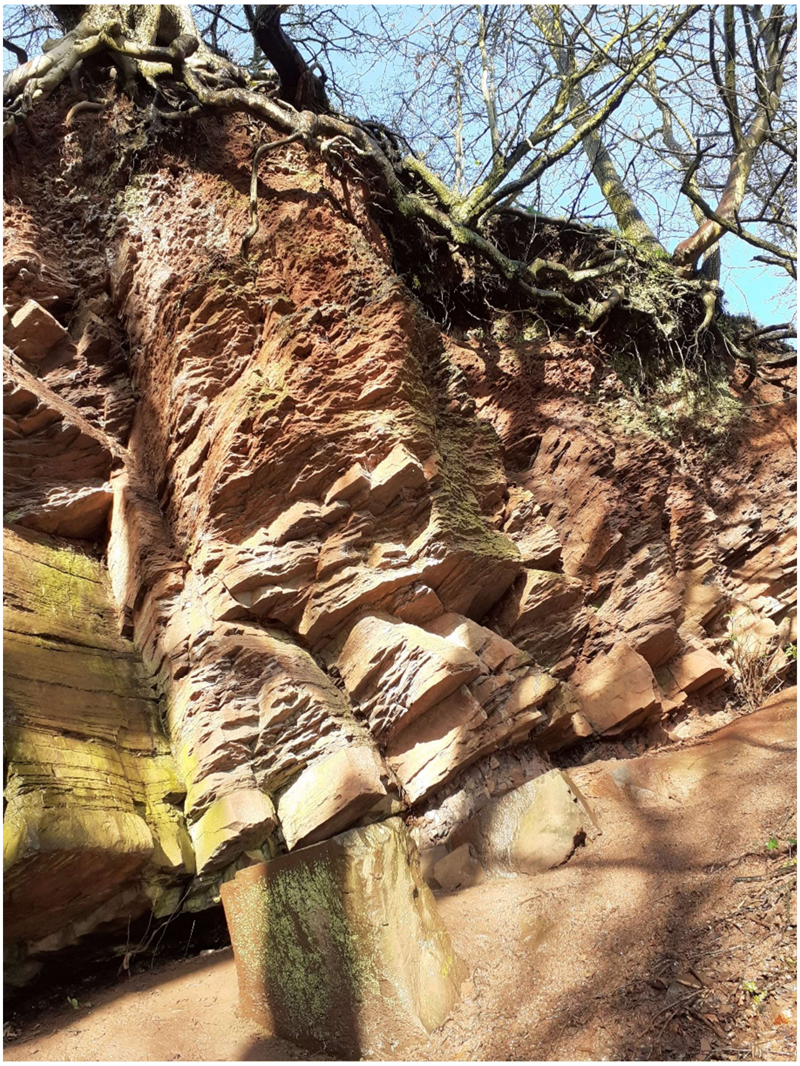
Geological ground model for planning and development of Greater Manchester

Urban Geoscience Programme

Open Report OR/20/033



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OPEN REPORT OR/20/033

Geological ground model for planning and development for Greater Manchester

Raushan Arnhardt, Helen Burke

Contributor/editor

S Bricker, V Banks, D Entwisle

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Bedrock outcrop at Hardy Wood, Tameside district [392789,393736], BGS © NERC

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Foreword

This report describes a geological ground model of the Greater Manchester Combined Authority area that could be used for planning, early stages of development and as part of a desk study to inform ground investigation. Manchester was selected for this study because the city has a long history of industrialisation and is currently being re-developed, including the installation of major infrastructure schemes.

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1 Introduction

The Greater Manchester Combined Authority area in northwest England, is one of the largest conurbations in the United Kingdom. It comprises ten boroughs (Figure 1) and covers a total area of 1277 km^2 with a population of 2.3 million people (Greater Manchester plan for Homes, Jobs and the Environment, 2019).

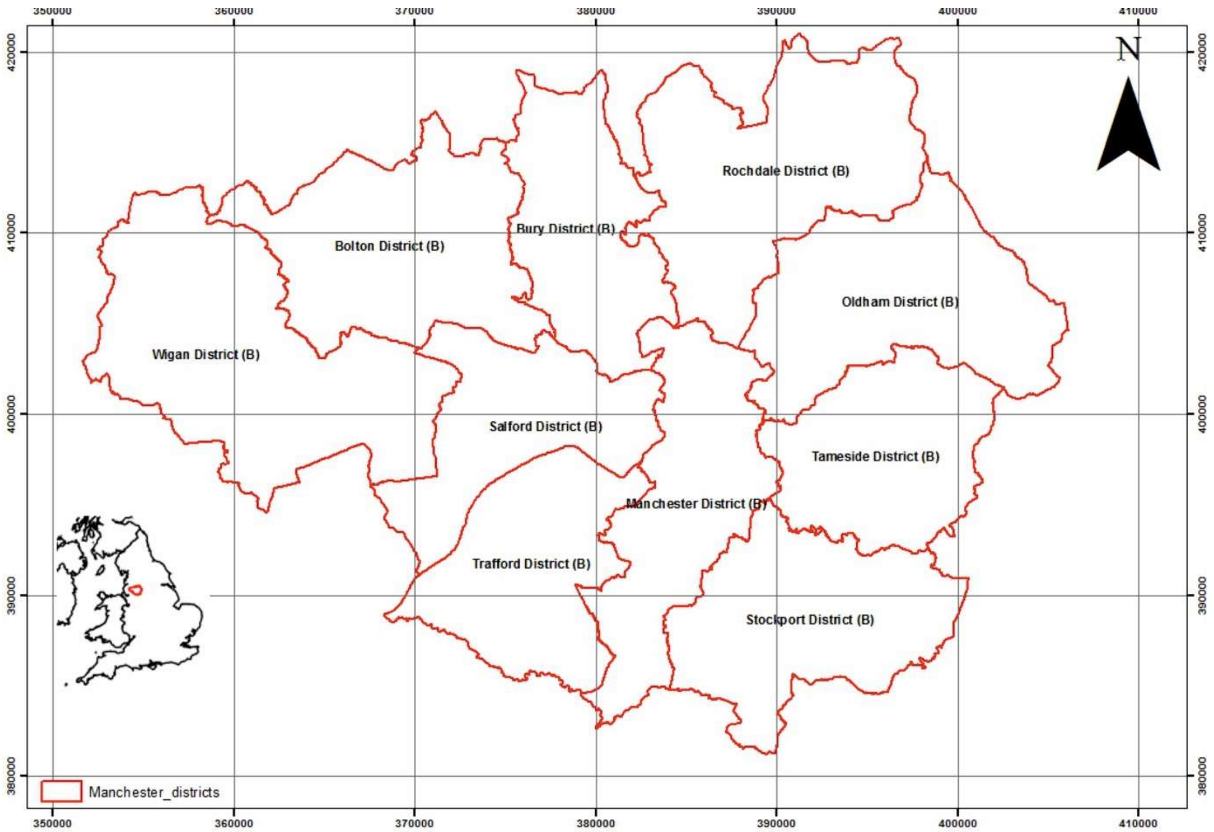

Figure 1 The Greater Manchester Combined Authority area

In the early 18th Century Manchester was a small town with a population of 10 000 (Greater Manchester Plan, 2017). However, from the mid18th to early 19th Centuries the town and its surroundings were the focus of major industrialisation, much of which was based on the production of cotton and textiles and therefore focused on watercourses for energy and transport. The population grew to 89 000 in the early 1800s with people mainly working in the cotton industry. Chemical factories, locomotive engineering, transport infrastructure and coal mining grew to support the cotton industry.

The expansion from a relatively small industry into a one of the largest producers of cotton in the world was due to the introduction of transport and steam power. The world’s first public passenger railway station (Manchester Liverpool Road) was opened in Manchester in 1830, followed by the Manchester Ship Canal in 1884. But the cotton industry declined in the early 1940s, leading to de-industrialisation and the loss of 24 000 jobs between 1974 and 1984 (Figure 2).

To tackle these issues, Greater Manchester Council released a regeneration plan in 1974 to develop the central area of the city. By 2019 the population of Greater Manchester had reached 2.3 million with growth expected to continue in the future (Greater Manchester Plan, 2019).

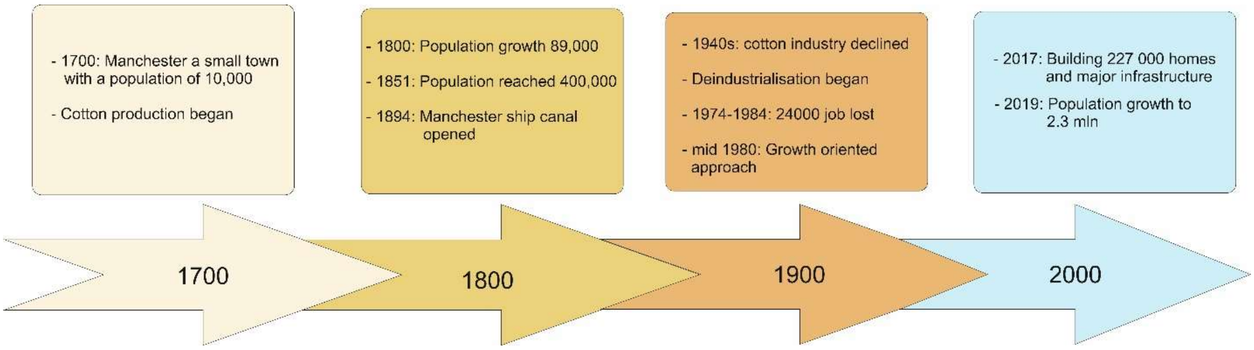

Figure 2 History of development of Manchester (Greater Manchester Framework 2017, 2019, Bridge et al, 2010)

The strategic plan of Greater Manchester Combined Authority released in 2017 considers building 227 000 homes in Greater Manchester in addition to major infrastructure projects (Manchester City Council, 2017):

- Ancoats, New Islington – high rise apartments and houses;
- Piccadilly Gateway – high rise office and apartment buildings;
- Piccadilly railway station (HS2);
- Whitworth Street Corridor – apartments, offices and arts venue;
- Water Street, comprising Knott Mill and St Georges, Castlefield – residential, commercial and public space;
- Oxford Road railway station;
- Deansgate/Spinningsfields – skyscrapers, offices, hotels, arts venues;
- Northern Quarter – high rise apartment building;
- Victoria railway station;
- NOMA and Green Quarter – high rise, apartments, offices and public space.

Figure 3 shows new development projects in the Greater Manchester Combined Authority area that exceed 10 ha. Such civil engineering projects, in the first instance, should consider the ground conditions using a desk study to collate and assess existing information, which will help developers and engineering consultants prepare conceptual ground models in order to identify potential risks related to sites. The aim of this report is to gather available data and information held by the British Geological Survey and other sources for the area, which could be used to inform the development of conceptual ground models for planning and development. More specifically we have highlighted datasets relevant to engineering geology and geological resources.

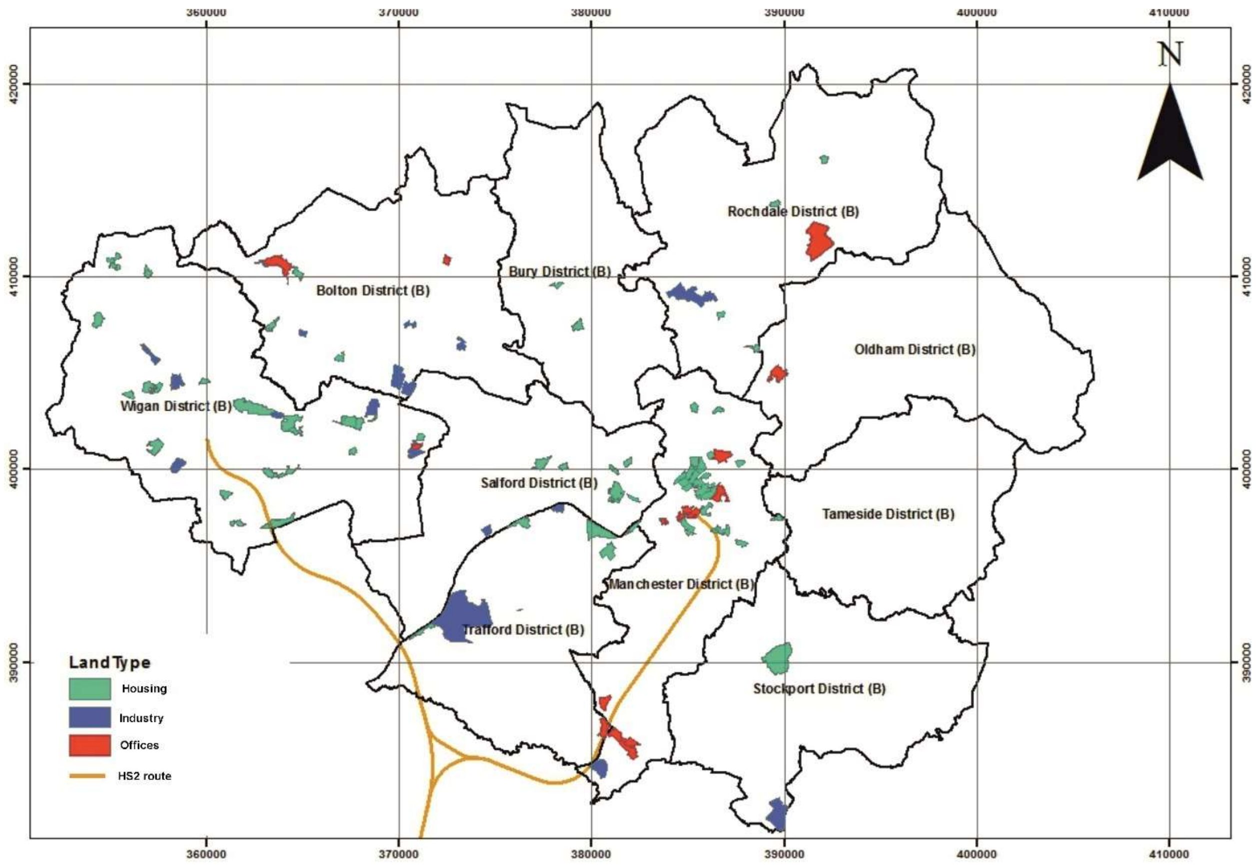

Figure 3 Map of planned infrastructure projects in Greater Manchester (Manchester City Council, 2017)

2 Topography

The Greater Manchester Combined Authority area lies in relatively low ground at the confluence of the rivers Mersey, Irwell and Irk. It is bounded to the north by the higher ground of the Rosendale Plateau and to the east by the Pennine Hills (Figure 4).

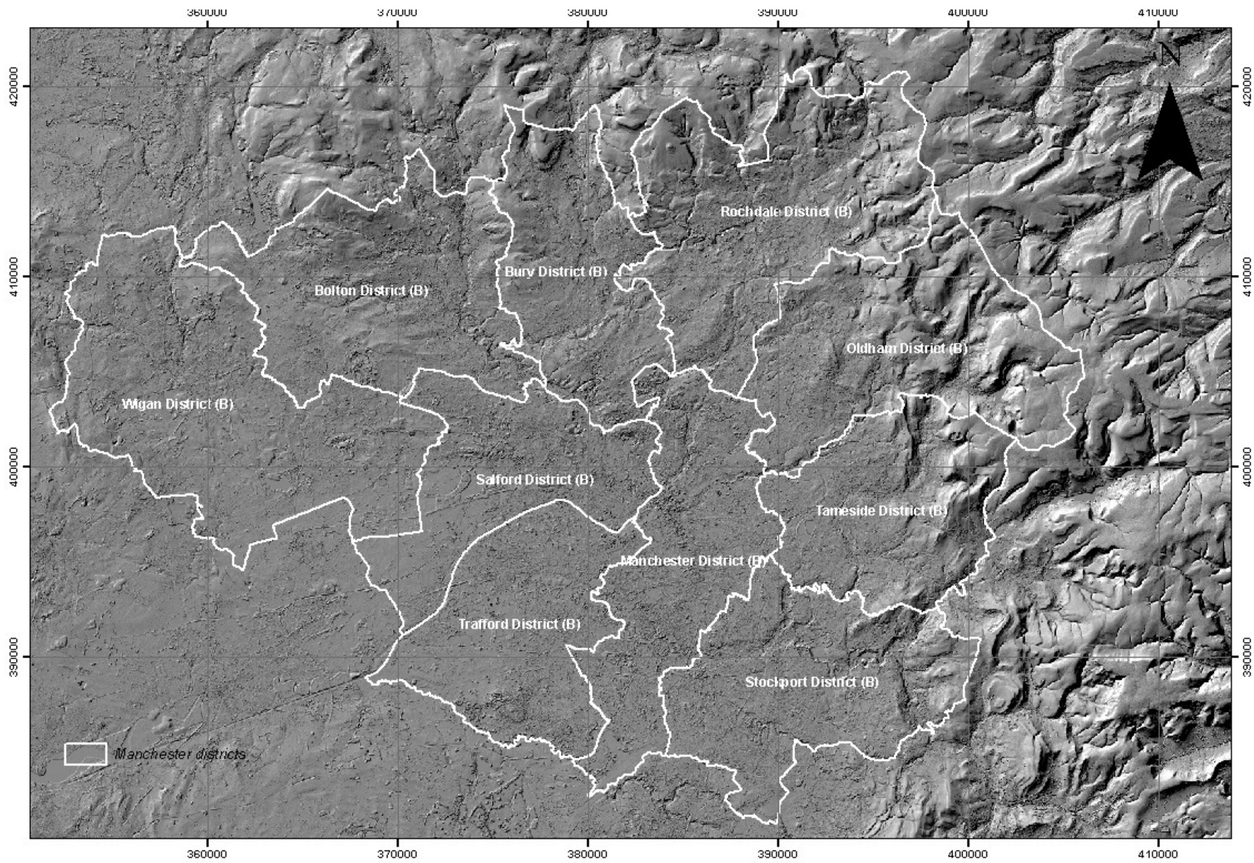

Figure 4 Next Map shaded relief showing the topography. Greater Manchester Combined Authority area and boroughs outlined in white. NEXTMap Britain elevation data from Intermap Technologies.

3 Data and information

Information used for this report:

- Digital 1:50 000 scale geological maps – BGS Geology 50K
- Geology sheets and memoirs – Preston (75), Rochdale (76), Huddersfield (77), Wigan (84), Manchester (85), Glossop (86), Stockport (98) and Chapel-en-le-Frith (99)
- Tectonic map of Britain, Ireland and adjacent areas, 1:1 500 000 Series, Sheet 1 (Pharoah et al, 1996)
- BGS borehole databases – Single Onshore Borehole Index and Borehole Geology
- BGS geotechnical database
  BGS BritPits database

4 Geological background

Manchester lies towards the eastern edge of the Cheshire Basin, bounded to the east by the Pennine Hills. This section describes the geology of the area in stratigraphic order from the most recent geological units through to the oldest, based on the published 1:50 000 scale geological maps of the area.

4.1 ARTIFICIAL GROUND

BGS classifies areas where the land surface has been modified through human activity as artificial ground, such as road/railway cuttings and embankments. The BGS Geology artificial ground theme uses five categories:

- Made ground – areas where the land surface has been raised, such as road/rail embankments and spoil heaps
- Worked ground – areas where the land surface has been lowered through the removal of material, such as quarries and road/rail cuttings
- Infilled ground – this term is used for areas where material has been removed and subsequently backfilled, such as infilled canals and backfilled quarries
- Landscaped ground – areas where the land surface has been re-shaped or levelled
- Disturbed ground - areas of shallow mineral workings where made and worked ground cannot be mapped separately, such as bell pits

Figure 5 shows the BGS Geology 1:50 000 scale artificial ground theme for the Greater Manchester area, coloured by artificial ground class. Several large polygons of made ground are mapped in the Salford area, associated with the Manchester Ship Canal and Trafford Park (Inset map in Fig 5). No artificial ground has been mapped in the southern part of the area. Table 1 presents the details of mapped artificial ground for Central Manchester (Bridge et al., 2010). Figure 6 shows the distribution of artificial ground in the Manchester 3D geological model area. Artificial ground is more widespread in the model than the geological maps because all instances of artificial ground are represented in the model (Price et al, 2012).

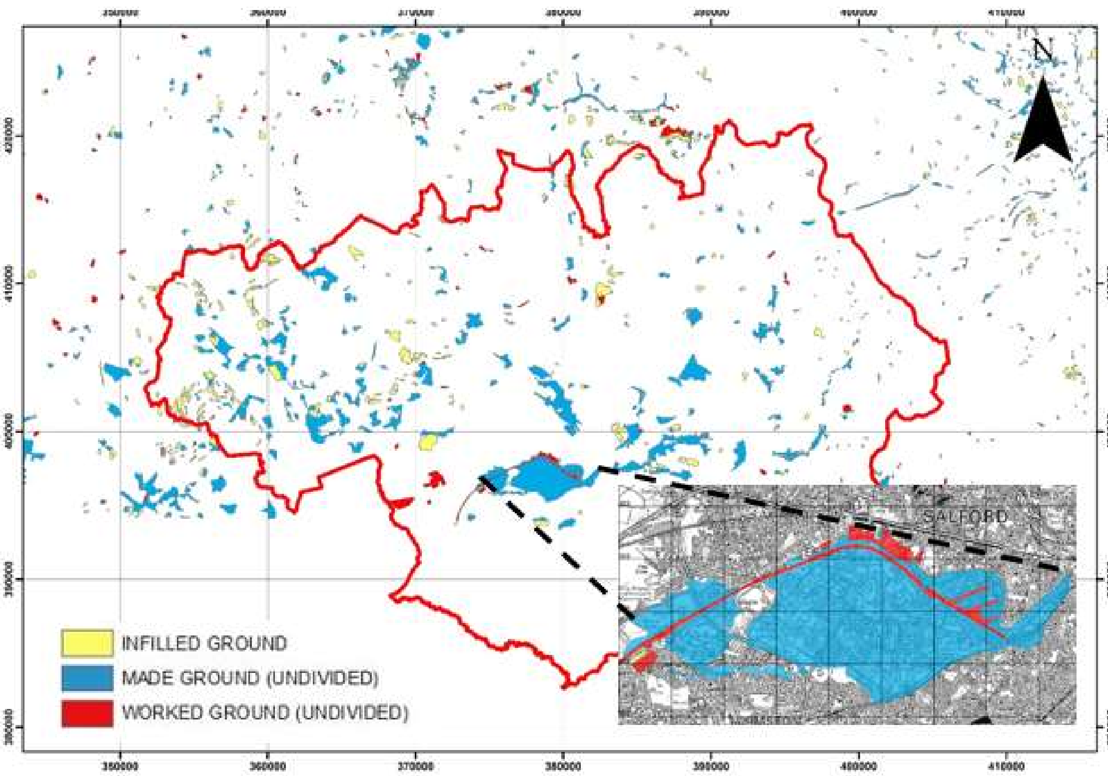

Figure 5 Distribution of artificial ground in the area of the 1:50 000 scale BGS Geology artificial ground theme. Inset map shows extensive made ground at Trafford Park and worked ground associated with the Manchester Ship Canal and docks at Salford Quays

Table 1 Characteristics of made, worked and infilled ground in Central Manchester (Bridge et al., 2010)

	Category	Thickness	Composition
Made ground	Undivided covers 60% of area	1-2 m; 3-7 m in Manchester and Salford city centres	Construction waste, may present inter and hazardous waste
	River Irwell	3-7 m but more than 8 m in Salford Quays	Colliery spoil, organic and inorganic waste
	Sewage works and domestic refuse sites	3-7 m; up to 10 m	Oily sandy ash with organic refuse
	Trafford Park Industrial Estate	1 – 2 m; 3-7 m, more than 8 m in eastern part of the Park	Waste materials from industrial development including chemical manufacturing industries
	Valley infill Medlock river valley	3-7 m; 8-12 m	Construction materials, colliery spoil, textile industry waste possible
	Valley infill Crofts Bank valley	3-7 m	Brick, metal and wood fragments
	Valley infill River Irk	1-4 m; up to 7 m	Railway land, waste from textile factories, spoil from brick pits and sandstone quarries
	Railway sidings Gorton	1-4 m	Railway sidings, good depots
	East Manchester	1-4 m, up to 7 m	Materials from industrial processes, spoil associated with coal mining
Worked ground	Manchester ship canal		
Infilled ground	Pits, quarries and artificial lakes		

Additional artificial ground information was gathered for the Manchester 3D geological model using historic and modern Ordnance Survey maps and boreholes (Figure 6). One discovery made through this work was that meander loops in the River Irwell were infilled with colliery spoil during construction of the Manchester Ship Canal (da Luz et al., 2015; Price et al, 2012). Boreholes record a variable composition for artificial ground, including fragments of cement, stones, bricks, timber, pottery, glass, metal, wood, plastic, coal and colliery waste.

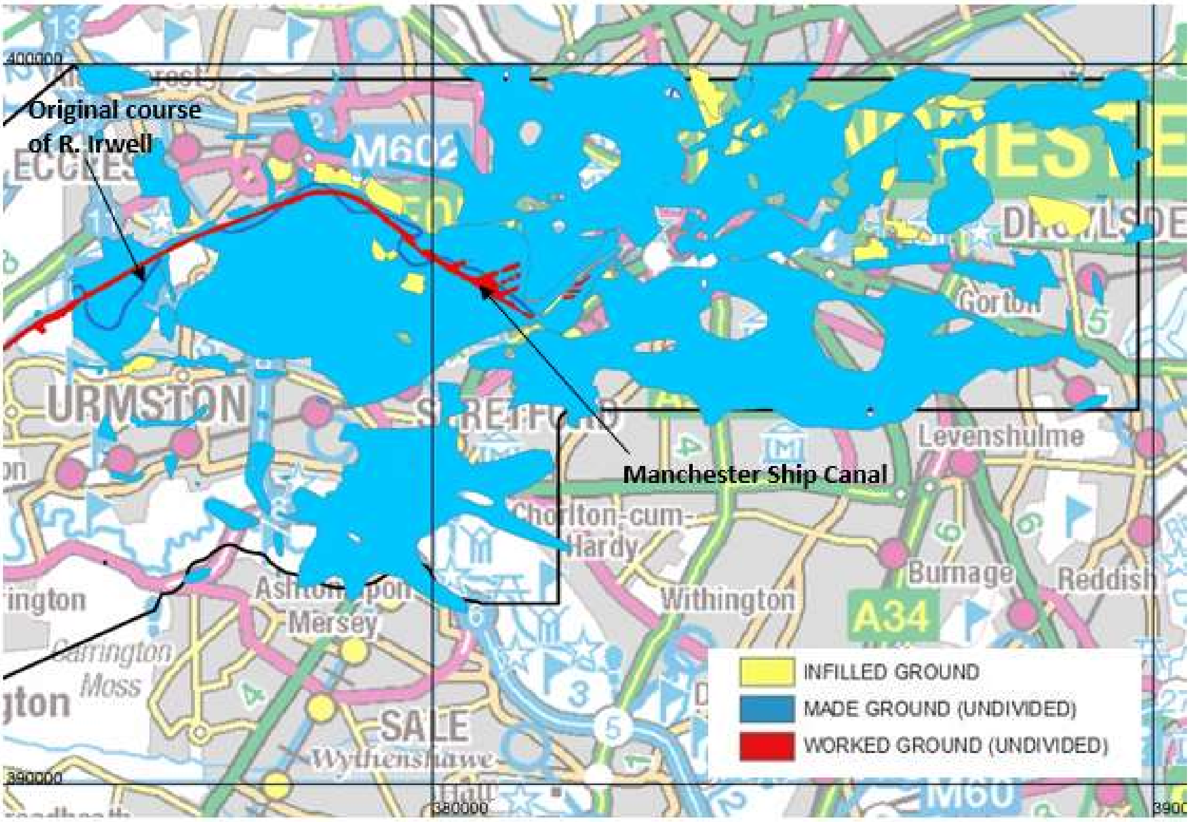

Figure 6 Distribution of artificial ground information gathered for the Manchester 3D geological model, showing more extensive made ground than the geological maps. Contains Ordnance Data © Crown Copyright and database rights [2020]. Ordnance Survey Licence no. 100021290

4.2 SUPERFICIAL DEPOSITS

Quaternary deposits overlie the bedrock in almost the entire area, reaching over 40 m in thickness in places (Crofts et al., 2012). The most widespread superficial deposit in the area is till. Till is poorly sorted eroded material transported and deposited by advancing ice. In the Greater Manchester area, the till consists of gravelly, sandy, silty clay to sandy, clayey gravel with clasts ranging up to boulder size. Till is part of a sequence of glacial sediments laid down during the Late Devensian, when the British Irish Ice sheet reached its maximum extent, the Devensian Limit, approximately 26 000 years ago (Crofts et al., 2012). Other Devensian sediments include sand & gravel and laminated silts and clays. Figure 7 shows the distribution of superficial deposits in the Greater Manchester area, which are summarised in Table 1.

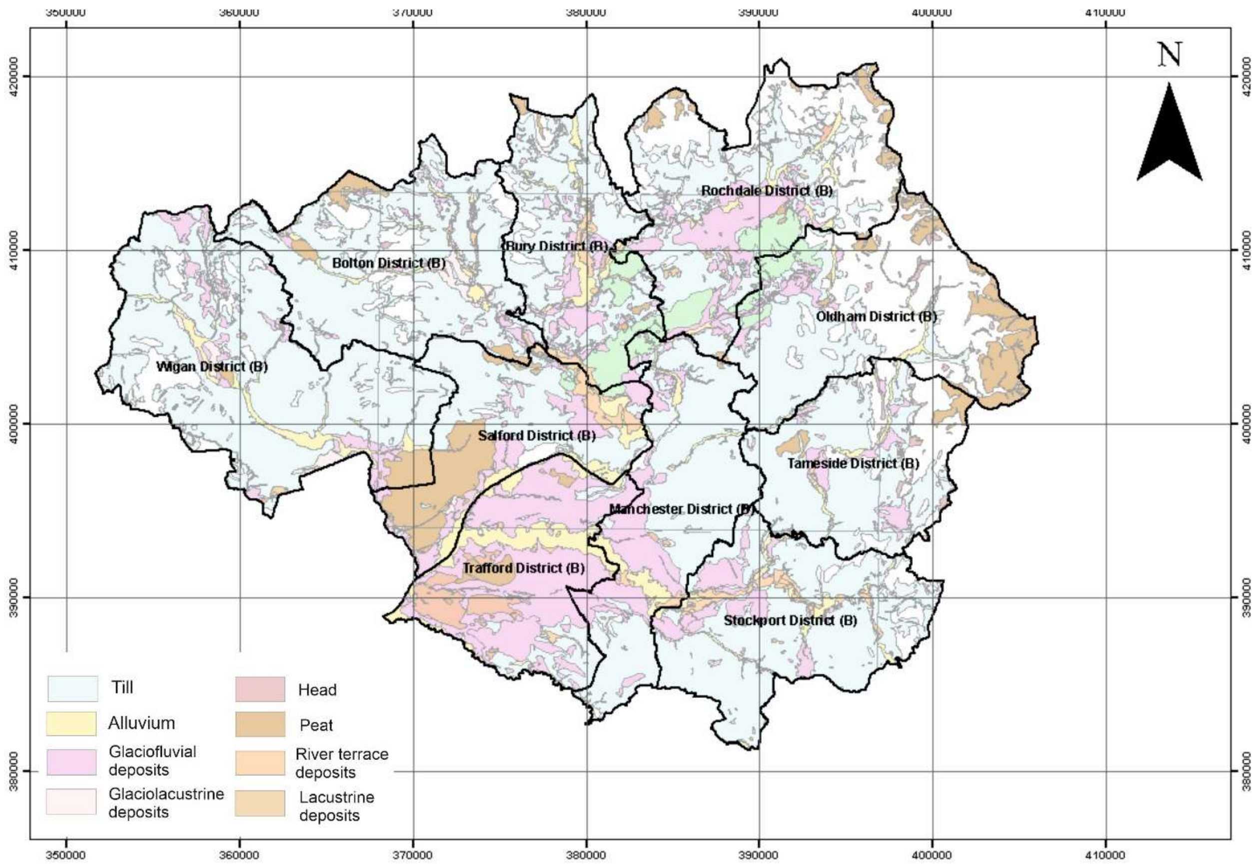

Figure 7 BGS Geology 1:50 000 scale superficial geology map

Table 2 Description of the superficial deposits

	Deposit	Description	Process	Thickness	Location
Holocene	Peat	Peat with pockets of sands on grey clayey silts	Organic deposits accumulating in areas of restricted drainage	Locally up to 9 m	Large patches mapped on the moors in the north-east of the study area, significant deposits at Chat Moss in the west of the area. Smaller patches elsewhere, e.g. Trafford Park
	Lacustrine deposits	Organic-rich, partly laminated, silt and clay	Lakes forming in hollows on poorly drained ground, may also underlie peat	3-10 m	Small isolated patches, mainly along the M62 between Heywood and Trub
	Alluvium	Silt and organic-rich clay with beds and lenses of sand, gravel and peat	Modern floodplain deposits	Up to 6-8 m	River valleys, including the Mersey, Irwell, Irk and their tributaries
Pleistocene	River terrace deposits	Stratified sandy gravel	Development of river systems following deglaciation	3 m	River valleys, including the Irwell, Roch and Mersey
	Head	Highly variable, gravelly, sandy, silty clay with clasts in a silty clay matrix	Head accumulates on slopes and in valley bottoms through the down-slope movement of material under periglacial conditions		Head is ubiquitous throughout the area, but only mapped where it has a significant thickness, such as Croal Channel in Bolton, the valley of Whittle Brook, and the foothills of the Pennines
	Glaciofluvial sheet deposits	Extensive spreads of sand and gravel	Deposited by meltwater as the Devensian ice sheet melted	Around 5m	Along the River Irk valley from the Chaderton area to the River Mersey. Extensive deposits in the south-west of the area
	Glaciofluvial deposits (undifferentiated)	Sand and gravel	Deposited by meltwater as the Devensian ice sheet melted	Variable, 19.5m recorded in Salford	The most extensive deposits occur in the Rochdale area, between Heywood and Milnrow, Darn Hill and Fishpool, near Whittle Brook
	Glaciolacustrine deposits	Laminated clay, silt and fine sand	Low energy glacial lake environment	Up to 5 m	Mapped in patches in the northern half of the area, mainly around Bolton, Wigan, Golborne and Urmston
	Glaciolacustrine deltaic deposits	Sand	Marginal glacial lake sediments where glacial rivers and streams drained into the lake	20 m	Only mapped in the Bolton area, interpreted to be associated with an ephemeral lake between a sandy ridge near Birch Services on the M62 and a bedrock high at Hares Hill to the north
	Stockport Glacigenic Formation till	Sandy, gravelly clay with cobbles and boulders. Includes clasts from the Lake District (Borrowdale volcanic rocks, Eskdale Granite), Carboniferous rocks and material from the Irish Sea	Glacigenic sediments deposited by advancing ice, derived from the Irish Sea	Variable, locally up to 35 m	West and south of the study area
	Brewood Till Formation	Red-brown, gravelly, sandy, silty clay with cobbles and boulders. Clasts derived from the Sherwood Sandstone Group and further afield, e.g. the Southern Uplands and the Lake District	Glacigenic sediments deposited by advancing ice, derived from the Irish Sea	3 to 17 m	South-east quadrant of the study area
	Yorkshire Dales Till Formation	Dark grey to greyish brown, extremely compact, stony sandy silty clay till. Clasts are predominantly locally derived Carboniferous lithologies	Glacigenic sediments deposited by advancing ice, derived from the Yorkshire Dales	Generally less than 10 m	Mapped in the north of the area

Holocene

Peat deposits are mapped in Trafford and comprises peat with pockets of sand. The peat at Trafford was originally 3 m thick (Tonks et al., 1931), but much of it was removed when the area was developed. Extensive peat deposits are mapped in the south-west of the area, such as Chat Moss. Veneers of peat are also mapped on the high ground in north-east of the area.

Alluvium is mapped in central Manchester and consists of silt and organic-rich clay with beds and lenses of sand, gravel and peat (Bridge et al. 2010). Its thickness is 6 to 8 m along the River Irwell. Alluvium has been modified because of the urban and industrial development in the area.

Lacustrine deposits are composed of laminated, silt and clay and sand, which accumulates in lakes and hollows on poorly drained ground.

Pleistocene deposits

River terrace deposits are composed of stratified sandy gravels and are mapped along river valleys, including the Irwell and Medlock. The river terrace deposits in the Irwell Valley mainly comprise silty sand overlying sand and gravel, with a thickness of around 3 m.

Head accumulates on slopes and in valley bottoms through the down-slope movement of material under periglacial conditions. It has a cariable composition, generally consisting of gravelly, sandy, silty clay with clasts in a silty clay matrix. Head is ubiquitous throughout the area, but is only mapped where it has a significant thickness, such as the Croal Channel in Bolton, the Whittle Brook valley, and the foothills of the Pennines.

Devensian deposits

Till is the most widely mapped Devensian deposit in the study area. Three till domains are mapped in the area, based on ice movement directions (McMillan et al. 2011). The Stockport Glacigenic and Brewood Till Formations belong to the Irish Sea Coast Glacigenic Subgroup and are derived from the west; the Yorkshire Dales Formation is derived from the north and belongs to the North Pennine Glacigenic Subgroup (Culshaw et al., 2017). These different source areas have influenced the composition of the tills. These till formations are summarised below and their spatial distribution is shown in Figure 8.

1. Stockport Glacigenic Formation occurs in the south and south-west of the area and consists of sandy, gravelly clay with boulders and cobbles, laminated clay and silt and lenses of sand gravel. Includes clasts from the Lake District (Borrowdale volcanic rocks, Eskdale Granite), Carboniferous rocks and material from the Irish Sea.
2. Brewood Till Formation is mapped in the south-east of the area and consists of red-brown, gravelly, sandy clay with cobbles and boulders. Clasts are locally derived from the Sherwood Sandstone Group and further afield, e.g. the Southern Uplands and the Lake District.
3. Yorkshire Dales Till Formation occurs in the north of the area and consists of dark grey to greyish brown, extremely compact, stony sandy silty clay. Clasts are predominantly locally derived Carboniferous lithologies.

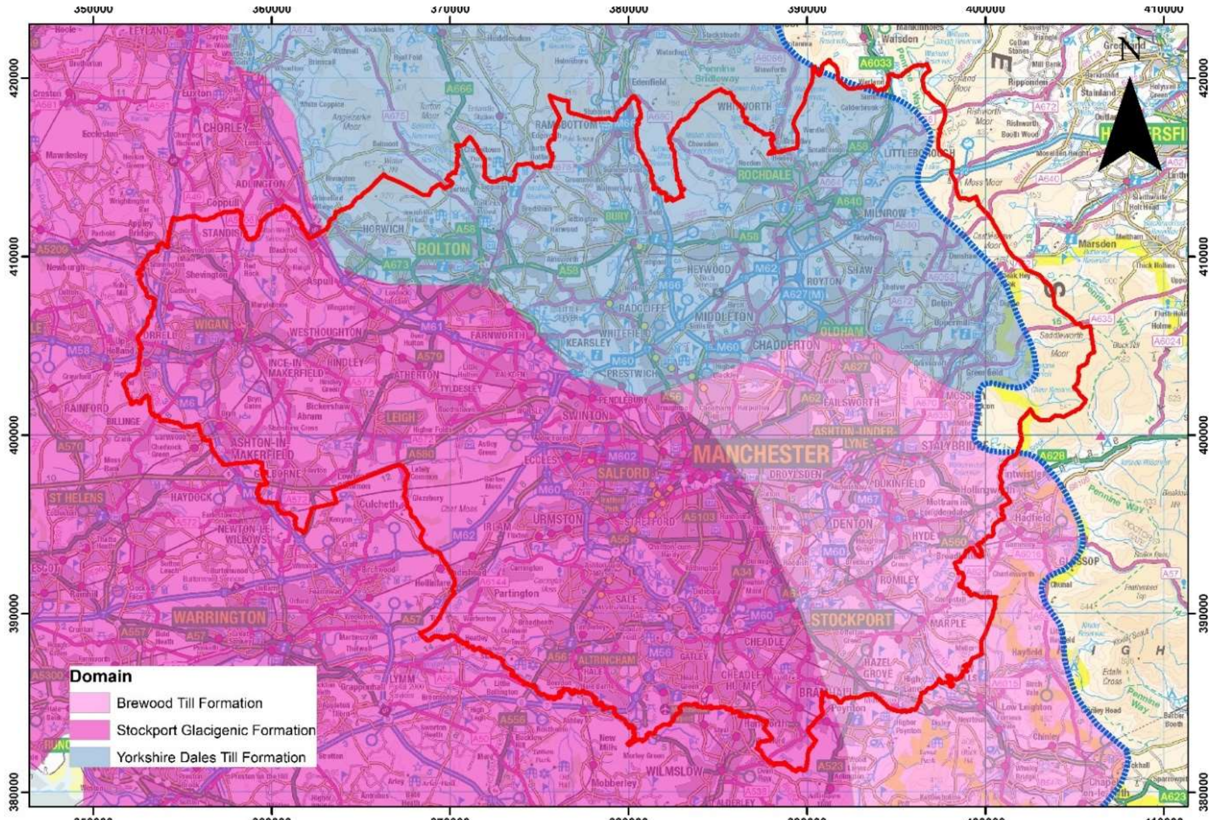

Figure 8 Map showing the three glacigenic formations that occur in the Greater Manchester area (from McMillan and Merritt, 2012). Devensian limit shown as a blue dashed line. Contains Ordnance Data © Crown Copyright and database rights [2020]. Ordnance Survey Licence no. 100021290

Although the tills appears to have a uniform composition on the geological map, boreholes reveal vertical and lateral lithological variation. A geological cross-section running north-south through the Greater Manchester Combined Authority area shows this complexity, with lenses of sand and gravel and laminated clay making up a significant proportion of the till (Figure 9).

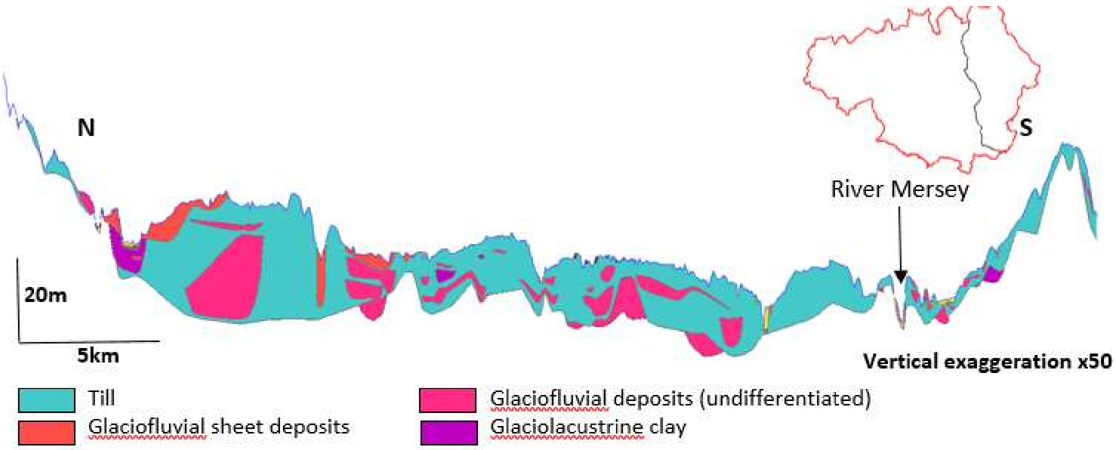

Figure 9 North-south oriented geological cross-section showing lithological variation in the till through Greater Manchester. The lithologies are till (sandy, gravelly clay with cobbles and boulders); glaciofluvial sheet deposits (fine to coarse grained sand and medium dense to dense gravels); glaciofluvial deposits undifferentiated (coarse grained sand and gravel with lenses of silt and clay); and glaciolacustrine clay (laminated clay, silt and sand)

Glaciofluvial sheet deposits are composed of sand and gravel and are mapped between Chaderton and the river Mersey.

Glaciofluvial deposits (undifferentiated) are composed of coarse grained sand and gravel with lenses of silt and clay. The most extensive glaciofluvial deposits (undifferentiated) are mapped in the Rochdale area, between Heywood and Milnrow, Darn Hill and Fishpool near Whittle Brook (Crofts et al., 2012). Further north the valleys of the rivers Irwell and Roch and their tributaries were filled with these deposits (Crofts et al., 2012).

Glaciolacustrine deposits are composed of laminated clay, silt and fine sand. These are mapped at Farnworth, south of Bolton.

Glaciolacustrine deltaic deposits are marginal glacial lake sediments mapped only in the Bolton area, where 20 m of sand and gravel is recorded (Crofts et al., 2012).

4.3 SUPERFICIAL DEPOSIT THICKNESS

A thin veneer of superficial deposits occurs on higher ground, mainly composed of peat, whilst a thick, almost continuous cover of superficial deposits occurs in the lower ground in the south and west of the district. Superficial deposits are absent in parts of the north-east and east of the study area. Figure 10 shows an extract from the BGS national superficial thickness dataset (Lawley and Garcia-Bajo, 2010), derived from boreholes and the mapped distribution of superficial deposits.

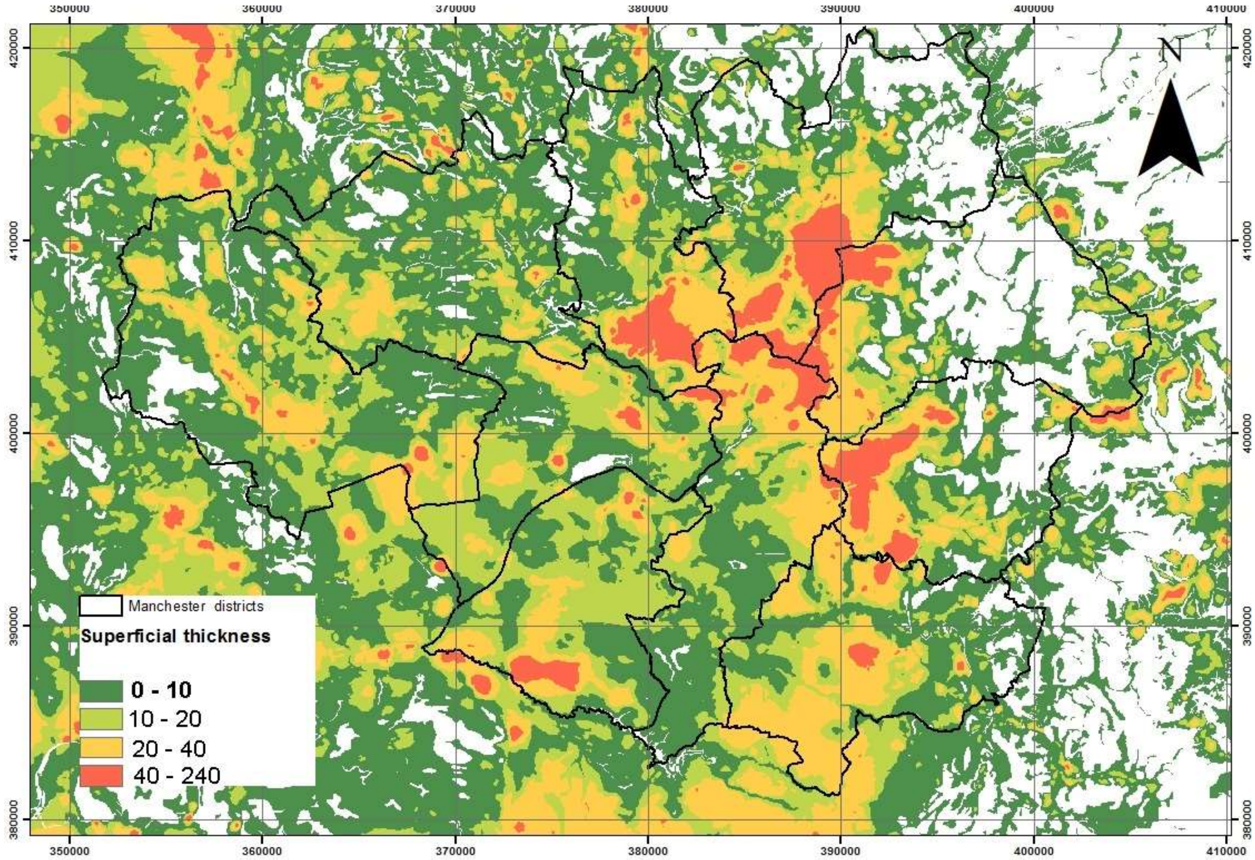

Figure 10 Extract from the BGS superficial deposit thickness (metres) dataset with a red to green colour ramp. White areas indicate where superficial deposits are absent

4.4 BURIED VALLEYS

The BGS 1:250 000 scale buried valleys dataset uses the thickness of superficial deposits proven in boreholes. Superficial deposits exceed 40 m in thickness towards the northern and eastern part of the area, covering central Manchester, Rochdale, Oldham, Tameside, Wigan and Stockport. Buried valleys containing 20-30 m of superficial deposits are recorded at Trafford and Salford (Figure 11).

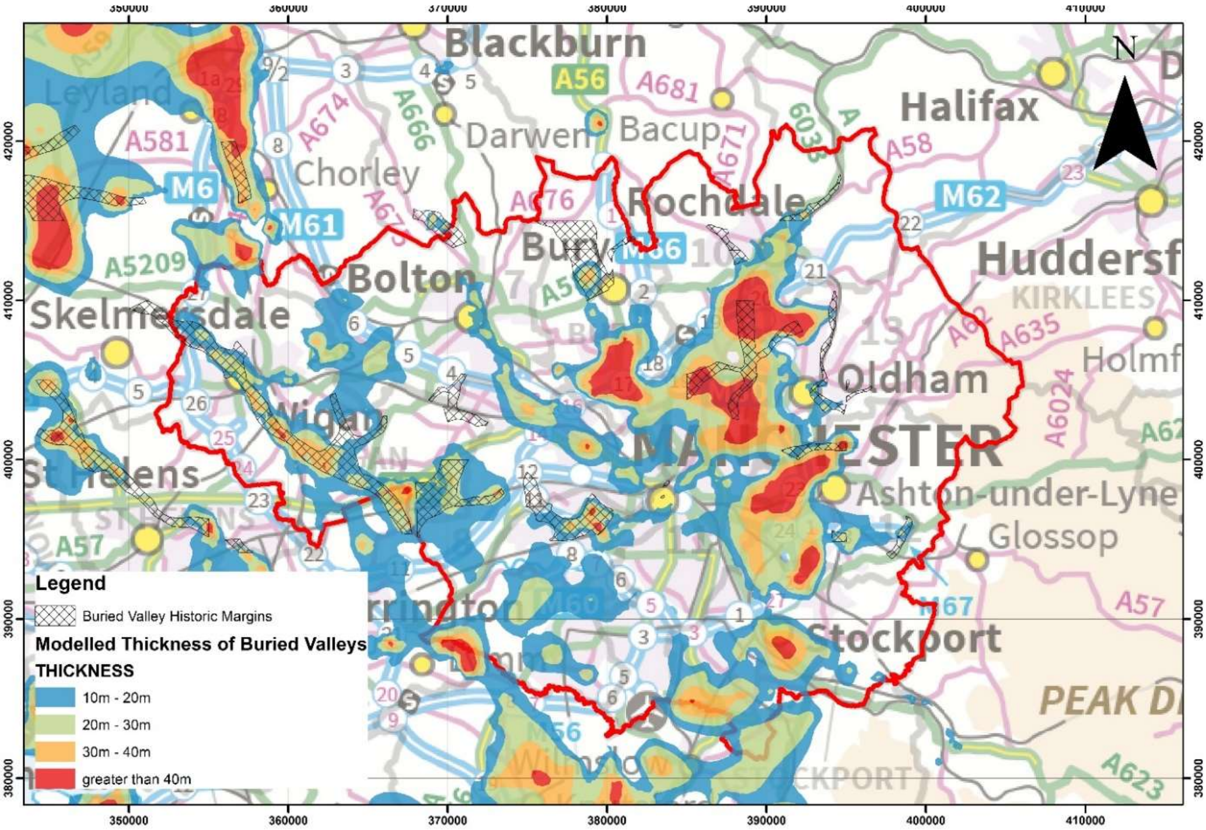

Figure 11 **BGS 1:250 000 scale Buried Valleys dataset. Areas in red indicate where superficial deposits are thicker than 40 m (Kearsey and Lee, 2019). Contains Ordnance Data © Crown Copyright and database rights [2020]. Ordnance Survey Licence no. 100021290**

4.5 BEDROCK GEOLOGY

The bedrock units in the study area were laid down during the Triassic, Permian and Carboniferous periods. The youngest rocks in the area belong to the Triassic Mercia Mudstone Group, mapped in the south. The Triassic Sherwood Sandstone Group, a regionally important aquifer in north-west England, underlies the Mercia Mudstone Group and is mapped through the south and centre of the district. Permian mudstones and sandstones of the Cumbrian Coast and Appleby groups underlie the Sherwood Sandstone Group and outcrop in a narrow band running through the centre of the area, curving to the south. Carboniferous rocks unconformably underlie the Permian strata and comprise the Warwickshire, Pennine Coal Measures and Millstone Grit groups. The bedrock units are displaced by numerous geological faults, which are discussed in Section 4.6.

Figure 12 is a 1:50 000 scale bedrock geology map of the Greater Manchester Combined Authority Area (BGS Geology 50K).

A north-south cross-section from the Manchester 1:50 000 scale geological map sheet (85), published in 2011, is shown in Figure 13.

Figure 14 is a Generalised Vertical Section of the bedrock units Permo-Triassic rocks and underlying Coal Measures Group, showing their thicknesses (from Bridge et al., 2010).

Table 3 summarises the main bedrock units, colour coded to match the bedrock map in Figure 12. The descriptions in Table 2 are based on the Pennines and adjacent areas regional guide (Aitkenhead et al., 2002) and geological map descriptions. Detailed descriptions are available in the BGS Lexicon of Named Rock Units at: https://www.bgs.ac.uk/lexicon/?src=topNav

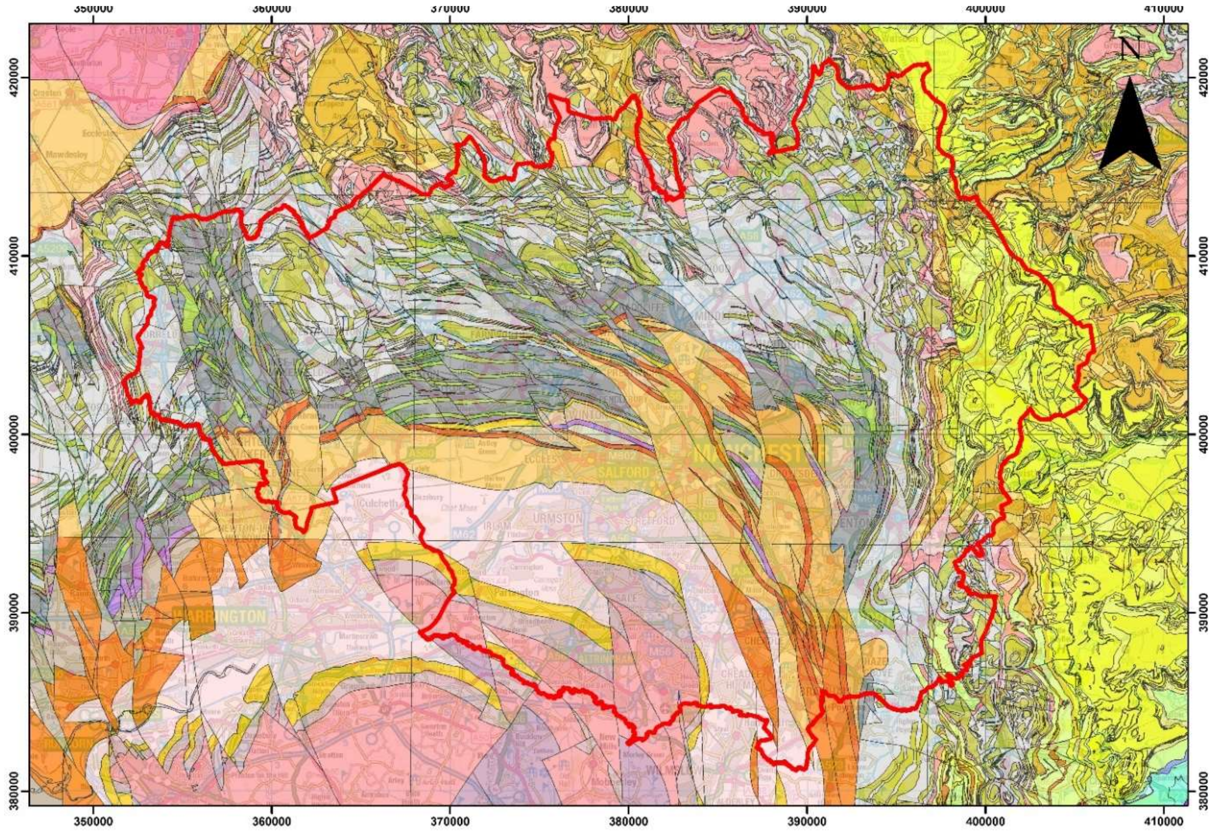

Figure 12 BGS Geology 1:50 000 scale bedrock geology map. Greater Manchester Combined Authority area outlined in red. Contains Ordnance Data © Crown Copyright and database rights [2020]. Ordnance Survey Licence no. 100021290

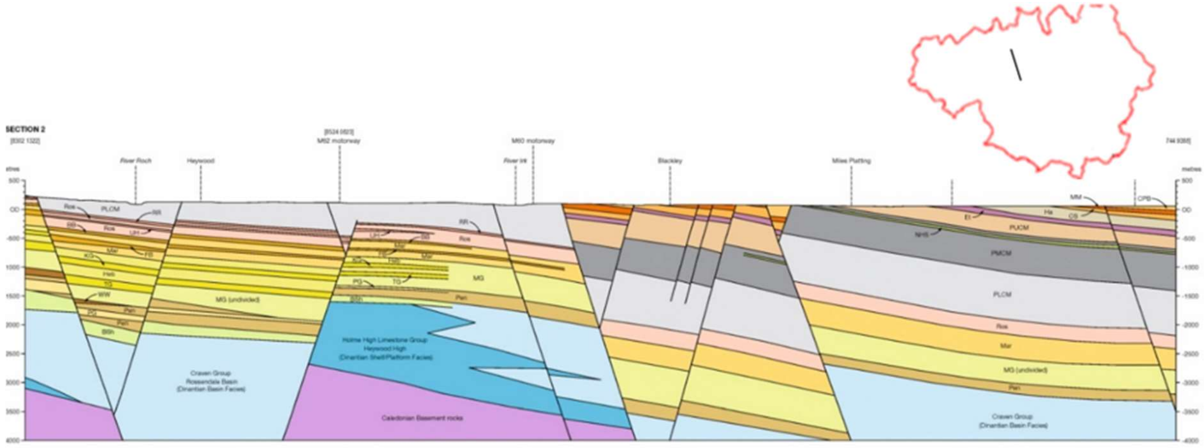

Figure 13 Geological cross-section of the bedrock (from BGS 1:50 000 scale map sheet 85, Manchester, published in 2011)

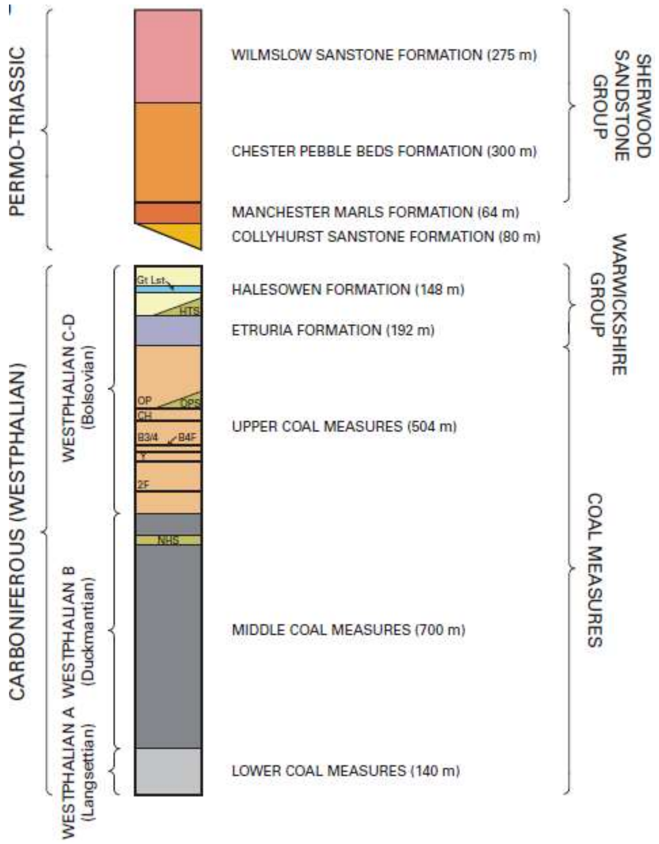

Figure 14 Generalised Vertical Section of the bedrock units beneath Greater Manchester and Salford (from Bridge et al., 2010)

Table 3 Main bedrock units in the area (units are coloured to match the Figure 12 bedrock geology map

		Group	Formation	Description	Thickness	Depositional environment	Location
Triassic	Early to Middle Triassic	Mercia Mudstone Group (MMG)	Sidmouth Mudstone Formation (SIM)	Red brown and green-grey mudstone with siltstones	500 m	Evaporitic enclosed basin	South-west of the area
			Tarporley Siltstone Formation (TPSF)	Interbedded and interlaminated siltstones, mudstones and sandstones	Around 100 m	Evaporitic enclosed basin	South-west of the area
		Sherwood Sandstone Group (SSG)	Helsby Sandstone Formation (HEY)	Fine to medium grained sandstone with a conglomerate base, locally micaceous	140 m	Fluvial/aeolian	Mapped in a band through the south-east of the area
			Wilmslow Sandstone Formation (WLSF)	Medium grained sandstone		Large aeolian sand dunes	South and west of the area
			Chester Formation (CHES)	Conglomerates with medium and coarse grained sandstones	Up to 440 m	Aeolian and fluvial	Mapped in a broad band through the centre and south of the area
			Kinnerton Sandstone Formation (KNSF)	Red brown coloured sandstone	Up to 50 m	Aeolian	Mapped in narrow bands in the far west of the area
Permian	Upper Permian	Cumbrian Coast Group	Manchester Marls Formation (MM)	Red-brown mudstone with limestone and siltstone beds	Thickens eastwards from 7m at Trafford park to 70 m at Aston-Under-Lyme	Marine	Mapped through the west, centre and south of the area
	Middle Permian	Appleby Group	Collyhurst Sandstone Formation (CS)	Fine to coarse grained red sandstone with dunes and interbeds	Up to 260m	Aeolian or a combination of aeolian and fluvial	Mapped through the west, centre and southern part of the area
Upper Carboniferous	Asturian (Westphalian D)	Warwickshire Group	Halesowen Formation (HA)	Grey-green micaceous sandstone and grey-green mudstone	up to 165 m	Delta plain environment	Mapped in the centre of the area
			Etruria Formation (ETM)	Mottled brown, red, purple, green and grey mudstones and siltstones with limestone beds	Up to 90 m	Fluvial	Mapped in the centre of the area
	Bolsovian (Westphalian C)	Pennine Coal Measures Group (PCM)	Pennine Upper Coal Measures Formation (PUCM)	Interbedded grey mudstone, siltstone and pale grey named sandstone units, commonly with coal seams. Absence of mudstones containing marine fossils are present	300-500 m	Delta plain environment, above sea level	Mapped in the centre of the area
			Pennine Middle Coal Measures Formation (PMCM)	Mudstone, siltstone and named sandstone units (sandstones are coloured green an Fig. 12)	Up to 745 m		Mapped in a broad band through the west and centre of the area
			Pennine Lower Coal Measures Formation (PLCM)	Mudstone, siltstone and named sandstone units with subordinate coal seams, seatearth beds and marine bands	Up to 840 m		Widely mapped in the north and east of the area

				(sandstones are coloured green on Fig. 12)			
		Millstone Grit Group (MG)	Rossendale Formation (ROSSE)	Mudstone and siltstone interbedded with fine to medium grained named sandstone units, subordinate seatearth and ironstone beds, marine bands and coal seams (sandstones are dark pink)	115 m	Sediment cycles associated with changes in sea level. Marine bands occur at the base, passing up into into mudstones, siltstones and sandstones. Topped with seatearths and coals associated with soils and vegetation respectively	Mapped in the north and east of the area
			Marsden Formation (MARSD)	Mudstone, siltstone and named sandstone units with seatearth beds, thin coal seams and marine bands (sandstones are dark yellow)	220 m		Mapped in the east of the area
			Hebden Formation (HEBD)	Feldspathic-arenite, mudstone, sandstone and siltstone with subsidiary coal and seatearth	210 m		Mapped in the east of the area

4.5.1 Mercia Mudstone Group (Triassic)

The youngest bedrock units in the area belong to the Mercia Mudstone Group, laid down in the Triassic period. These rocks are mapped in the south-west of the area, comprising the Sidmouth Mudstone Formation and the underlying Tarporley Siltstone Formation.

Sidmouth Mudstone Formation, previously divided into the Lower Keuper Marl and Lower Saliferous Beds, reaches 500 m thick and occurs in the south of the study area (Crofts et al., 2012). The upper part of the Sidmouth Mudstone Formation in the study area is the Northwich Halite Member, formerly named Lower Saliferous Beds. The Northwich Halite Member consists of halite with partings of mudstone and reaches around 80 m thick, recorded in a borehole at Mobberley near Manchester airport, south of the study area (Wilson, 2003).

The Bollin Mudstone Member directly underlies the Northwich Halite Member, and consists of grey green dolomitic siltstone and fine grained sandstone interbedded with mudstone (Howard et al, 2008).

Beneath the Bollin Mudstone Member the Sidmouth Mudstone Formation predominantly consists of structureless reddish brown mudstone and siltstone with common grey-green reduction patches and spots (Howard et al, 2008). The Sidmouth Mudstone Formation includes units comprising several beds of interlaminated mudstone and siltstone, ranging in thickness from a few centimetres to 4 m. (Howard et al, 2008).

Tarporley Siltstone Formation, formerly named Keuper Waterstones, comprises interlaminated and interbedded reddish brown and greenish grey mudstones and siltstones with thin fine to medium grained sandstones. Gypsum nodules occur sporadically in the mudstone beds. The Tarporley Siltstone Formation is interpreted as inter-tidal deposits within an evaporitic basin. It is commonly about 100 m thick, thickening to 280 m south of Altrincham, according to Wilson (1993), although the 280 m is likely to include a substantial part of the overlying Sidmouth Mudstone Formation because the two units interdigitate (Howard et al, 2008). The Tarporley Siltstone formation includes desiccation surfaces, pseudomorphs of halite, cross-lamination, burrows and a few reptilian footprints (Wilson, 1993). The base of the Tarporley Siltstone Formation is indistinct because it interdigitates with the underlying Sherwood Sandstone Group.

4.5.2 Sherwood Sandstone Group (Triassic)

The Triassic Sherwood Sandstone Group underlies the Mercia Mudstone Group. It consists of red brown sandstones with subordinate beds of red-brown mudstone (Crofts et al., 2012). The Sherwood Sandstone Group is the United Kingdom's second most important aquifer and the major aquifer for north-west England (Aitkenhead et al., 2002). Four formations belonging to the Sherwood Sandstone Group are mapped in the area, described from youngest to oldest below. Further lithostratigraphical detail can be obtained from Ambrose et al., 2014. Individual sandstone members are separated by more clay rich units that can be identified using gamma logs.

Helsby Sandstone Formation, formerly named Keuper Sandstone, is mapped in a band through the south-east of the area. It is described in the BGS Lexicon of Named Rock units as cross-bedded, locally micaceous, fine to medium grained sandstone with a conglomeratic base. The formation was deposited in fluvial and aeolian (windblown) conditions and is 140 m thick (Taylor et al., 1963).

Wilmslow Sandstone Formation, formerly named Upper Mottled Sandstone, is mapped in the south and west of the area and reaches up to 920 m thick in the Cheshire Basin (Ambrose et al., 2014). It consists of medium-grained sandstone with large-scale shallow angle cross-bedding, interpreted as large aeolian sand dunes.

Chester Formation, formerly named Chester Pebble Beds Formation, is mapped in a broad band through the centre and south of the area. It consists of a lower unit of sandstone and an upper cross-bedded sandstone with mudstone beds. The maximum total thickness of the Chester Formation is 440 m (Crofts et al., 2012).

Kinnerton Sandstone Formation, formerly named Lower Mottled Sandstone, is mapped in a narrow band in the far west of the area. It consists of up to 50 m of red-brown coloured sandstone and its deposition is likely to be during the late Permian-early Triassic (Crofts et al., 2012; Ambrose et al., 2014).

4.5.3 Cumbrian Coast Group (Upper Permian)

The only unit of the Cumbrian Coast Group in the study area is the **Manchester Marls Formation.** This unit has a thin outcrop band through the west, centre and south of the area and consists of red brown mudstones with carbonate (limestone and dolomite) and siltstone beds of marine origin (Crofts et al., 2012). The Manchester Marls Formation thickens eastwards, from 7 m at Trafford Park to over 70 m at Ashton-Under-Lyme (Crofts et al., 2012).

4.5.4 Appleby Group (Middle Permian)

The **Collyhurst Sandstone Formation** of the Appleby Group is mapped through the west, centre and southern part of the district, unconformably overlying the Coal Measures Group (Crofts et al., 2012). The Collyhurst Sandstone Formation is up to 260 m thick and consists of red and orange, fine to medium grained sandstone (Crofts et al., 2012). The depositional environment is interpreted as aeolian or a combination of aeolian and fluvial (Crofts et al., 2012).

4.5.5 Warwickshire Group (Asturian, Upper Carboniferous)

The Warwickshire Group conformably overlies the Pennine Upper Coal Measures Formation, both of which were deposited in a delta plain system that was above sea level for long periods of time (Crofts et al, 2012). The Warwickshire Group is mapped in narrow bands in the centre of the Greater Manchester Combined Authority area with large fault offsets. Two formations of the Warwickshire Group are present in the area, the upper of which is the Halesowen Formation and the basal unit is the Etruria Formation. These sediments were deposited in alluvial and lacustrine environments. Their red colour is attributed to iron oxidation at or shortly after deposition (Waters and Davies, 2006).

The **Halesowen Formation** consists of grey-green mudstone and grey-green micaceous sandstone (litharenite), with thin coals and limestone beds (Spirobis) (Aitkenhead et al., 2002). The Holt Town Sandstone marks the base of the Halesowen Formation in part of the area, its thickness reaching up to 30 m. The Halesowen Formation has a maximum thickness of 165 m (British Geological Survey, 2011).

The **Etruria Formation** is up to 90 m thick and composed of mottled brown, red, purple, green and grey poorly bedded alluvial mudstones and siltstones (Aitkenhead et al, 2002).

4.5.6 Pennine Coal Measures Group

The study area lies within the South Lancashire Coalfield, with rocks of the Pennine Coal Measures Group outcropping in the north, south and east of the area. The Group rests conformably on the underlying Millstone Grit Group and is up to 2000 m thick (Crofts et al., 2012). The Pennine Coal Measures Group was laid down in coarsening up cycles of interbedded mudstone, siltstone and sandstone with subordinate coal and seatearth (Crofts et al., 2012). The mudstones tend to be dark grey to black, weathering to orange and can be planar laminated or micaceous or massive (Crofts et al., 2012). The Pennine Coal Measures Group is divided into three formations, all of which are mapped in the Greater Manchester area:

The **Pennine Upper Coal Measures Formation** is 300-500 m thick in this area and consists of mudstone and siltstone with subordinate medium grained sandstones, seatearths with five named coal seams (British Geological Survey, 2011).

The **Pennine Middle Coal Measures Formation** is up to 745 m thick (British Geological Survey, 2011) and contains 23 named coal seams, 14 of which have been worked using both deep and opencast mining methods (Crofts et al., 2012).

The **Pennine Lower Coal Measures Formation** is up to 840 m thick (British Geological Survey, 2011) and contains 41 named coal seams, 27 of which have been worked by deep and opencast mining.

4.5.7 Millstone Grit Group (Namurian, Upper Carboniferous)

The oldest rocks in the area belong to the Millstone Grit Group, mapped in the north and east of the area. Several small inliers occur within the Coal Measures Group in the north of the area. Reaching a total thickness of up to 2000 m, the Millstone Grit Group is composed of fine to coarse grained sandstones with fine gravel laid down in deltaic and lagoonal conditions. Thin local gravel beds occur at some levels. Dark yellow sandstones are interbedded with mudstone, siltstone, subordinate marine bands and thin coal seams (Crofts et al., 2010). A total of 50 marine bands are recorded in the Millstone Grit Group of the Pennines. The Millstone Grit Group is divided into six formations, the upper three of which outcrop in the study area:

The **Rossendale Formation** is 115 m thick (Crofts et al., 2010) and is mapped in the north and east of the area. It consists of fine to very coarse-grained and pebbly feldspathic sandstone, interbedded with grey siltstone and mudstone with subordinate marine black shales, thin coals and seatearths (Aitkenhead et al., 2002).

The **Marsden Formation** is 220 m thick (Crofts et al., 2010), mainly mapped in the east of the area, and consists of feldspathic-arenite, mudstone, sandstone and siltstone with subsidiary coal and seatearth.

The **Hebden Formation** is the oldest bedrock unit mapped in the study area. It has a total thickness of 210 m (Crofts et al., 2010) and includes the 45-80m thick Lower Kinderscout Grit (Crofts et al., 2010). Feldspathic-arenite, mudstone, sandstone and siltstone with subsidiary coal and seatearth.

4.6 GEOLOGICAL STRUCTURE

A total of 1237 geological faults are mapped in the area at 1:50 000 scale (Figure 15). The vast majority of these faults occur in the Pennine Coal Measures Group, where they are easily identified and affect mining operations. These faults are thought to have developed as a result of extension during the Permian because their orientation does not match the major sedimentary basin bounding faults that developed during the early Carboniferous (Aitkenhead et al, 2002).

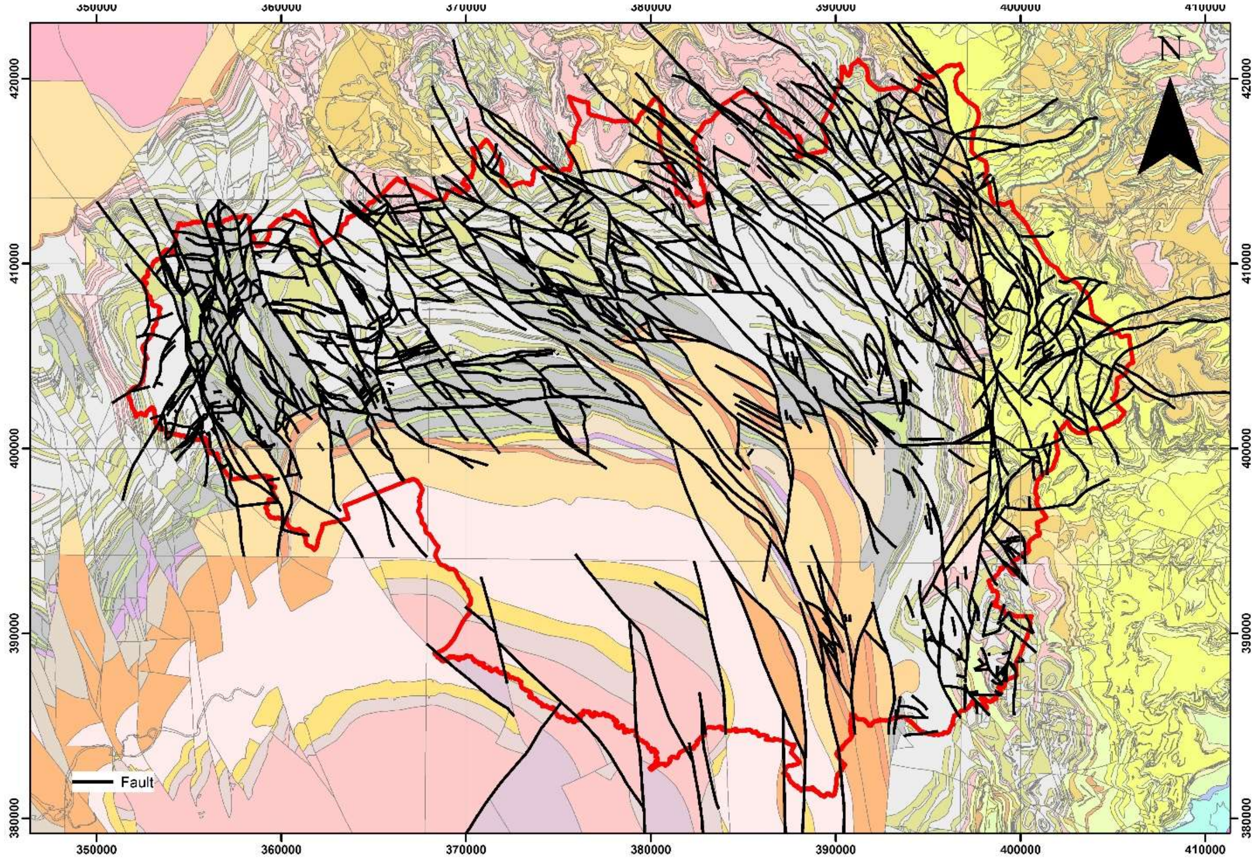

Figure 15 BGS Geology 1:50 000 scale bedrock geology map and fault network. Faults are displayed as black lines

5 Mineral resources

Understanding the distribution of mineral resources and their historic exploitation is valuable for urban geoscientists who may have a resource need or a requirement to manage historic resource exploitation in the context of development.

Total of 2157 surface and underground workings were recorded in the BGS BritPits minerals database within the study area (Cameron, 2013). The main mineral resources in the area are coal, crushed rock aggregate, brick clay, and sand and gravel and peat.

5.1 COAL

Coal has been worked on a large scale in the district from the Pennine Middle and Lower Coal Measures formations. The Coal Authority's interactive map viewer shows extensive underground coal workings to the north-west and east of Manchester city centre. Deep coal mining operations in the area ceased in 1991 with the closure of Agecroft Colliery at Pendlebury (Crofts et al, 2012). Opencast coal mining in the area began in the Second World War (Aitkenhead et al., 2002) and the last remaining opencast site was Cutacre, south of Bolton.

The BGS Britpits database contains 330 records of surface and underground coal workings in the area, most of which exploit seams in the Pennine Middle Coal Measures Formation (Figure 16). Most coal workings were underground (309 records), open pit or surface workings were recorded for 20 coal mines in the boroughs of Wigan, Bolton and Tameside and one for both open and underground workings in Wigan.

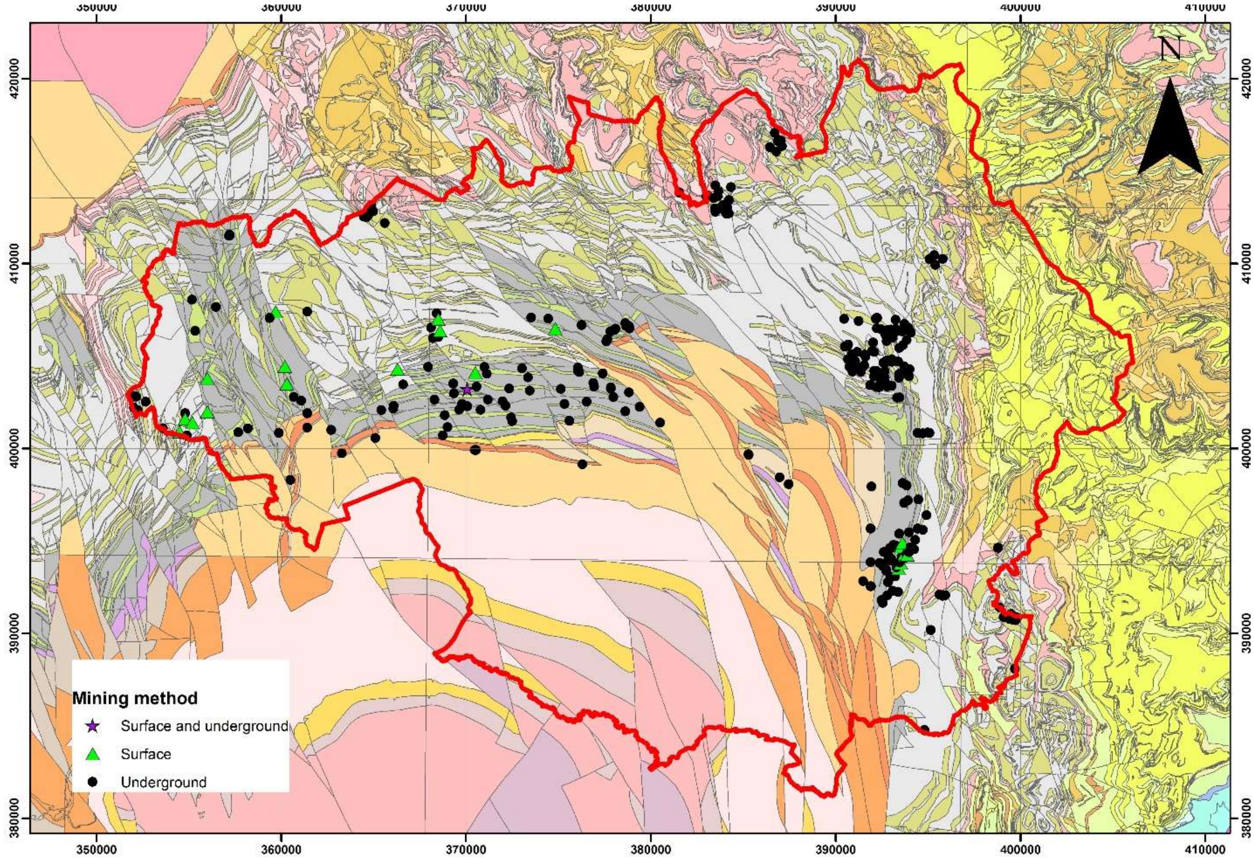

Figure 16 Coal workings in BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock.

5.2 ASSOCIATED ACTIVITIES TO COAL MINE: FIRECLAY

The Coal Measures Group in the area has also been worked for fireclay. Fireclays are seatearths or palaeosols (fossil soils) usually found beneath coal seams (Aitkenhead et al., 2012). The BGS Britpits database has 17 records of fireclay works in the area. All but three are underground workings and eight sites have also been mined for coal. The majority of the fireclay workings are in the Pennine Lower Coal Measures Formation (Figure 17).

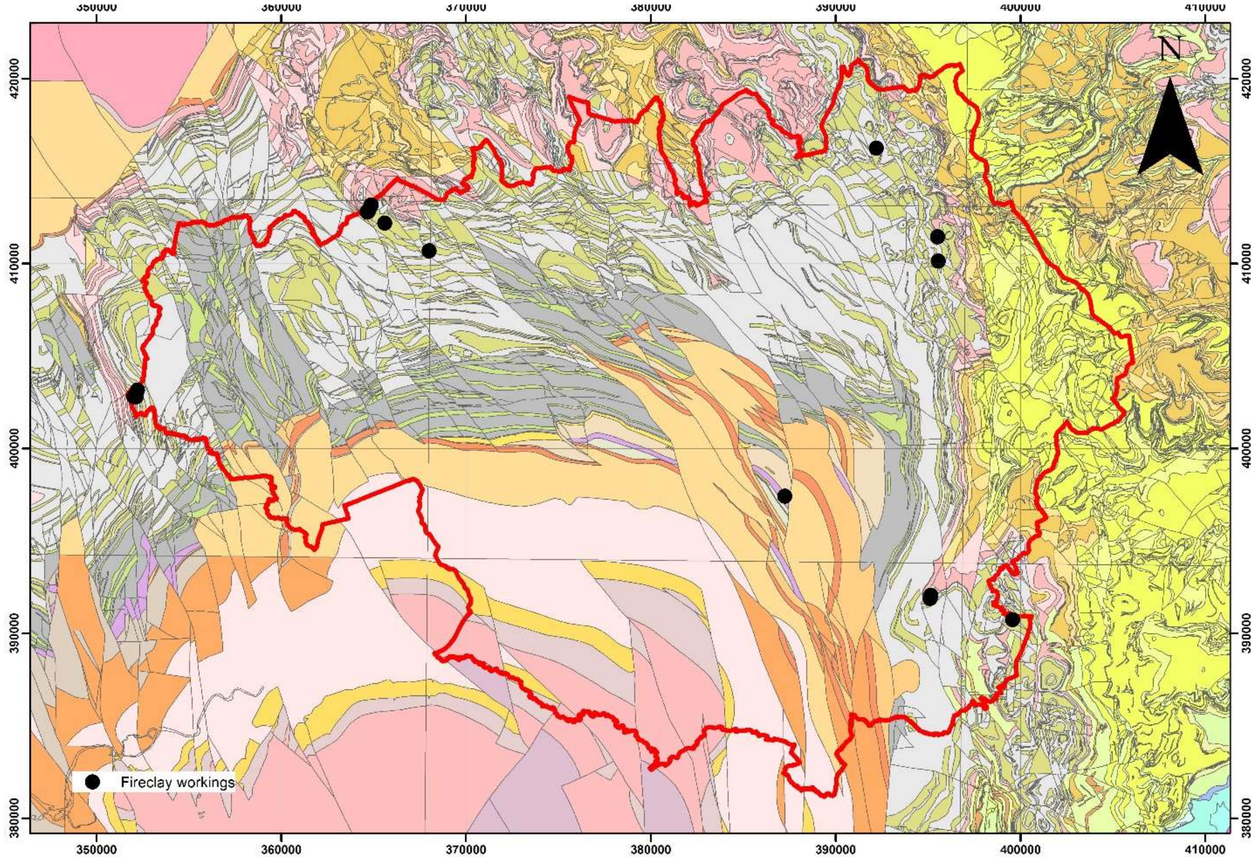

Figure 17 Fireclay workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock. Greater Manchester Combined Authority area outlined in red

5.3 BUILDING STONE AND CRUSHED ROCK AGGREGATE

The main sources of building stone in the study area are Carboniferous and Permo-Triassic sandstones (Minchin et al., 2006). Local sandstones were worked for block stone, flagstones and roofing 'slate' (Minchin et al., 2006).

Crushed rock aggregates are used in road surfacing, or mixed with cement to produce concrete, construction fill and drainage (Minchin et al., 2006). Most of the Carboniferous sandstones in the area are lower quality because of their relatively high porosity and low strength, therefore used for construction fill and sand for reconstituted stone products (Minchin et al., 2006). The BGS Britpits database contains five records of crushed rock aggregate workings in the Greater Manchester Combined Authority area (Figure 18).

Limestone was mined and quarried for use in slow setting cement to line colliery shafts (Crofts et al., 2012). Two areas of limestone workings are Ardwick Lime Works, where the Great Mine Limestone Member of the Halesowen Formation was extracted in surface and underground workings; and Leigh Lime Pits in the Blackmoor area, where limestone was quarried from the Manchester Marls Formation (Figure 19).

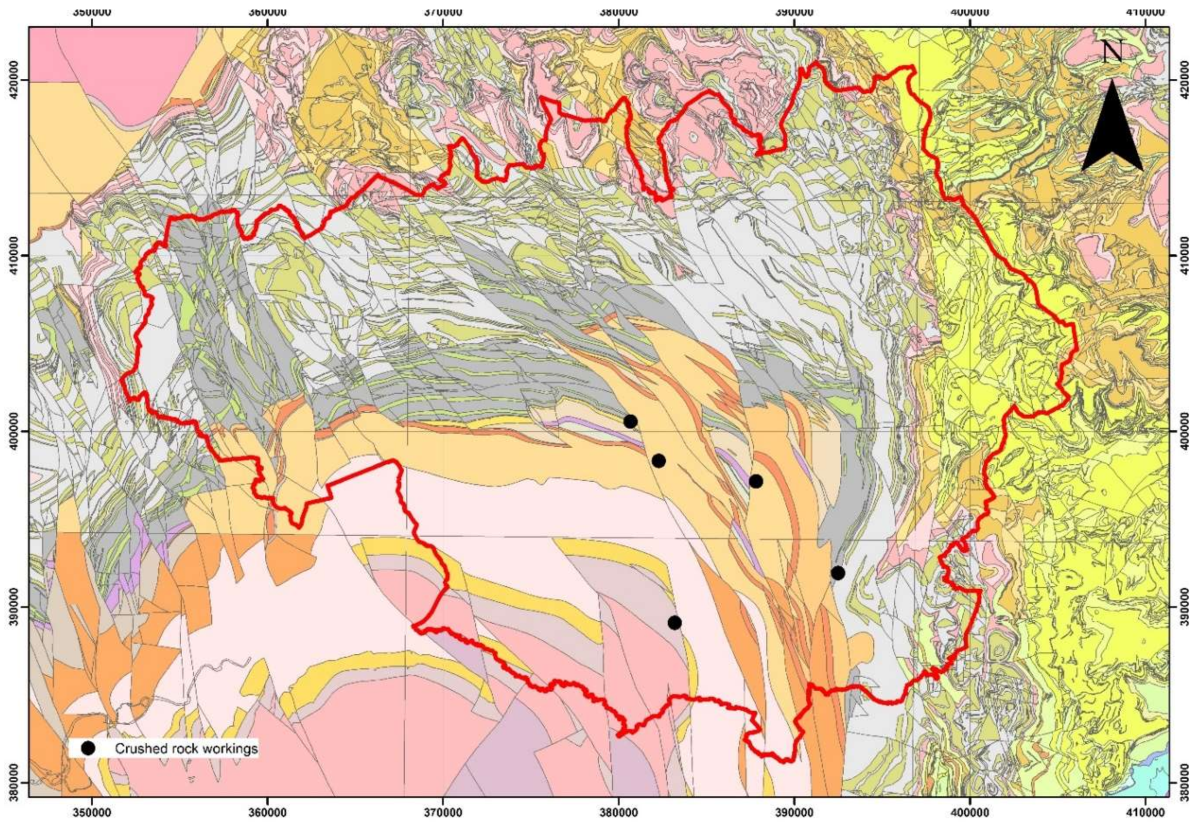

Figure 18 Crushed rock aggregate workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock. Greater Manchester Combined Authority area outlined in red

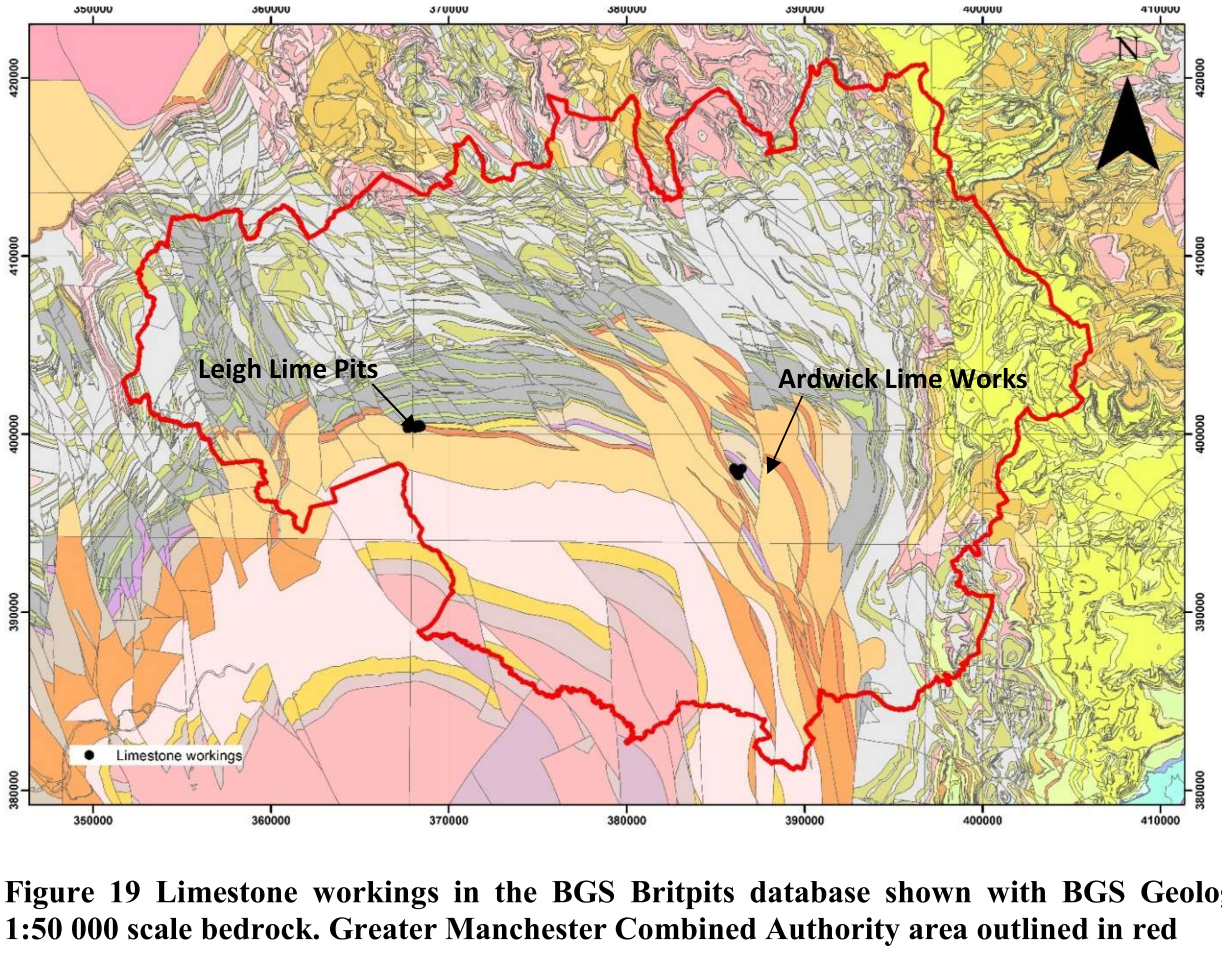

Figure 19 Limestone workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock. Greater Manchester Combined Authority area outlined in red

5.4 CLAY

Manchester's architecture is dominated by brick, so it is not surprising that brick clays have been extracted in Manchester for over 200 years (Minchin et al., 2006). Pennine Coal Measures Group mudstones are the principal resource for brick clay in north-west England (Minchin et al., 2006). Brick clays are used to produce structural clay products such as facing and engineering bricks, pavers, clay tiles and clay pipes. It can also be used in cement manufacture, construction fill and for lining and sealing landfill sites (Minchin et al., 2006).

A total of 362 clay workings are recorded in the BGS Britpits database. Of these, 262 exploit superficial clays, with the vast majority extracting glacial till. The remaining 100 clay pits target bedrock mudstones, some of which occur in sandstone units (Figure 20). Harwood Quarry near Bolton is the only clay pit in the Area to be listed as active in the BGS Britpits database. This quarry extracts clay from the Pennine Lower Coal Measures Formation to produce high quality brick clay for use in facing, engineering and paving bricks (Crofts et al., 2012).

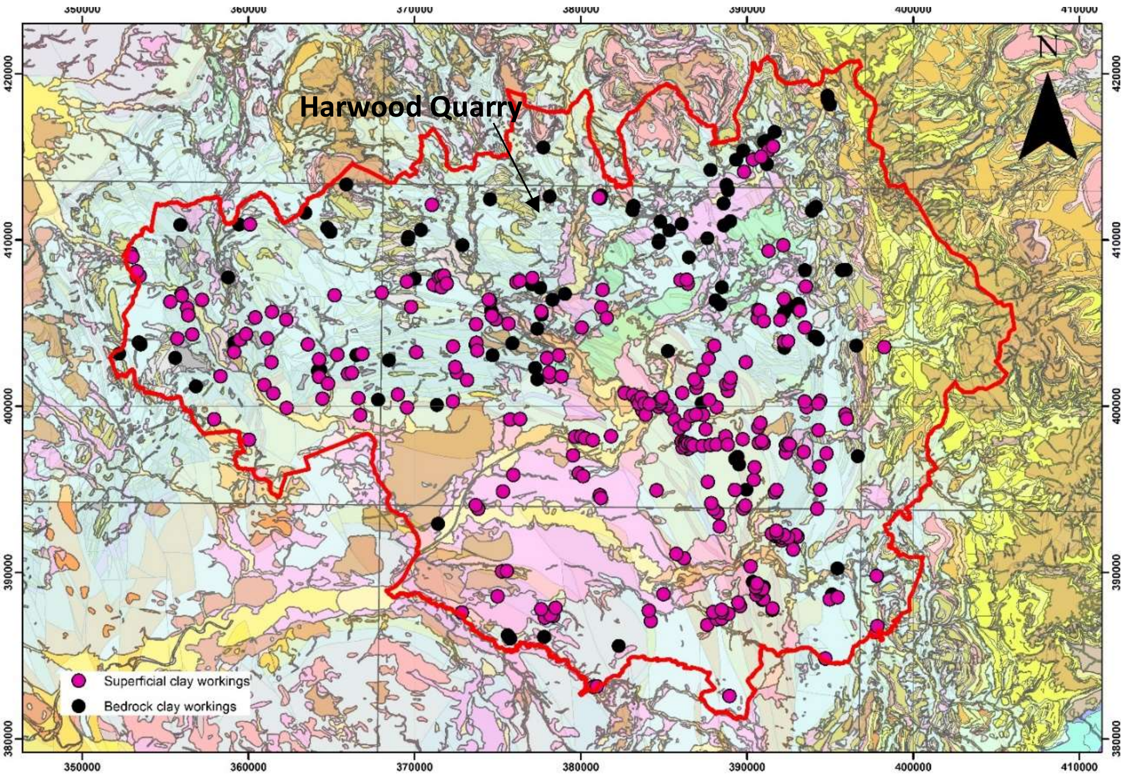

Figure 20 Clay workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock and superficial. Greater Manchester Combined Authority area outlined in red

5.5 SAND AND GRAVEL

The BGS Britpits database has 358 records of sand, sand & gravel and silica sand workings within the Greater Manchester area. Of these, 302 use Quaternary deposits as a resource (not including silica sand) and 45 target bedrock units (Figure 21). The primary uses for sand are as fine aggregate in concrete, mortar and asphalt (Aitkenhead et al., 2002). The main uses for gravel are as coarse concrete aggregate and construction fill (Aitkenhead et al., 2002). The main sand and gravel resources in the area comprise river terrace gravels and glaciofluvial deposits. Extensive sand and gravel workings in the Bury area and between Royton and Rochdale have targeted these deposits (Crofts et al., 2012). Large potential resources of sand and gravel in Bury, Trafford and Rochdale have been sterilised by extensive urban development (Minchin et al, 2006). Weakly cemented Sherwood Sandstone Group bedrock is worked in the Greater Manchester area for building sand and construction fill (Aitkenhead et al., 2002). The weathered zone of the Chester Formation has been worked at Morleys Hall Quarry, just to the north of Chat Moss (Crofts et al., 2012).

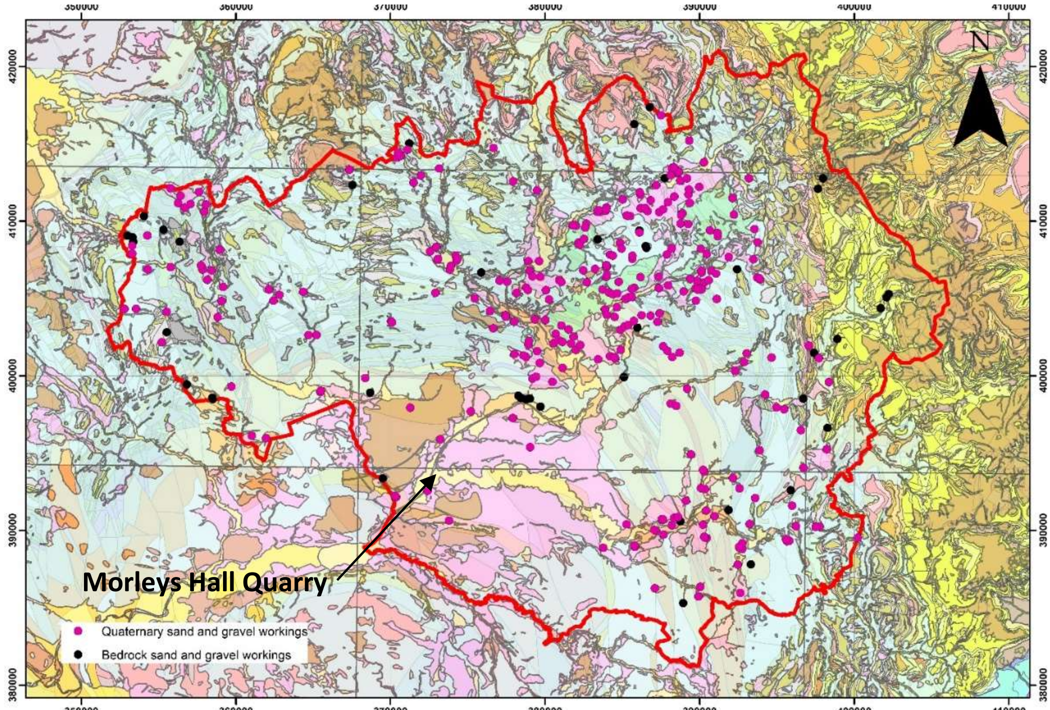

Figure 21 Sand and gravel workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale bedrock and superficial. Greater Manchester Combined Authority area outlined in red

5.6 PEAT

Extensive peat deposits associated with a raised bog at Chat Moss cover an area of 2,587 hectares with a thickness of up to 9 m (Minchin et al., 2006). These peat deposits are used in horticulture as a growing medium and soil improver (Minchin et al., 2006). The BGS Britpits database records a cluster of five peat workings in the Chat Moss area, three of which are still active (Figure 22).

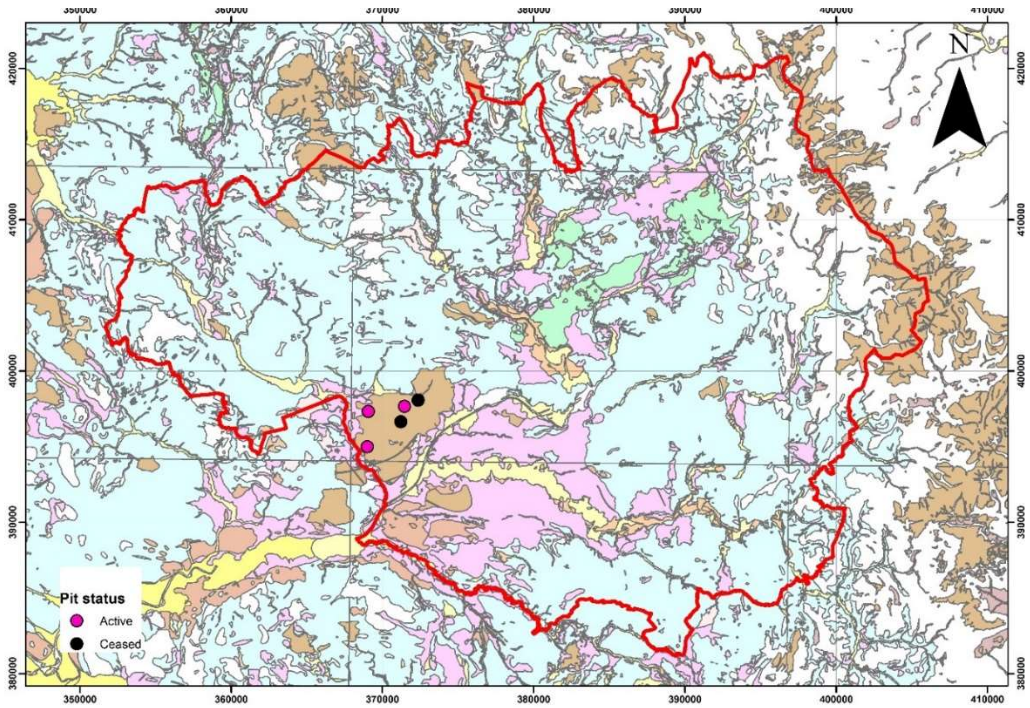

Figure 22 Peat workings in the BGS Britpits database shown with BGS Geology 1:50 000 scale superficial

5.7 SUMMARY OF MINERAL RESOURCES

Table 4 summarises the mineral resources described from Section 4.1 to Section 4.7. This is based on a spatial query on the BGS Britpits database to select those that are located in the area and the geological source material recorded in the database.

Table 4 Mineral resources in the Greater Manchester Combined Authority area (BGS Britpits database)

Mineral resources	Borough names	Sources	Specific use
Coal	Bolton, Oldham, Manchester City Council, Wigan, Salford, Rochdale, Bury, Salford, Tameside	Pennine Lower and Middle Coal Measures formations	Industrial use
Fireclay	Bolton, Oldham, Rochdale, Stockport Manchester City Council, Wigan	Pennine Lower and Middle Coal Measures formations	Industrial use
Limestone	Manchester City Council, Wigan	Permian Manchester Marl Formation, limestone	Slow setting cement
Building stone and crushed rock aggregate	Salford, Stockport, Manchester City Council	Carboniferous limestone	Road surfacing, construction fill, drainage
Clay	Bolton, Oldham, Manchester City Council, Wigan, Salford, Rochdale, Bury, Tameside, Stockport	Quaternary deposits: till, alluvium, glaciolacustrine deposits; Pennine Lower and Middle Coal Measures formations	Clay products (facing, bricks, clay tiles)
Peat	Trafford	Peat	Horticultural use

6 Engineering parameters

Engineering parameters were obtained from the BGS geotechnical database. Reviews from other published sources were provided for deposits where no geotechnical data were available. Table 5 presents performed tests and the number of samples for each formation in Central Manchester.

Table 5 Performed tests and number of samples

Formation	Test performed	Number of tests
Peat	Plasticity	6
Alluvium	Plasticity	232
	SPT	258
	Triaxial test UU	148
Stockport Glacigenic Formation (STPTG)	Lithology	14899
	Density	3832
	Consistency	13027
	Plasticity	985
	Particle size distribution	178
	SPT	386
	Triaxial test UU	1355
Brewood Till Formation (BDTI)	Plasticity index	26
	SPT	62
	Triaxial test UU	37
Manchester Marl	Points load test	26
	SPT	10
Upper Coal Measures	Points load test	189

6.1 ENGINEERING PARAMETERS OF SOILS

ORGANIC SOIL

This is dominantly composed of fibrous to amorphous peat with pockets of sand on greyish clayey silts. It is very soft to firm with bulk density of 1.5 Mg/m^3 and dry density of 0.7 Mg/m^3. Plasticity values are shown in Figure 23. The water content of samples ranged from 50% for 2.5 m – 4 m depth.

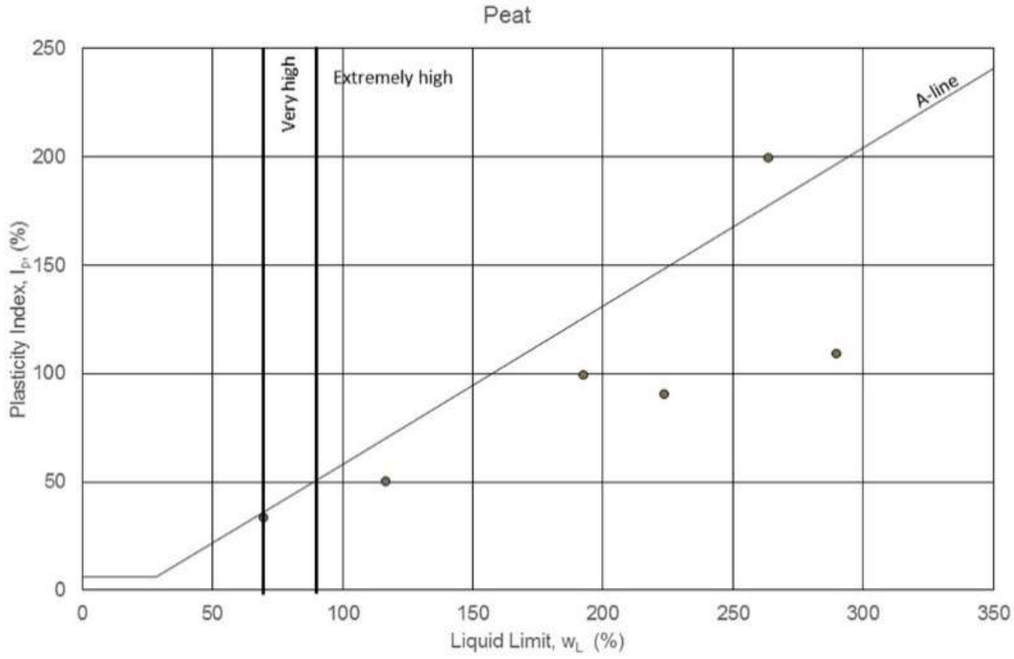

Figure 23 Plasticity chart of peat

Fine/coarse

Alluvium (recent floodplain deposits)

Comprises an upper layer of soft grey silty clay, underlain by several metres of dense grey or brown coarse sand, gravelly sand or gravel. The particle size distribution presented in Figure 24 shows silty sand with gravel. The plasticity chart for alluvium shows a liquid limit ranging from low to medium (Figure 25). Bulk densities are from 1.2 to 2.2 Mg/m^3 and dry densities are 0.4 to 2.0 Mg/m^3. Figure 26 presents N-values obtained from SPT. The values used for coarse-grained soil relate to density description whereas for fine grained material they are not used for this purpose.

Values from triaxial undrained shear strength vs dry density (Figure 27) indicate limited correlation between dry density and undrained shear strength, with strengths of up to 100-120 kPa for dry densities of 1.2 -1.8 Mg/m^3.

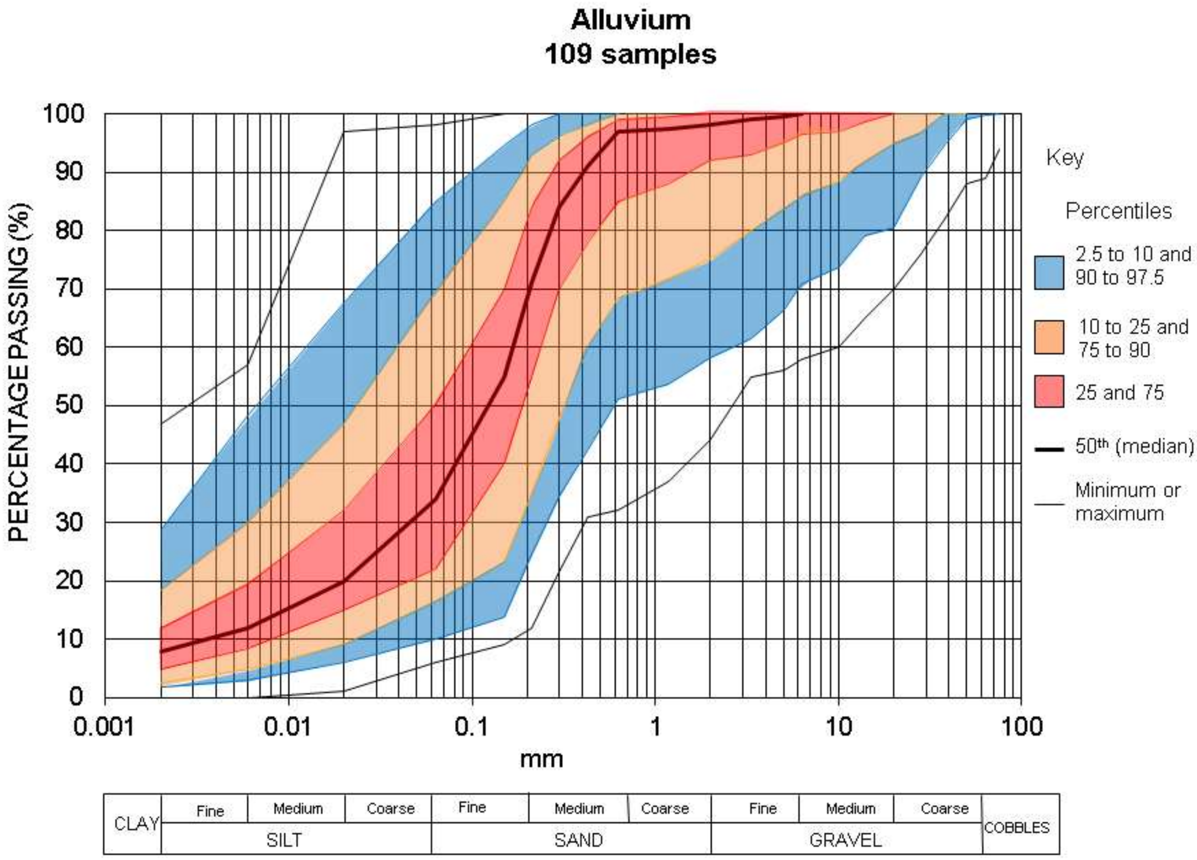

Figure 24 Particle size distribution of alluvium

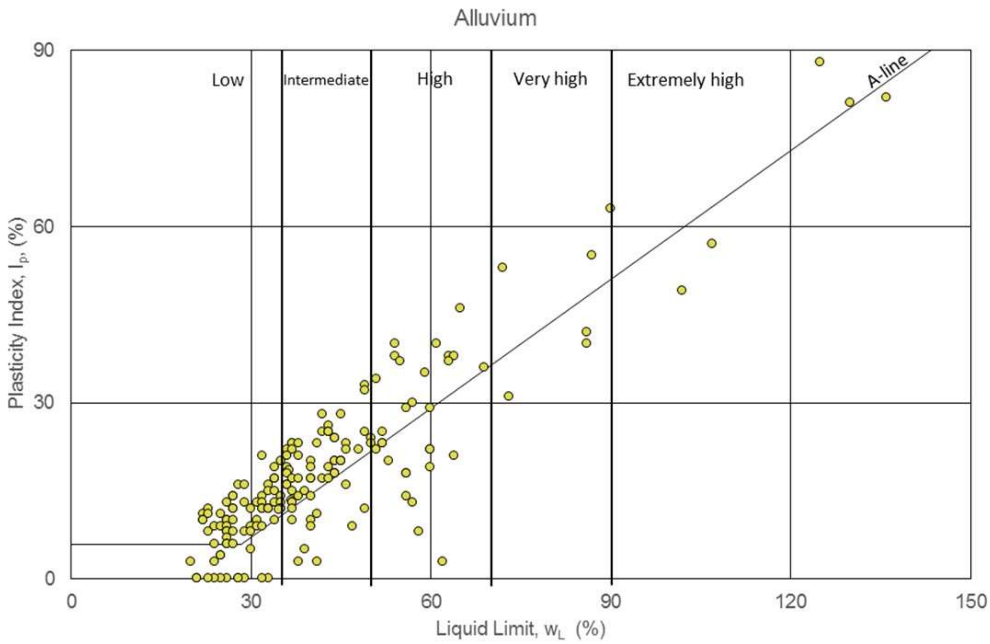

Figure 25 Plasticity chart of alluvium

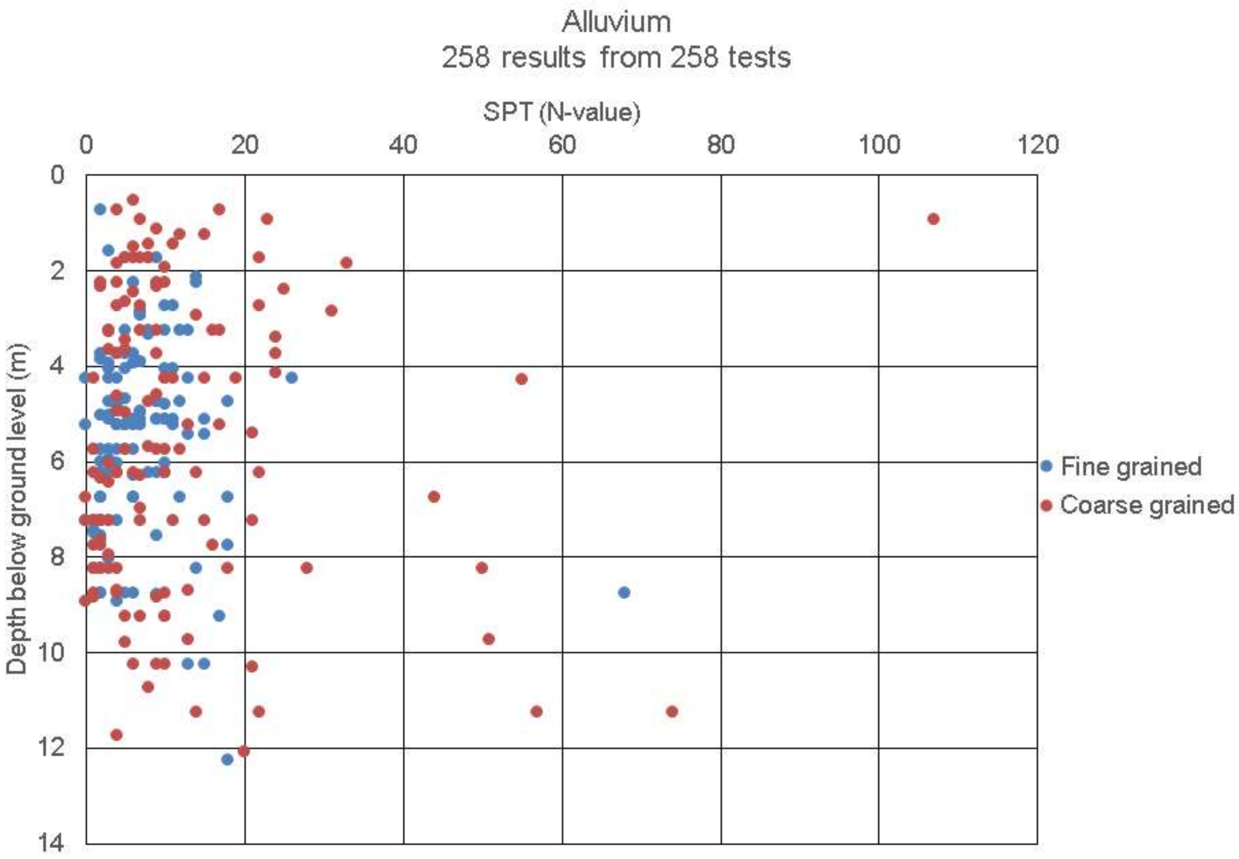

Figure 26 SPT N-values for Alluvium (values are not corrected for overburden)

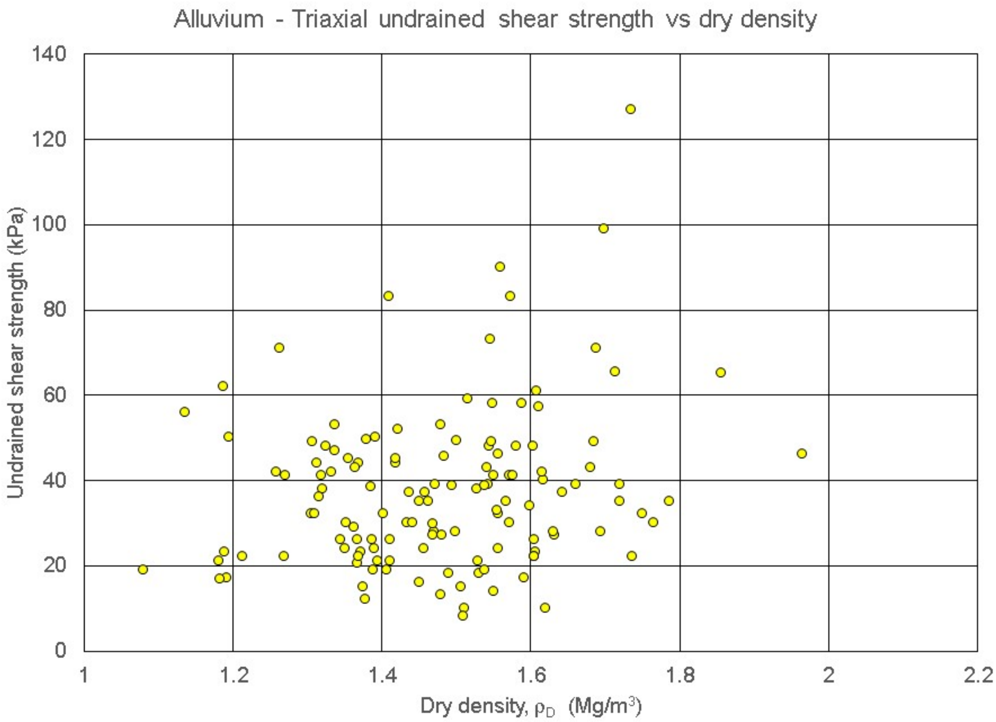

Figure 27 Triaxial undrained shear strength vs dry density

Stockport Glacigenic Formation (STPTG)

The Stockport Glacigenic Formation is a mixed glacigenic sequence of till (sandy, gravelly clay with cobbles and boulders), sand, gravel and laminated clay and silt with occasional boulders up to 2 m in size.

Figure 28 shows the combined lithology of the formation and lithology of individual units within the Stockport Glacigenic Formation, indicating the dominance of clay for till and glaciolacustrine deposits, and sand and gravel for glaciofluvial deposits. The Formation has been further subdivided in terms of the position of sediment accumulation in the context of the glacier, i.e. supra-glacial (at glacier surface), intra-glacial and sub-glacial till (Culshaw et al., 2017).

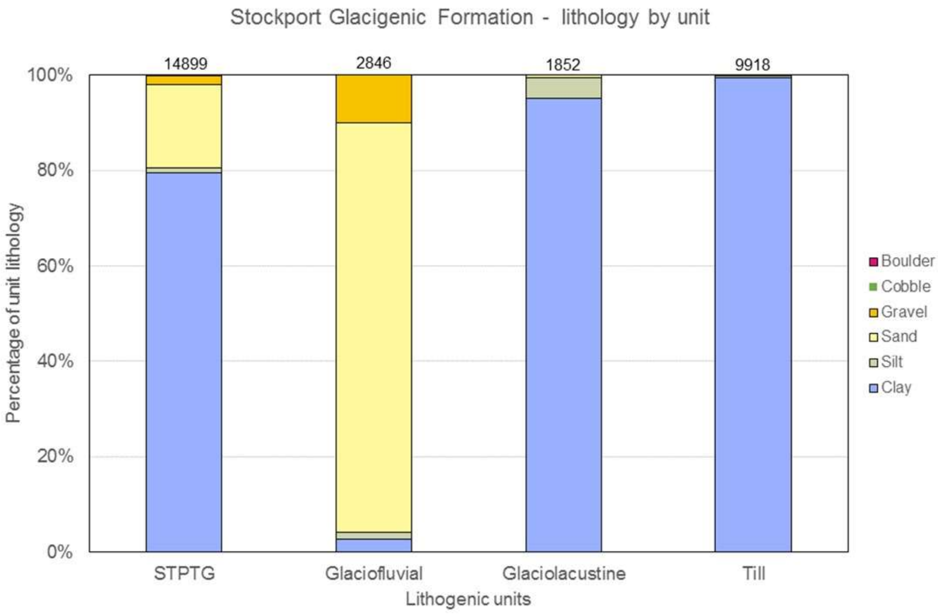

Figure 28 Lithology of the Stockport Glacigenic Formation. The first bar of the plot is the percentage of the overall principal described lithologies for all STPTG then the data identified as glaciofluvial, glaciolacustrine and till. Deposition types are assumed from the description

The subdivisions of the Formation have been subject to density analysis. Notable from this analysis is the higher proportion of very dense and dense sediment in the intra- and sub-till and the higher proportion of loose and very loose sediments in the sheet deposits and supra-till. (Figure 29). The consistency of the till ranges from soft to firm to very stiff to weak; whilst that of the glaciofluvial deposits ranges from very soft to stiff to very stiff, with more than 40% for the samples falling in the very soft to firm categories (Figure 30). The liquid limit is between 20% and 60% for till (Figure 31) and 20% to 70% for glaciolacustrine deposits (Figure 32). Plasticity indices for clayey till generally range from about 10-30%, indicative of soils with low to moderate potential for shrinkage (Jones and Terrington, 2011).

The particle size distribution of the formation (Till) is silty sand and some gravel. Similar variation of particle size distribution is shown for glaciolacustrine deposits (Figure 33), but with a greater range in the proportion of clay, which reaches higher percentages in the glaciolacustrine deposits.

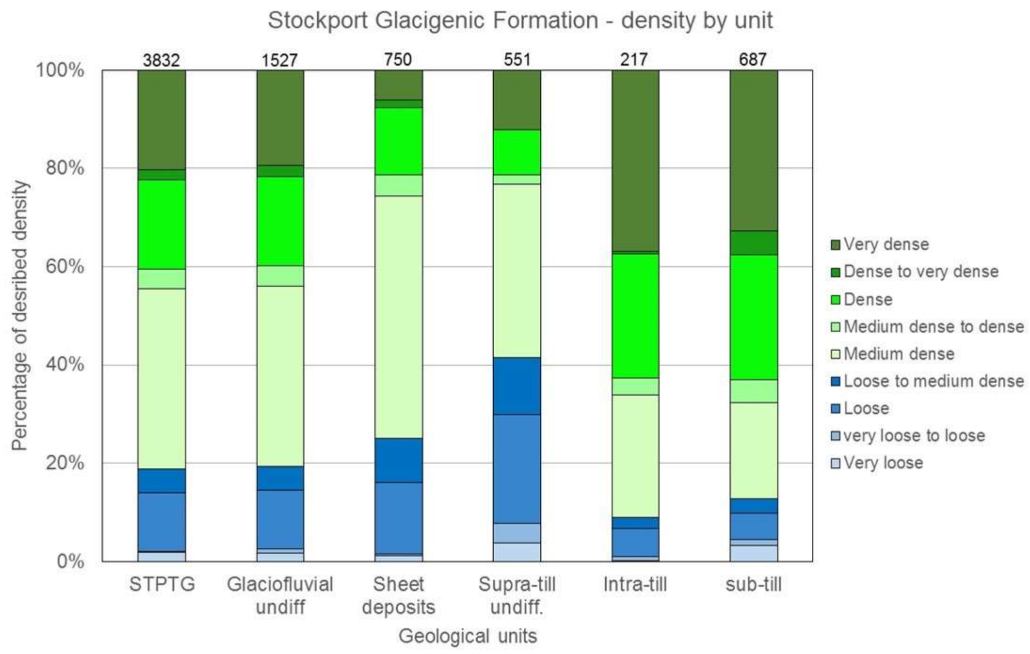

Figure 29 Density of the Stockport Glacigenic Formation

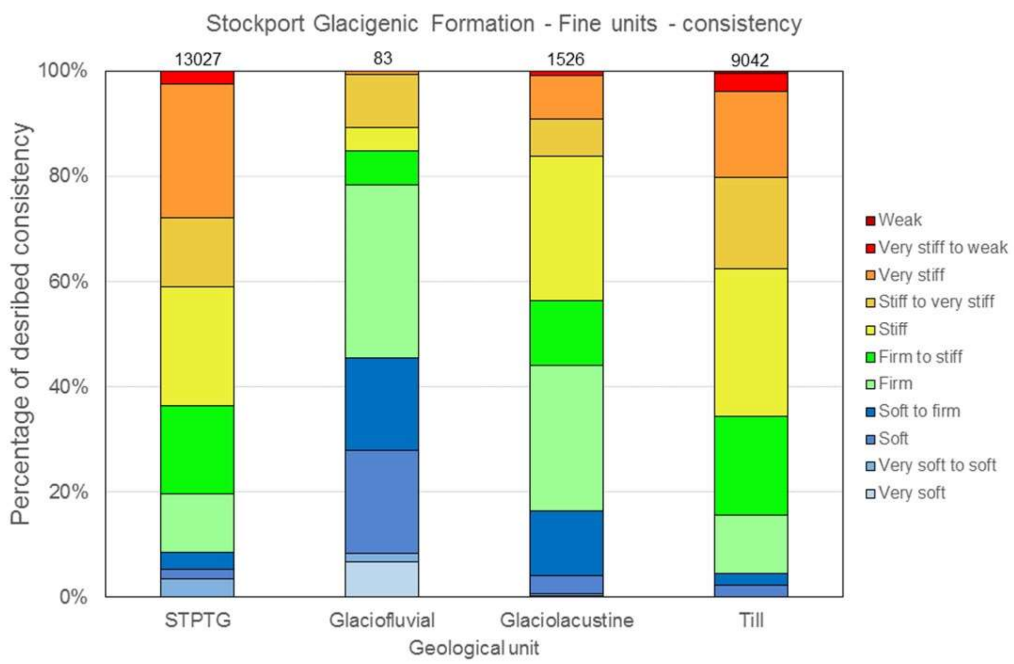

Figure 30 Consistency of the Stockport Glacigenic Formation

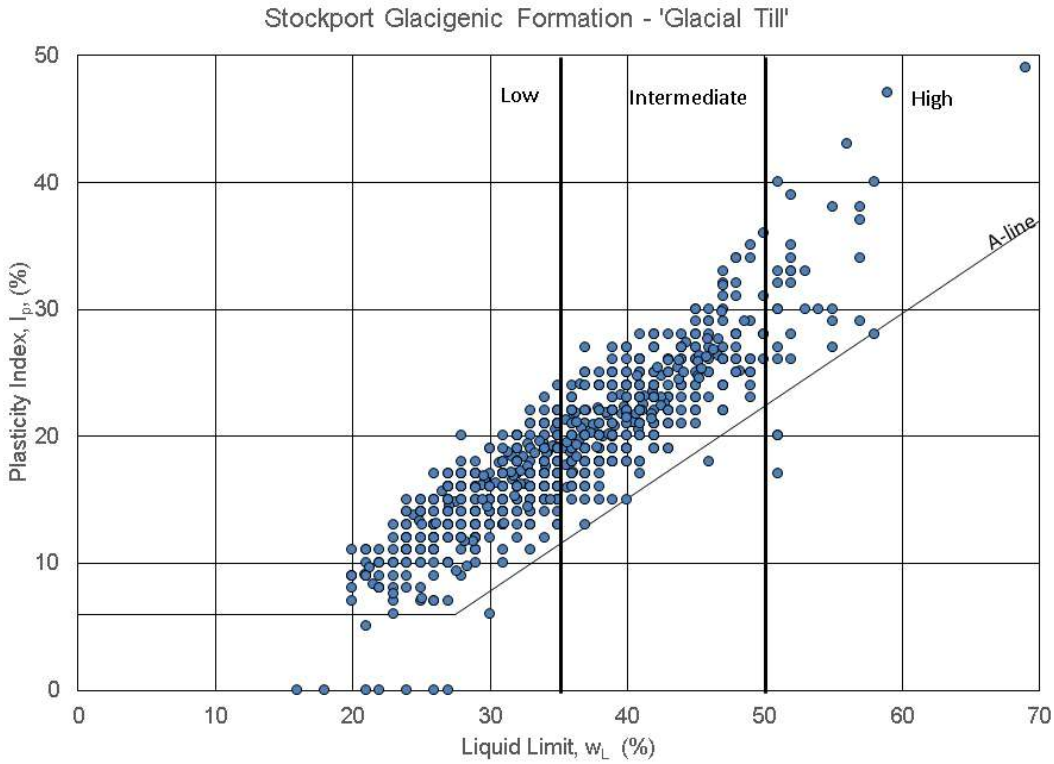

Figure 31 Plasticity chart of Glacial Till of the formation STPTG

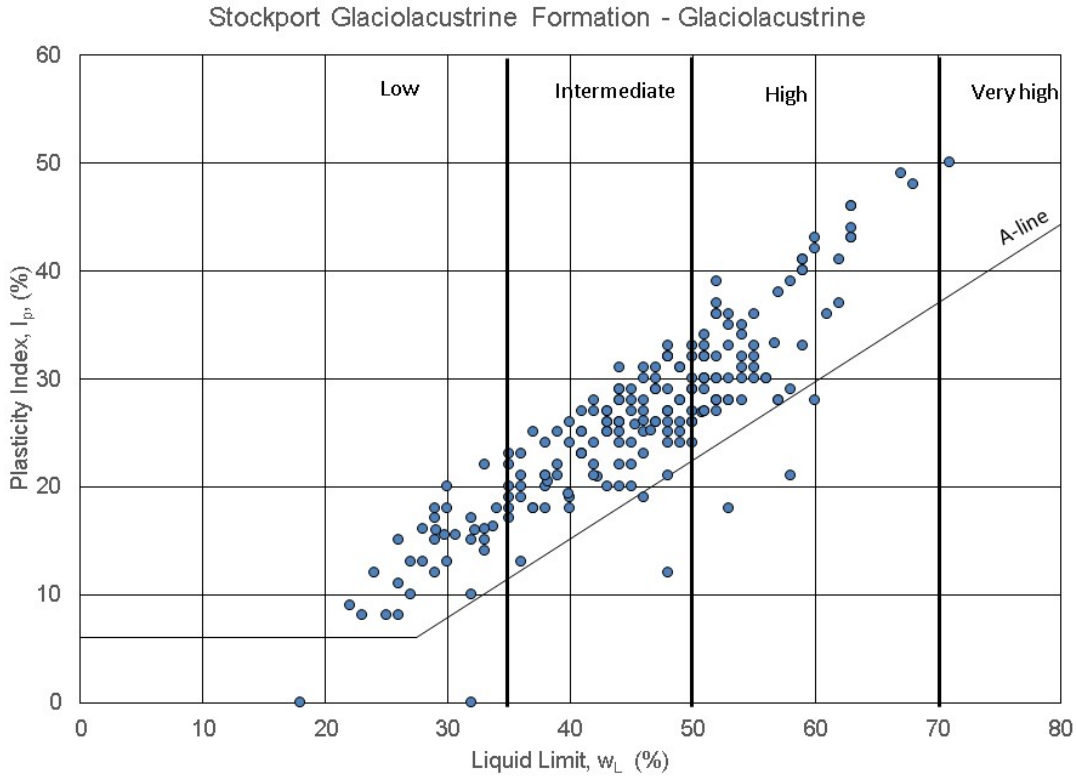

Figure 32 Plasticity chart of Glaciolacustrine of the formation STPTG

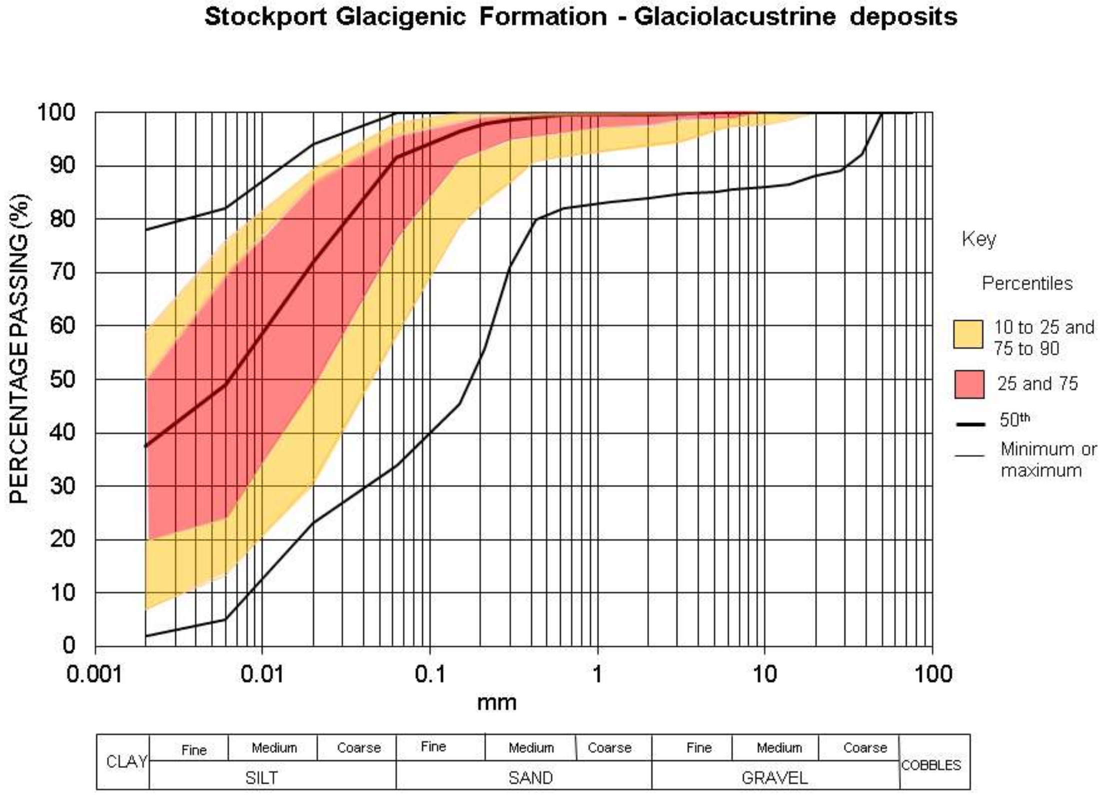

Figure 33 Particle size distribution of glaciolacustrine deposits

When the bulk density of supra-till, intra-till and sub till glaciolacustrine deposits is plotted against depth the data shows a variation of bulk density mainly from 1.8 Mg/m^3 to 2.3 Mg/m^3. Sub-till at depths from 20 to 30 m indicate lower bulk density ranging from 1.8 to 2.2 Mg/m^3. Dry density ranges from 1.3 to 2.1 Mg/m^3 the largest values for supra till, intra till and undifferentiated. Standard penetration test N values show a marked increase with depth in the supra- and sub-till, with SPT N values reaching > 100 at depths of about 30 m. There is significantly more scatter in the SPT N values (not corrected for overburden) associated with the intra-till; it is possible that this reflects the influence of confined water on some of the results. (Figure 34) and ranges until 80 to 100 and more (max 150) in till (Figure 35). Figure 36 presents voids ration vs normal stress for glaciolacustrine deposits of the formation.

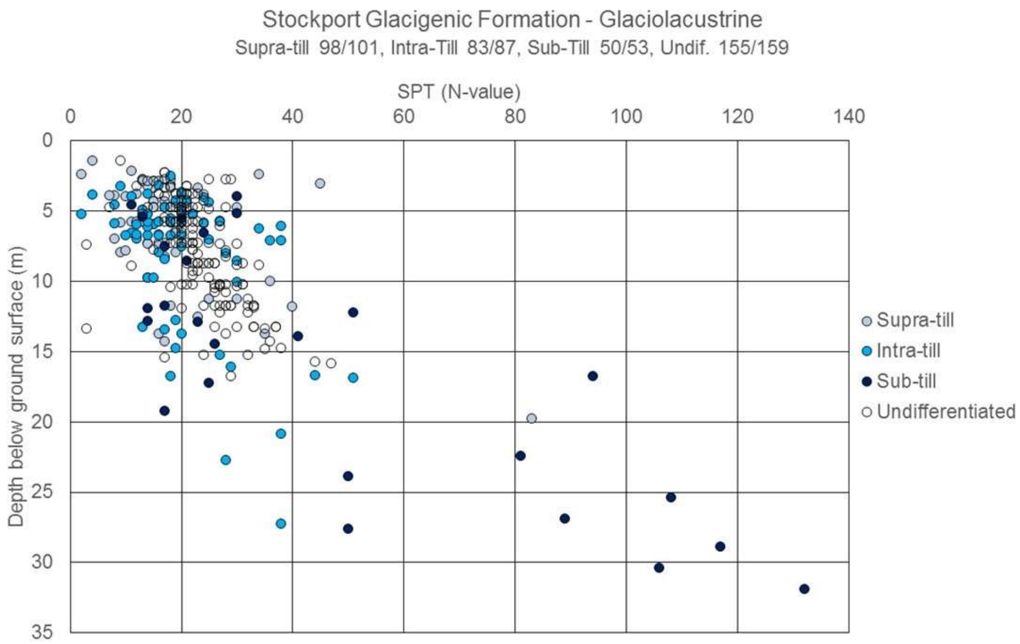

Figure 34 SPT N values (not corrected for overburden) of supra – till, intra – till and sub-till

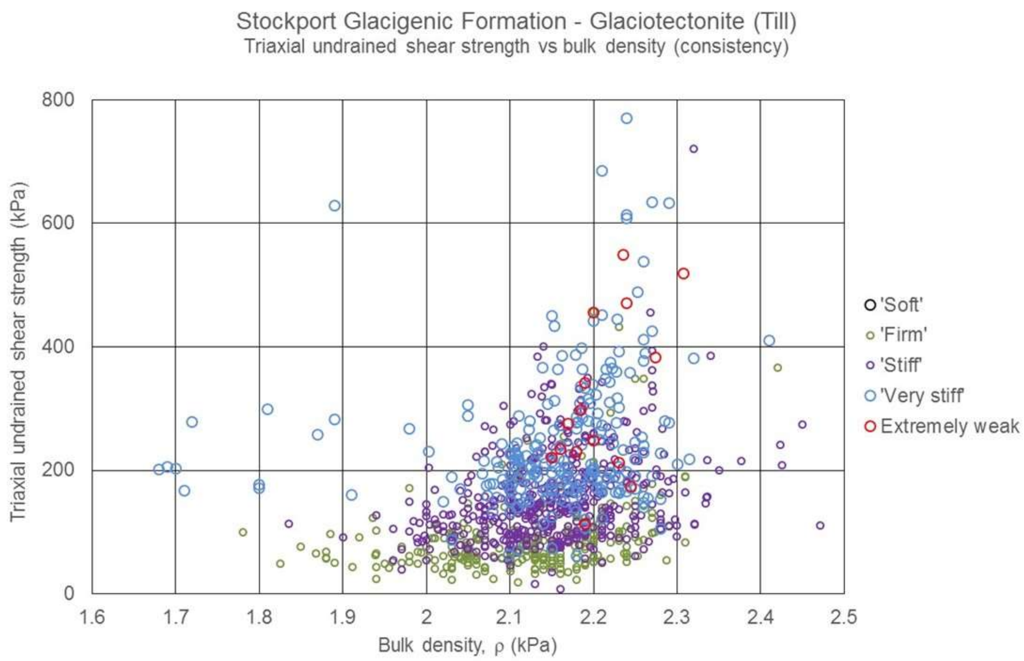

Figure 35 Bulk density against undrained shear strength of the Stockport Glacigenic Formation (Till)

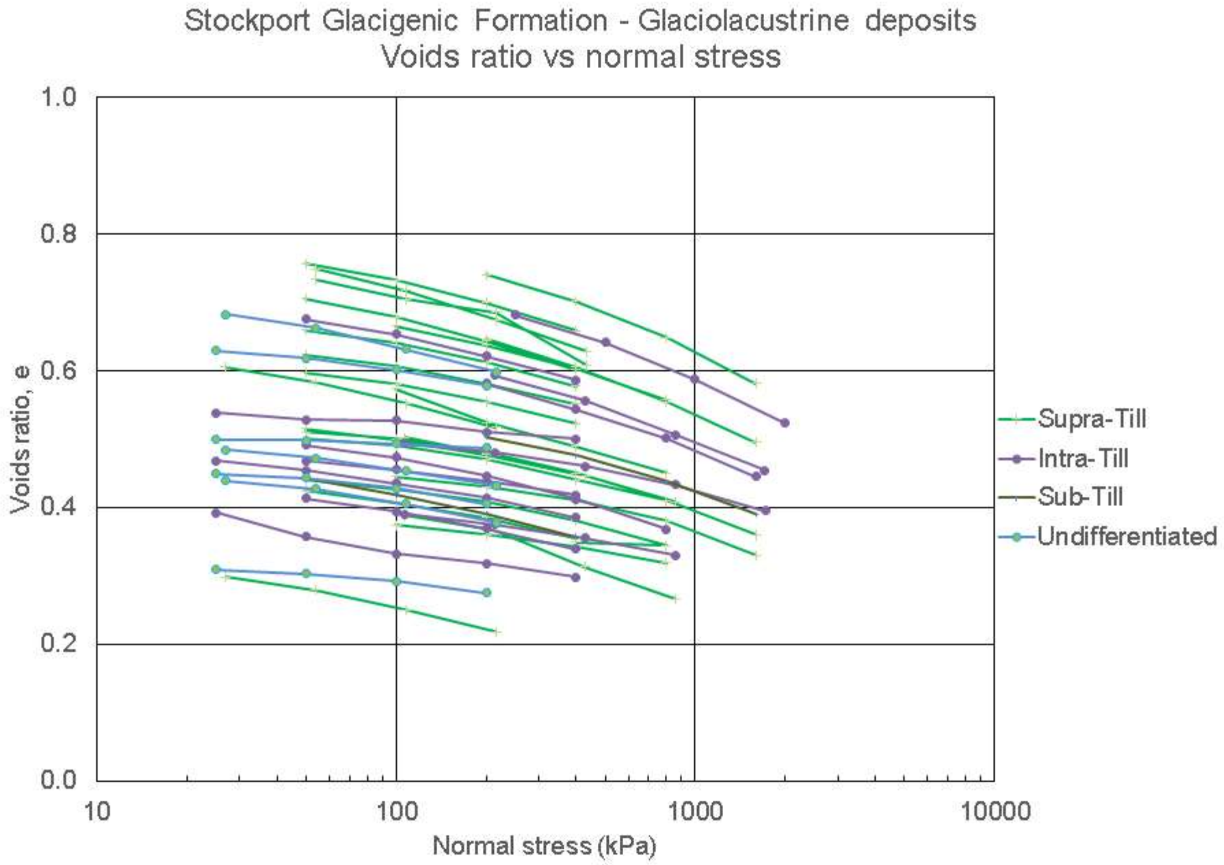

Figure 36 Voids ratio vs normal stress of the Stockport Glacigenic Formation – Sub Till glaciolacustrine

Brewood Till Formation (BDTI)

The Brewood Till Formation comprises firm to stiff reddish-brown, dark brown, or brown gravelly, sandy clay with cobbles.

The liquid limit ranges from 30 to 55% for glaciolacustrine deposits (Figure 37) with plasticity indices ranging between 12 and 30 demonstrating that the glaciolacustrine deposits are of low to high plasticity. Similar values are also shown for till (Figure 38), although the values are more clustered in the low to intermediate plasticity range with a single high plasticity value with a plasticity index that exceeds 35%. SPT values for the till shown in Figure 39.

Figure 40 shows triaxial undrained shear strength vs dry density for both till and glaciolacustrine deposits. For higher densities of till higher shear strength are observed up to 450 kPa.

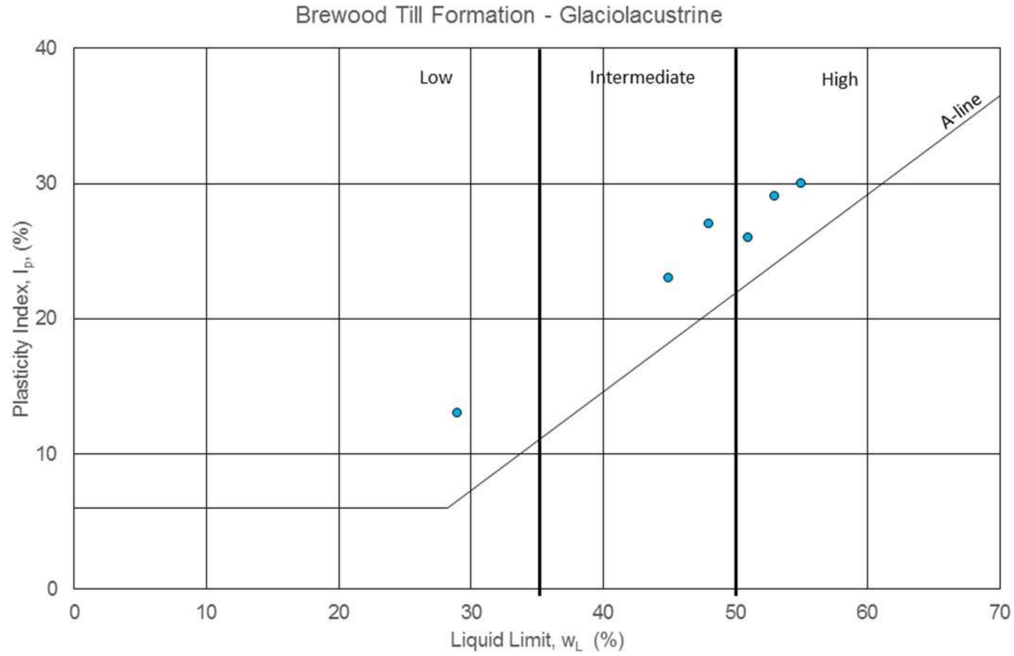

Figure 37 Plasticity chart for glaciolacustrine deposits in the Brewood Till Formation

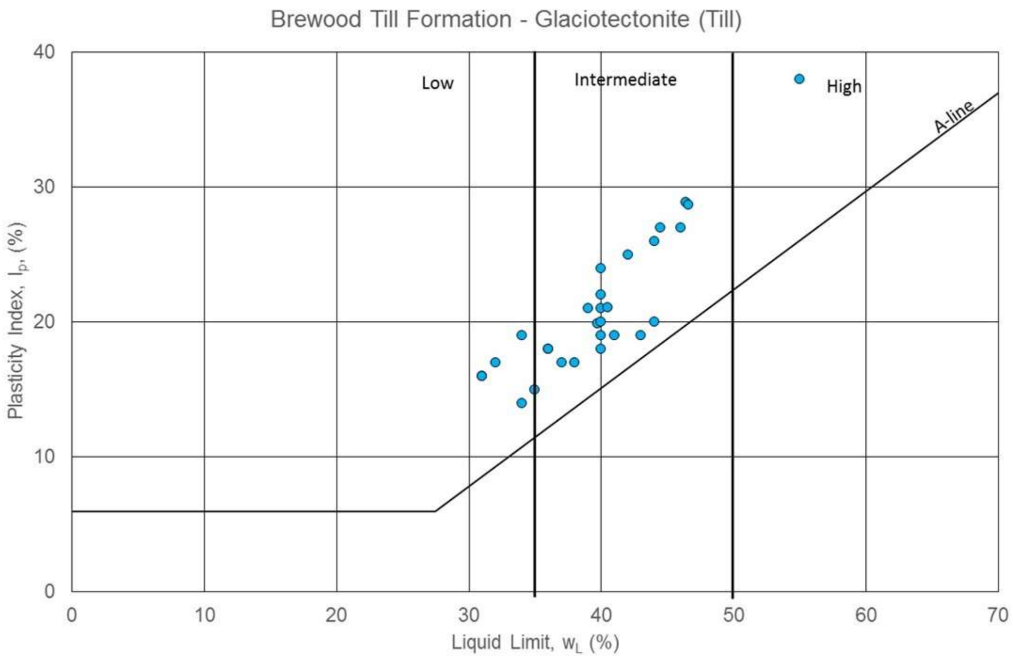

Figure 38 Plasticity chart for till in the Brewood Till Formation

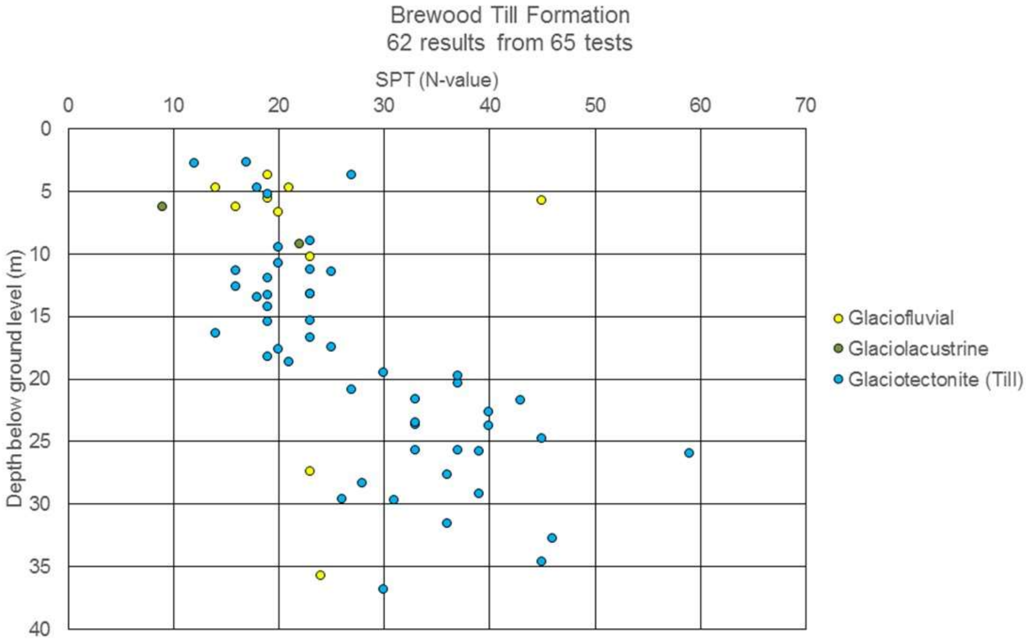

Figure 39 SPT N-values against depth for the Brewood Till Formation

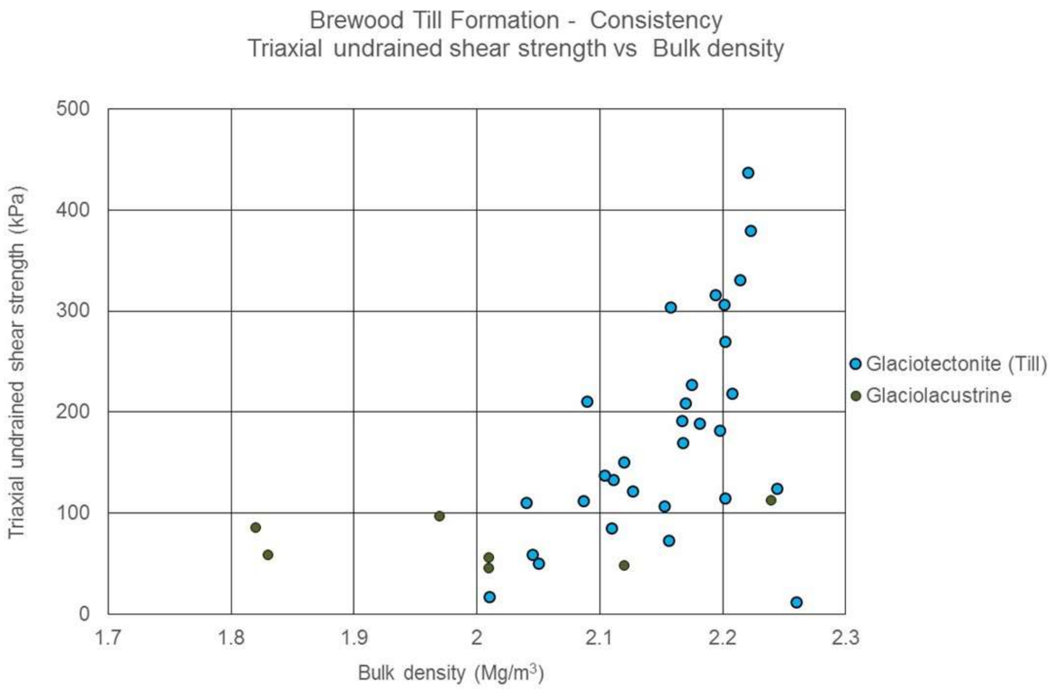

Figure 40 Triaxial undrained shear strength vs bulk density for Brewood Till formation

Yorkshire Dales Formation (YDTI)

Firm to extremely weak dark grey to greyish brown, gravelly, sandy clay or mudstone with cobbles and boulders (Culshaw et al. 2017). No geotechnical properties were recorded in the area.

Glaciofluvial deposits

Glaciofluvial deposits are composed of medium dense to dense sand and gravel.

Made ground

Made ground in the Greater Manchester Combined Authority area is highly variable in thickness, composition and geotechnical properties (Bridge et al., 2010).

6.2 ENGINEERING PARAMETERS OF ROCKS

Weak sandstone: Collyhurst Sandstone Formation and Sherwood Sandstone Group

The Collyhurst Sandstone Formation is moderately weak to moderately strong yellow, reddish brown fine to medium-grained poorly to very well sorted sandstone. The Sherwood Sandstone Group is mainly composed of weak to moderately weak red, medium to fine grained, well sorted sandstone.

Strong sandstone: Millstone Grit Group

Millstone Grit Group sandstones are moderately to well jointed, thinly to thickly bedded, fine to coarse-grained with mudstone and siltstone interbeds. They are strong to moderately strong when fresh or slightly weathered.

Weak mudstone: Manchester Marls Formation

The Manchester Marls Formation consists of stiff to weak reddish brown or purple mudstone, weathering to soft to stiff clay. The point load strength values (mean = 0.18 kPa) are shown in Figure 41 and SPT N-values range from 25 up to 120 at 8 m depth, but with a considerable scatter (Figure 42).

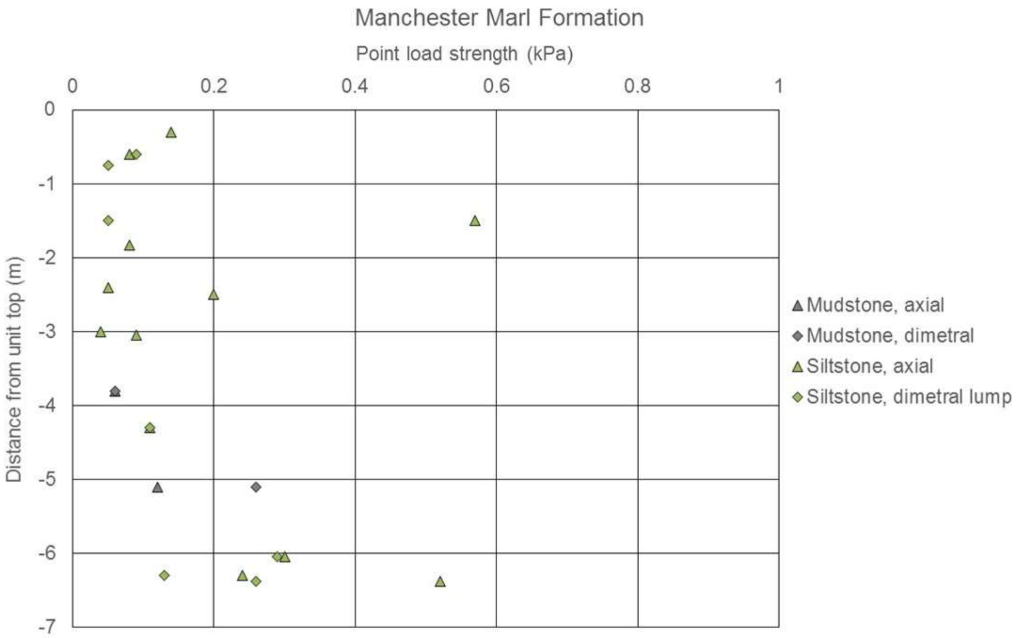

Figure 41 Point load strength of the Manchester Marl Formation

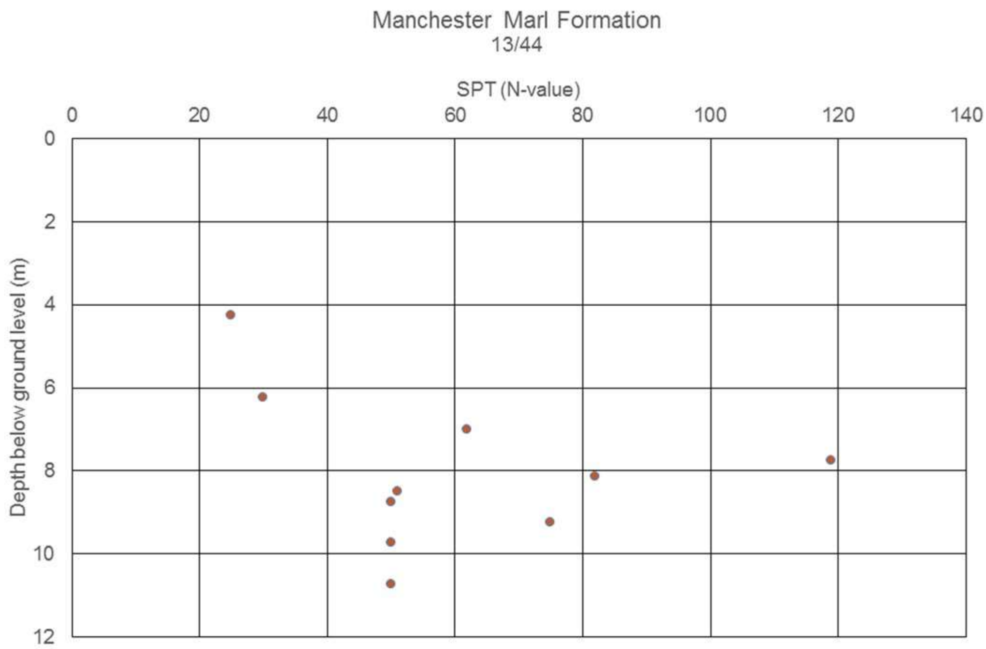

Figure 42 SPT N values of the Manchester Marl Formation (values are not corrected for overburden)

Mercia Mudstone Group

The Mercia Mudstone Group predominantly consists of mudstone and can be described as a weak rock. Properties may vary on the state of weathering. No soil properties were recorded in the area but Hobbs et al., 2002 carried out research on Mercia Mudstone Group in five regions in the UK (Wessex Basin, Sommerset/Avon, South Wales, Worcester/Knowle Basins, Stafford/Needwood basins, Cheshire Basin, West Lancashire, Carlisle Basin, East Midlands). The median index properties were obtained using data from all five regions (Table 6). The Mercia Mudstone Group has a low swelling potential due to its aggregated structure. It may contain halite and gypsum (Hobbs et al., 2002).

Table 6 Overall median index properties of Mercia Mudstone Group in five regions in the UK (Hobbs et al., 2002)

Number of tests	Index properties	Overall median values
452	Bulk density	1.96 – 2.27 Mg/m^3
536	Dry density	1.68 Mg/m^3
3429	Natural moisture content	18-20%
208	Particle size distribution	Clayey, sandy silt with fine gravel
2598	Liquid limit	30-52%
2511	Plastic Limit	18-28%

Strong mudstone: Pennine Upper Coal Measures Formation

The Pennine Upper Coal Measures Formation is composed of moderately weak to strong dark grey to grey laminated mudstone, siltstone and shale. Figure 43 shows point load strengths for mudstones and sandstones of the formation, ranging up to 3.2 kPa.

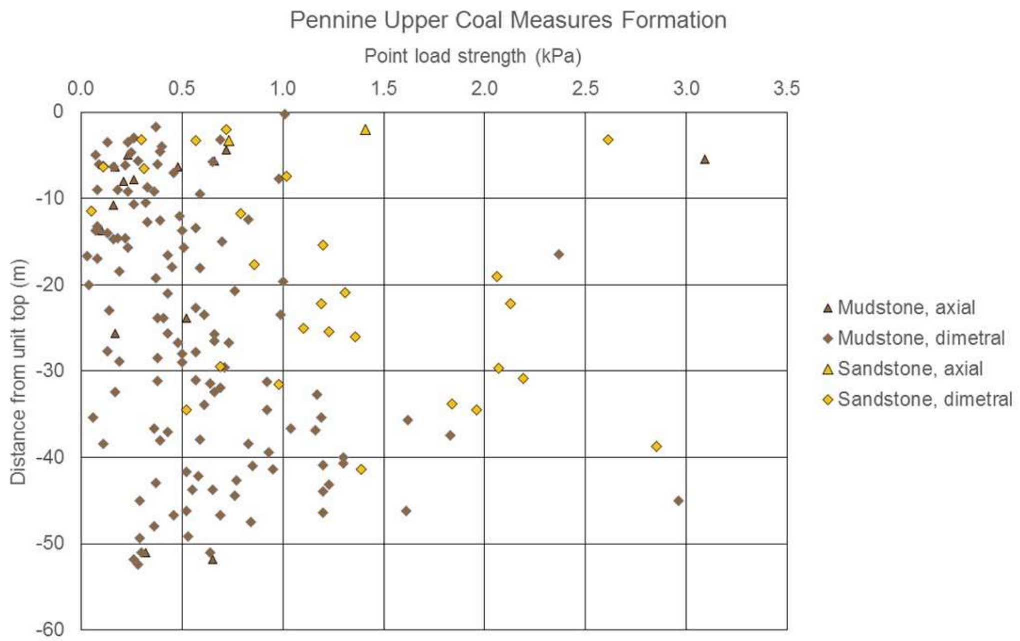

Figure 43 Point load strength of the Pennine Upper Coal Measures Formation

7 Engineering ground conditions

Ground conditions can be described as engineering soil and engineering rock. In engineering terms this classification system mainly depends on the physical and chemical characteristics and the thickness of a unit, rather than its age. Table 4 summarises the geological units for the area and their soil and rock characteristics.

Table 7 Engineering ground conditions of superficial deposits and bedrock

Geological unit	Engineering geological unit	Description	Foundation conditions	Engineering fill	Excavatability
Peat	Organic	PEAT with pockets of sands and clayey silts	Generally unsuitable for most foundation types	Unsuitable for fill	May be excavated with hand tools
Alluvium	Coarse	Occasionally laminated sandy, silty CLAYS and SILTS Loose to dense fine to coarse grained SANDS and GRAVELS with clay lenses	Low bearing capacities, high compressibility may pose problems for foundations	Unsuitable for fill	May be excavated. Immediate trench support required. Running conditions likely in granular material. Cut-offs and/or dewatering usually required due to high water tables
Stockport Glacigenic Till Formation (STPTG)	Fine	Sandy, gravelly CLAY with presence of boulders and cobbles. Laminated clay and silt separated by lenses of sand gravel	Generally good foundation conditions but depends on presence of water bearing sand and silt layers	Laminated clays may be unsuitable to use as fill	May be excavated. Ponding water may cause problems during working. Excavations in clays generally stable in short term. Running sand issues may occur below water table
Brewood Till Formation (BDTI)		Reddish-brown, gravelly, sandy CLAY with cobbles and boulders	Generally good foundation conditions but depends on the presence of water bearing sand and silt layers	Laminated clays may be unsuitable to use as fill	May be excavated. Ponding water may cause problems during working. Excavations in clays generally stable in short term. Running sand issues may occur below water table
Yorkshire Dales Till Formation (YDTI)		Firm to extremely weak dark grey to greyish brown, gravelly, sandy CLAY	Generally good foundation conditions but depends on the presence of water bearing sand and silt layers	Laminated clays may be unsuitable to use as fill	May be excavated. Ponding water may cause problems during working. Excavations in clays generally stable in short term. Running sand issues may occur below water table
Glaciofluvial sheet deposits	Coarse	Fine to coarse grained SANDS and medium dense to dense GRAVELS with occasional cobbles. Sandy clays and silts, sometimes laminated, occur locally	Generally good foundation conditions but might be locally poor	Coarse granular soil fill	May be excavated. Trench support required. May be water bearing
Made ground, infilled ground	Highly variable artificial deposits	Highly variable in thickness, composition and geotechnical properties	Highly variable	Highly variable	May be excavated

Bedrock					
Collyhurst Sandstone Formation	Weak sandstone	Moderately weak to moderately strong yellow, reddish brown fine to medium-grained poorly to very well sorted SANDSTONE. Weathers to medium dense to very dense sand	Generally good foundation conditions when weathered material is removed. Fissures and faults and permeable nature may cause risk from accumulation of the hazardous gases	Generally suitable as fill	Fresh rock may require blasting, pneumatic tools and ripping. Weathered material can be excavated by digging
Sherwood Sandstone Formation	Weak sandstone	Weak to moderately weak red, medium to fine grained, well sorted SANDSTONE. Weathers to medium dense to very dense sand	Generally good foundation conditions when weathered material is removed. Fissures and faults and permeable nature may cause risk from accumulation of the hazardous gases	Generally suitable as fill	Fresh rock may require blasting, pneumatic tools and ripping. Weathered material can be excavated by digging
Millstone Grit Group	Moderately strong sandstone	Moderately to well-jointed, thinly to thickly bedded, fine to coarse-grained SANDSTONES with mudstone and siltstone interbeds. Strong to moderately strong when fresh or slightly weathered	Generally good foundation conditions. Rock strength decreases with increased weathering	Generally suitable for fill	Weathered sandstone may be excavated by digging. Fresh rock may require ripping and pneumatic tool
Manchester Marl Formation	Weak mudstone	Stiff to weak, reddish brown or purple MUDSTONE	Generally good foundation conditions	Generally suitable for fill	Weathered material may be excavated by digging.
Mercia Mudstone Group	Weak mudstone	Red-brown, brown, calcareous CLAY and MUDSTONE	Generally good foundation conditions	Generally suitable for fill	Weathered material may be excavated by digging.
Upper Coal Measures Formation	Strong mudstone	Moderately weak to strong dark grey to grey laminated MUDSTONE, SILTSTONE, and SHALE	Generally good foundation conditions when soft material is removed	Generally suitable as fill if moisture content is low	Fresh rock may require blasting, pneumatic tools and ripping. Weathered sandstone may be excavated by digging.

7.1 ENGINEERING DESCRIPTION OF SOILS

Organic

Peat

Peat deposits are located mainly in Trafford. No geotechnical properties were found in the area apart from six samples to obtain plasticity. The results show medium to high plasticity. The deposit is generally unsuitable for most foundation types and unsuitable as a fill material because of its low strength. Peat is excavatable with hand tools.

Fine/coarse

Alluvium (recent river deposits)

Particle size distribution of alluvium shows silty sand with some gravel with plasticity from low to medium. SPT N-values show loose to medium dense for the area. Poor foundation conditions but might be locally poor due to soft highly compressible zones with a risk of severe differential settlements and loose granular deposits that may be prone to piping. Rafts or piles to dense gravels or sound bedrock are usually required. Alluvium is unsuitable as fill and is can be excavated.

Tills

Stockport Glacigenic Till Formation (STPTG)

Lithology of the formation mainly clay (80%) and sand (20%) with density ranging from loose, medium dense, dense to very dense. Consistency can be described as firm, firm to stiff, stiff to very stiff. SPT N-values indicate that consistency increases by depth. Generally, till does not present major problems for shallow foundations. However, lithological variations and potential differential settlements have to be considered. The formation can be excavated.

Brewood Till Formation (BDTI)

The formation has medium to high plasticity for glaciolacustrine deposits and medium plasticity for tills. It is stiff to very stiff. The Brewood Till Formation provides generally good foundation conditions, but this depends on the presence of water bearing sand and silt layers. Ponding of water may cause problems during excavation. Excavations in clays are generally stable in the short term. Running sand may occur below the water table. The formation can be excavated.

Yorkshire Dales Formation (YDTI)

No geotechnical parameters were found but the formation is tend to be firm to extremely weak dark grey to greyish brown, gravelly, sandy clay or mudstone with cobbles and boulders (Culshaw et al. 2017).

Glaciofluvial deposits

No index or strength parameters were found for this region but the deposits have generally good foundation conditions but might be locally poor.

Made ground

Made ground in the area is highly variable in thickness, composition and geotechnical properties.

7.2 ENGINEERING DESCRIPTION OF ROCKS

Weak sandstone

Collyhurst Sandstone and Sherwood Sandstone Group

No geotechnical properties were found for both formations in the geotechnical database. However, Collyhurst Sandstone Formation is moderately weak to moderately strong yellow, reddish brown fine to medium grained poorly to very well sorted sandstone. The Sherwood Sandstone Group is weak to moderately weak red, medium to fine grained, well sorted sandstone. Both sandstones provide good foundation conditions when weathered material is removed. The permeable nature of sandstone, coupled with geological faults, can lead to the risk of hazardous gas accumulations.

These sandstones provide generally good foundation conditions provided that the depth of weathered rock head is defined. Weathered rock can be excavated by digging, however strong rock may require ripping.

Strong sandstone

Millstone Grit Group
No geotechnical parameters were found for the Millstone Grit Group in the study area but it tends to be moderately to well-jointed, thinly to thickly bedded, fine to coarse-grained sandstone with mudstone and siltstone interbeds (BGS Lexicon). Strong sandstone provides good foundation conditions but faults and weathering zones should be considered in site investigation. It is suitable for general fill and can be excavated where the rocks are weathered.

Weak mudstone

Manchester Marls Formation
The Manchester Marls Formation is stiff to weak, reddish brown or purple mudstone. The data from the BGS geotechnical database for the area present only a few data from the SPT N-values and point load test which show a dense nature of the formation. It provides generally good foundation conditions provided highly weathered zones are assessed. Ripping or pneumatic tools maybe required for excavations at depth in fresh rock.

Mercia Mudstone Group
Mercia Mudstone Group is brown and red-brown, calcareous clay and mudstones with occasional beds of impersistent green siltstone and fine-grained sandstone (BGS Lexicon). In the absence of geotechnical data for the group, no detailed ground conditions can be provided. However, other sources indicate that it provides reasonable good foundations conditions. The main geotechnical hazards are the presence of halite and gypsum and it may subject to shrinking and swelling (Hobbs et al, 2002). It can be excavated.

Strong mudstone

Pennine Upper Coal Measures Formation
Moderately weak to strong dark grey to grey laminated mudstone, weathering to stiff to very stiff silty clays and silty sandy clays. It provides generally good foundation conditions, however the presence of highly weathered zones need to be assessed. It is suitable for general fill. Ripping may be required for strong rock but digging may be suitable for weathered rock. Potential geotechnical hazards are abandoned shallow mine workings and ground gas accumulation.

8 Slope stability

The BGS National Landslides Database contains 424 entries within the Greater Manchester Combined Authority area. This corresponds with the highest ranked areas in the BGS GeoSure landslide susceptibility dataset, rated D and E, (Lee and Diaz Doce, 2014) and 197 mapped landslides in the BGS Geology 1:50 000 scale mass movement layer (Figure 44).

One of the largest landslides in the Greater Manchester Combined Authority area occurs in the banks of the River Irwell between Lower Kersal and Higher Broughton, where the River Irwell has undercut a steep slope in the glacial sands and clays. Known as 'The Cliff', this undercutting has caused landslides that have damaged houses and roads in the area (Aitkenhead et al., 2002). Landslides in similar geological settings are also present further upstream along the River Irwell at Hurst and along the banks of River Roch near Whitefield (Crofts et al., 2012). Landslides caused by unstable glacial deposits have damaged pipelines, roads and buildings in Salford and Bury.

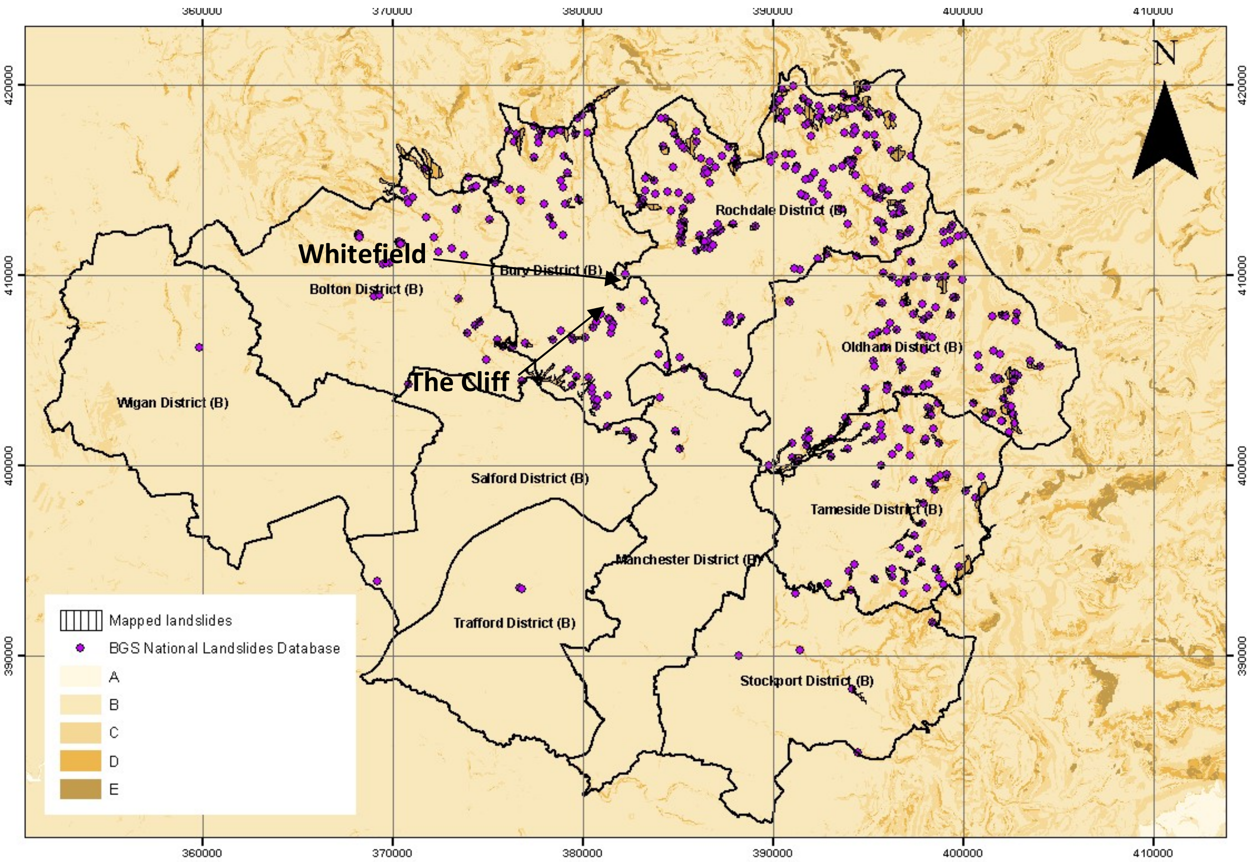

Figure 44 BGS National Landslide database entries (purple dots) and the BGS Geology 1:50 000 scale mass movement layer (black hatched areas). BGS GeoSure landslide potential: A – No slope instability identified; B- Slope instability is unlikely; C- Possibility of slope instability; D – Significant potential for slope instability; E – Very significant potential for slope instability

9 Water resources

9.1 SURFACE WATER

Figure 45 illustrates rivers and canals in the Greater Manchester Combined Authority Area. The main surface water sources are labelled in the map. The flood risk data is available at the website of the Environment Agency (www.environment-agency.gov.uk).

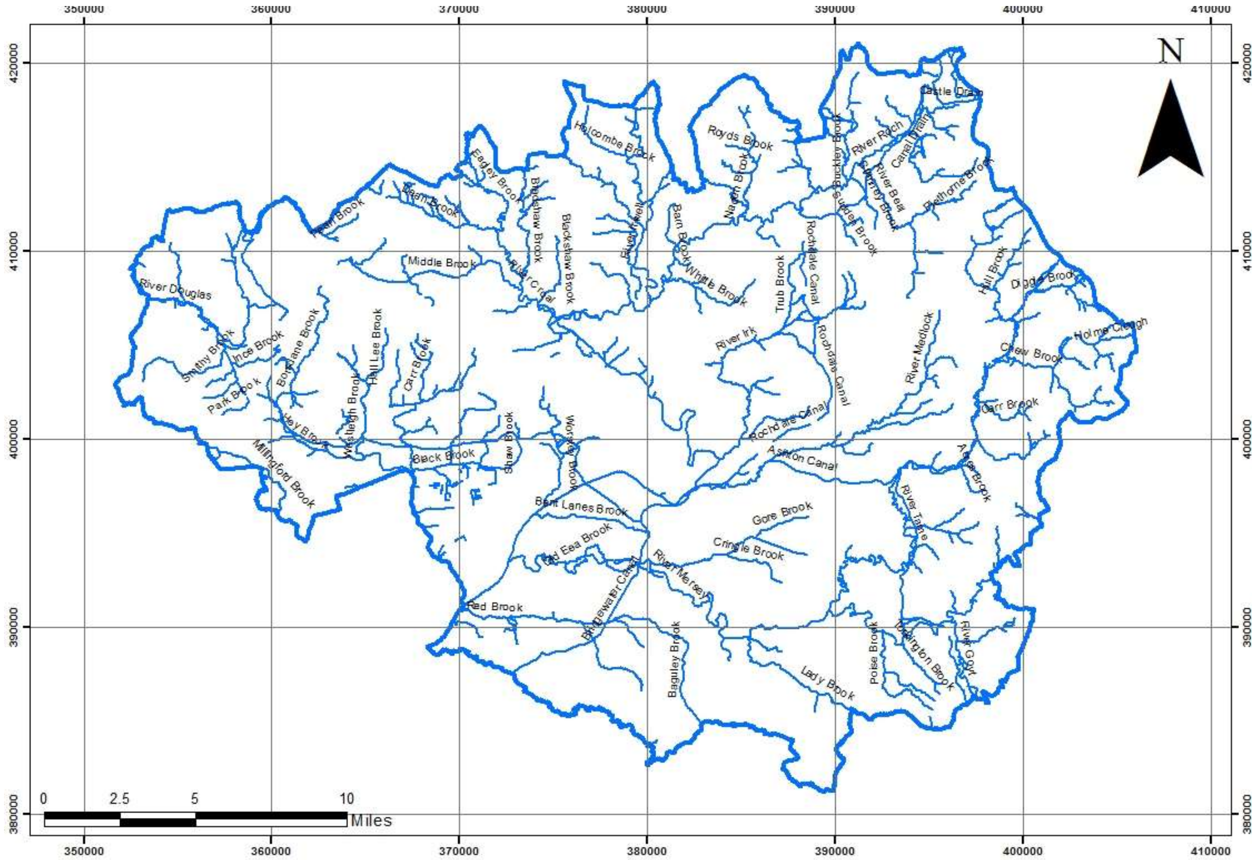

Figure 45 Rivers and canals in the Greater Manchester Combined Authority Area

9.2 GROUNDWATER

The principal aquifer in north-west England is the Triassic Sherwood Sandstone Group. The Helsby, Wilmslow and Chester Formations occur in the Greater Manchester Combined Authority area. The mechanism for groundwater flow in these sandstones is a combination of fissure and intergranular flows (Ingram, et al 1981; Walthall and Ingram, 1984; Campbell, 1982). Minor aquifers in the area include the Permian Collyhurst Sandstone Formation, located on the south part of Greater Manchester, and Coal Measures Group sandstones.

A detailed study of the urban hydrogeology of central Manchester was undertaken by BGS and the Environment Agency in 2004 concluded that groundwater abstraction is mainly concentrated at Trafford and the Irwell Valley (Kessler et al., 2004). High demand for groundwater to support industry led to an average groundwater abstraction rate of 20Ml/d at Trafford Park in the 1960s. By the 1990s the average abstraction rate had been reduced to 8 Ml/d (Kessler et al., 2004).

9.2.1 Aquifer designation

Superficial deposits

Figure 46 shows aquifer designations for the superficial deposits in the area. A secondary A aquifer of glaciofluvial deposits covers the south-west to north-east of the area, located mainly in boroughs of Trafford, Salford, Bury and Rochdale.

Secondary B aquifers (till) are located in north-west and south-east of the Greater Manchester Combined Authority area. Table 8 lists the aquifer designations for the superficial deposits of the GMCA boroughs.

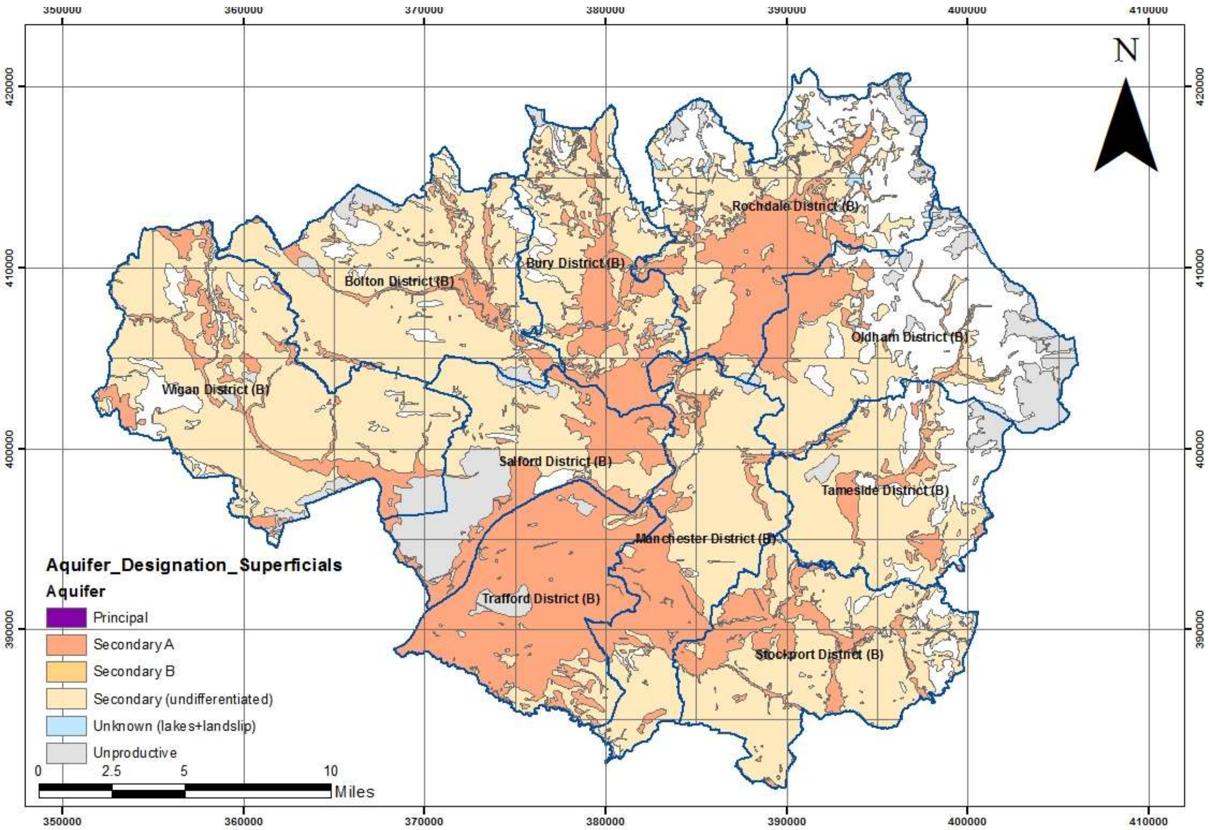

Figure 46 Aquifer designation for superficial deposits. BGS aquifer designation map. 1:50,000 scale

Table 8 Aquifer designation for superficial deposits

Aquifer	Superficial deposits	Boroughs
Secondary A	Glaciofluvial sheet, glaciofluvial deposits (sand and gravel)	Trafford, Manchester, Salford, Rochdale, Stockport, Bury, Wigan, Bolton
Secondary B	Till (Devensian)	Manchester, Wigan, Bolton, Bury, Bolton, Rochdale, Oldham, Tameside, Stockport

Bedrock

The Sherwood Sandstone Group is designated a principal aquifer (highly permeable bedrock or superficial deposits that supports water supply) and is present across large parts of Central Manchester, Trafford, Salford, Wigan and Stockport. The northern part of the area is mainly underlain by Secondary A aquifers (Carboniferous Coal Measures Group and Millstone Grit Group) and secondary B aquifers which are permeable layers that support water supplies associated with the Mercia Mudstone Group are located on south-west of the area (Figure 47). Table 9 provides aquifer designations for the bedrock of GMCA boroughs.

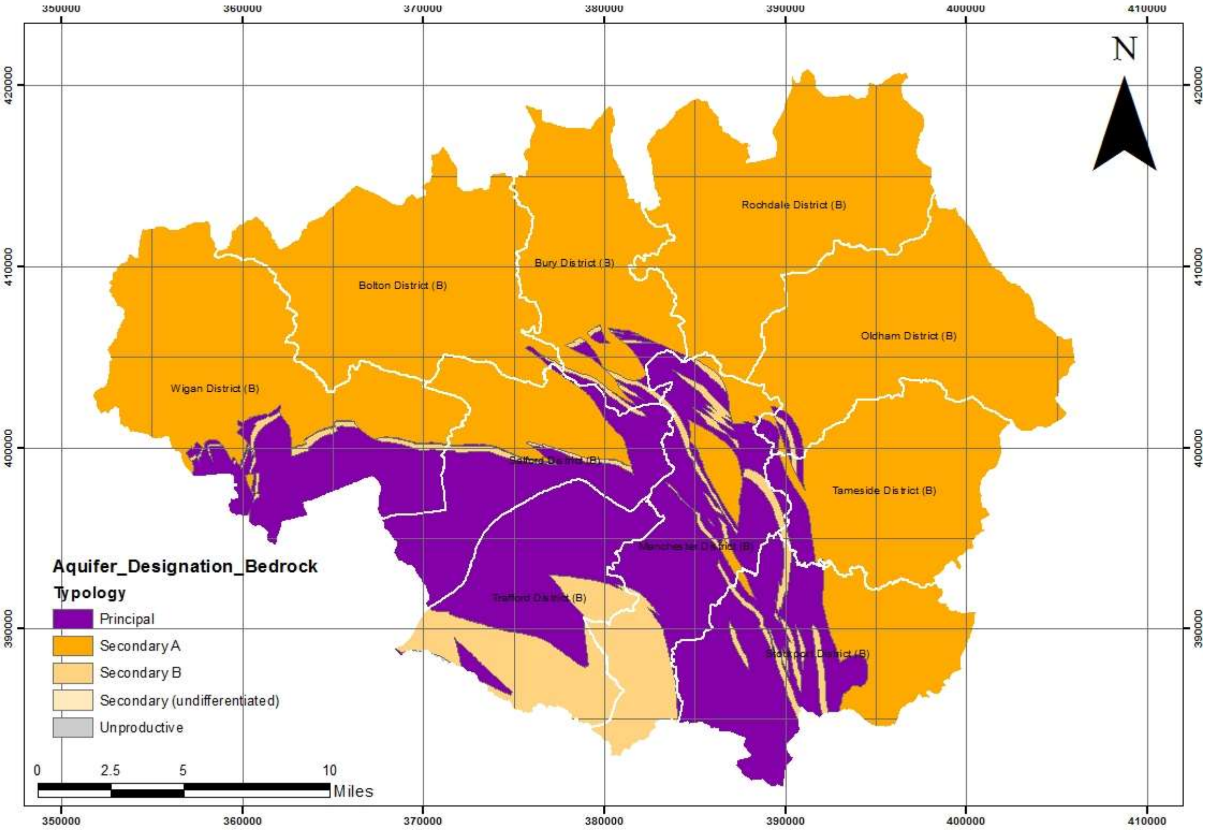

Figure 47 Aquifer designation for bedrock. BGS aquifer designation map. 1:50 000 scale

Table 9 Aquifer designation for bedrock

Aquifer	Bedrock	Boroughs
Principal	Sherwood Sandstone Group	Manchester, Salford, Trafford, Stockport Wigan, Bury
Secondary A	Coal Measures and Mill Stone Grits of the Carboniferous	Wigan, Bolton, Bury, Rochdale, Oldham, Tameside
Secondary B	Mercia Mudstone Group	Manchester, Trafford

9.3 HYDROGEOLOGICAL PROPERTIES OF THE SUPERFICIAL DEPOSITS

A 3D geological model of Manchester and Salford was produced by BGS to show the permeability of superficial deposits overlying the Sherwood Sandstone aquifer and the connectivity between them (Kessler et al, 2004). Each modelled superficial unit was assigned a hydraulic conductivity range using Brassington, 1998 and Allen et al., 1997, based on inferred permeability ratings. These hydrogeological properties are summarised in Table 10.

Table 10 Hydraulic properties of superficial deposits (Kessler et al., 2004)

Model unit	Lithology	Inferred permeability	Estimated hydraulic conductivity range (md^{-1})
Alluvial overbank deposits	Silt, clay, peat	Weakly permeable	$10^{-5} – 10^{-2}$
Alluvial river channel deposits	Sand, gravel, peat	Permeable	$10^{-3} – 10^{4}$
River terrace deposits	Sand, gravel, possibly with a clay rich upper surface	Permeable	$10^{-3} – 10^{4}$
Outwash sheet deposits	Silty sand, on clayey sand and gravel	Permeable	$10^{-4} – 10^{2}$
Glaciolacustrine deposits	Laminated silts and clay	Weakly permeable	$10^{-6} – 10^{-4}$
Glaciolacustrine sands and silts (ice-contact)	Loose, fine sands overlying laminated silts	Permeable	$10^{-2} – 10^{1}$
Till	Till, interbedded sands, impersistent laminated clays	Generally weakly permeable but some permeable lenses	$10^{-4} – 10^{1}$
Basal sand and gravel deposits	Clayey sand and gravel	Permeable	$10^{-5} – 10^{3}$

9.4 SUSTAINABLE DRAINAGE SYSTEMS (SUDS)

Figure 48 shows the compatibility of the ground for the use of infiltration Sustainable Drainage Systems (SuDS). The SuDS map is summarised in Table 11, which indicates that the most suitable boroughs for SuDS are Bury, Rochdale and Oldham.

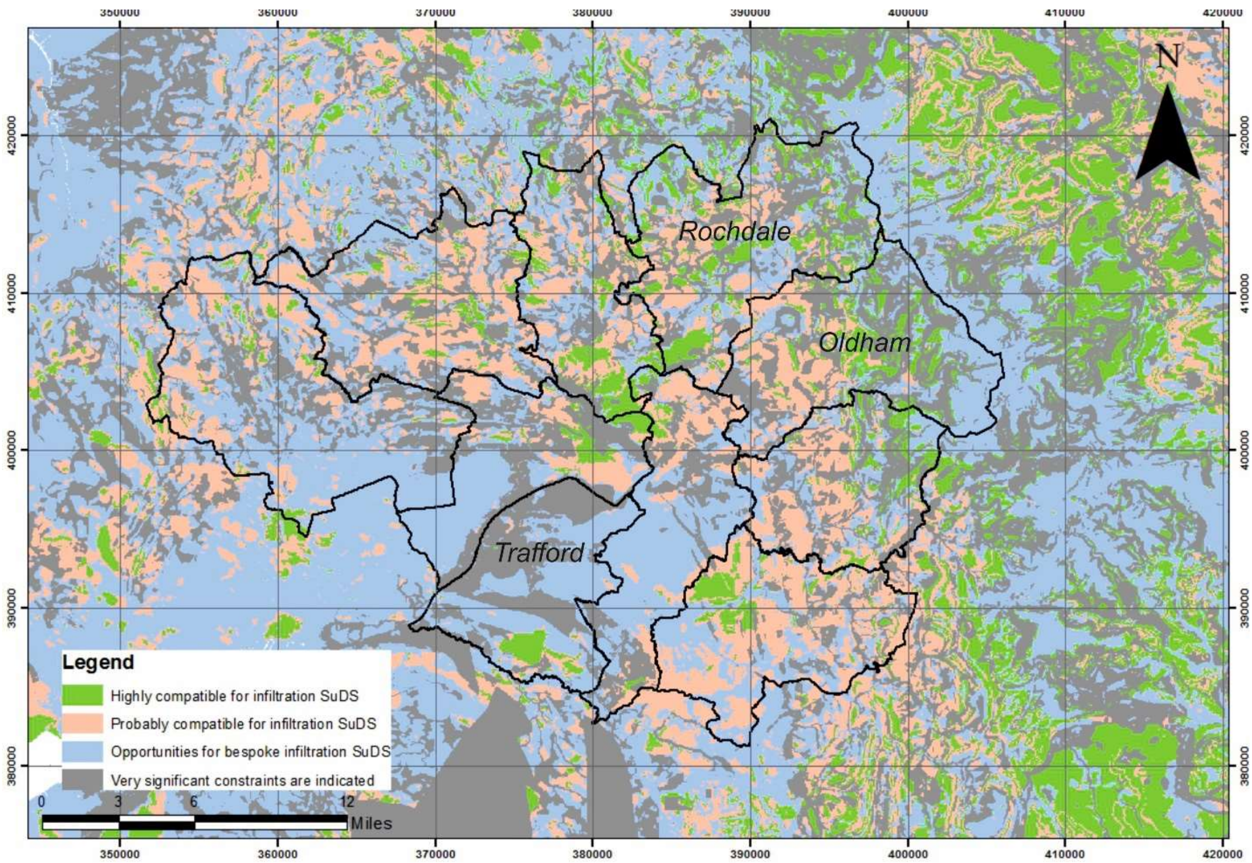

Figure 48 Map showing the BGS Infiltration SuDS map

Table 11 SuDS compatibility of the area (BGS SuDS dataset)

District	SuDS highly compatible (Area km2)	% area SuDS highly compatible	SuDS probably compatible (Area Km2)	% area SuDS probably compatible
Bolton	8	6	68	49
Bury	20	**20**	37	37
Manchester	7	6	29	25
Oldham	33	**23**	41	29
Rochdale	44	**28**	42	27
Salford	8	9	17	17
Stockport	10	8	56	44
Tameside	17	**16**	43	42
Trafford	9	8	12	11
Wigan	8	4	70	37

9.5 GROUNDWATER FLOODING

BGS groundwater flooding data (Figure 49) shows that the most of the Greater Manchester Combined Authority area has limited groundwater flooding potential. However, some boroughs such as Salford, Trafford and Wigan have more potential for groundwater flooding to occur at the ground surface associated with alluvium and terrace gravels (Table 12).

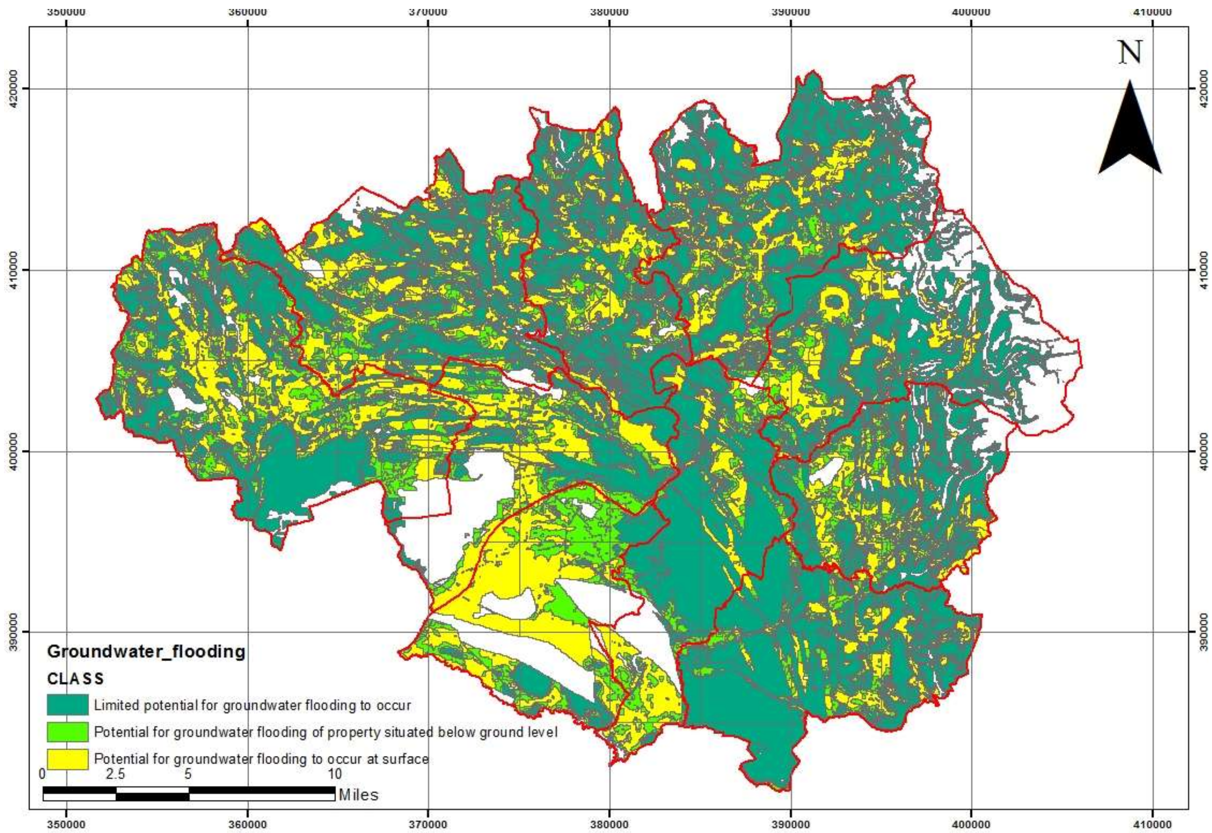

Figure 49 Groundwater flooding map. Data extracted from BGS Groundwater Flooding Data

Table 12 Groundwater flooding data for the area (BGS Groundwater flooding dataset)

District	Potential for groundwater flooding to occur at surface		Potential for groundwater flooding of property situated below ground level		Limited potential for groundwater flooding to occur	
	(Area km^2)	% area	(Area km^2)	% area	(Area km^2)	% area
Bolton	35	25	27	19	70	50
Bury	21	21	16	16	58	58
Manchester	21	18	18	15	66	57
Oldham	22	15	13	9	65	46
Rochdale	29	18	24	15	91	57
Salford	28	**28**	18	**19**	27	28
Stockport	14	14	16	12	95	75
Tameside	19	19	18	17	53	51
Trafford	40	**40**	28	**27**	11	11
Wigan	48	**48**	43	**23**	83	44

10 Summary

The Greater Manchester Combined Authority area has a long industrial legacy, beginning in the 18th century with the textile industry, which led to sustained population growth. However, after deindustrialisation, the area faced challenges such as job losses and legacy land quality issues. Due to the efforts of the Manchester authorities to implement regeneration plans and growth strategies the city has established itself as one of the primary urban centres in the UK.

To support land use planning and urban development in Greater Manchester, e.g. housing and the construction of new infrastructure, this report provides an account of the geology of the area applied to key planning factors e.g. engineering geology, hydrogeology and mining.

The bedrock in Greater Manchester is composed of Triassic, Permian and Carboniferous rocks. Superficial deposits comprise three till types (Brewood Till Formation, Stockport Glacigenic Formation and Yorkshire Dales Till Formation), glaciofluvial deposits, alluvium and peat deposits located in Trafford and Chat Moss areas. This report demonstrates the influence of the variation in geological properties on planning and development considerations.

The BGS Geosure dataset highlights areas of high landslide potential, most notably in the north and east of Greater Manchester. Significant geological constraints for the implementation of infiltration SuDS are observed in the south portion of Great Manchester centred around the district of Trafford. This is largely coincident with the presence of glaciofluvial deposits and peat. This area is also most at risk of groundwater flooding at the ground surface.

A review of the engineering geology of the bedrock highlights internal variation in engineering properties at the geological unit scale, associated with variation in lithology, depositional setting and weathering profiles. Whilst engineering geology properties of the bedrock units show generally favourable conditions, e.g. for foundations, additional localised factors need to be considered, including the presence of faults – particularly in the Coal Measures Group and Sherwood Sandstone Group, and the depth of the weathered zone. Due to coal extraction, coal seams may cause potential for ground gas accumulation in addition to ground hazards associated with abandoned mine workings. For planning purposes, information about coal mining in the area should be also assessed.

Regarding the superficial deposits, the area is covered by three till formations, which provide generally good foundation conditions depending on till composition and geological history. The presence of water bearing sand and silt layers should also be considered in site investigation. Alluvium in the Trafford, Manchester, Salford, Bury and Wigan districts generally has low bearing capacities. Detailed site investigation is required for any engineering works. The influence of buried valleys on superficial thickness, lithology and geological properties should be further considered. Poor foundation conditions associated with peat deposits are observed in the south-eastern part of the Greater Manchester Combined Authority area.

Development of the conceptual ground model for Greater Manchester highlights the influence of geological processes such as faulting, weathering and glacial activity on the properties of the geological formations and supports detailed characterisation of the internal variability of within geological formations, over and above traditional stratigraphically mapping and modelling.

A summary of the main geological, engineering geological, hydrogeological characteristics and mineral resources for each boroughs are provided in Table 13.

Table 13 Summary of the main geological characteristics and uncertainties in Greater Manchester

Borough	Geology		Engineering geology		Mineral resources	Hydrogeology			
						Aquifer designation		Groundwater flooding	SuDS
	Superficial	Bedrock	Superficial	Bedrock		Superficial	Bedrock		
Bolton	Till, Peat, Alluvium, Glaciolacustrine deltaic deposits	Pennine Middle, - Lower Coal measures; Rossendale Fm	Peat	Mudstone, siltstone, shale; shallow mine workings	Coal, fireclay, clay	Secondary A, B	Secondary A		
Bury	Glaciofluvial deposits, Glacial deposits, Alluvium, Till	Chester FM, Manchester Marl, Millstone Grit, Collyhurst Sandstone Fm	Sands and gravels	Moderately strong to strong mudstone, sandstone; potential hazard from mine workings, weathering, faults and fissures	Coal, clay	Secondary A, B	Principal, Secondary A		SuDS is highly compatible for 20% of the area
Manchester	Glaciofluvial deposits, Alluvium, Till	Manchester Marl, Middle Coal Measures, Collyhurst Sandstone Fm, Etruria Fm, Wilmslow Sandstone Fm, Mercia Mudstone, Halesowen Fm	Sands and gravels	Mudstone, siltstone, shale, sandstone; presence of halite, may be swelling and shrinkage, faults and fissures, accumulation gases, shallow mine workings	Coal. Fireclay, limestone, building stone, clay	Secondary A, B	Principal, Secondary B		
Oldham	Glaciofluvial deposits, Peat, Glacial deposits, Alluvium, Till	Hebden Fm, Lower, - Middle Coal Measures, Manchester Marl	Sands and gravels	Mudstone, sandstone, shallow mine workings	Coal, fireclay, clay	Secondary B	Secondary A		SuDS is highly compatible for 23% of the area
Rochdale	Glaciofluvial deposits, Glacial deposits, Alluvium, Till,	Rossendale Fm, Lower,-Middle Coal Measures	Sands and gravels	Mudstone, siltstone, shale, shallow mine workings	Coal, fireclay, clay	Secondary A, B	Secondary A		SuDS is highly compatible for 28% of the area

Salford	Glaciofluvial deposits, Peat, Alluvium, Till	Helsowen Fm, Middle Coal Measures, Manchester Marl, Wilmslow Sandstone Fm, Sherwood Sandstone Fm	Sands and gravels, peat	Mudstone, siltstone, shale, faults and fissures, accumulation of hazardous gases, shallow mine workings	Coal, building stone, clay	Secondary A	Principal	28% of the area has potential for gw flooding to occur at surface, 19% of the area for gw flooding of properties below ground level	
Stockport	Glaciofluvial deposits, Alluvium, Till	Manchester Marl, Collyhurst Sandstone Fm, Chester Fm, Lower Coal Measures, Millstone Grit, Rosendale Fm	Sands and gravels	Mudstone, siltstone, shale. faults and fissures; accumulation of hazardous gases, shallow mine workings	Fireclay, building stone, clay	Secondary A, B	Principal		
Tameside	Glaciofluvial deposits, Alluvium, Till	Upper,-Middle Coal Measures, Collyhurst Sandstone Fm, Etruria Fm, Millstone Grit	Sands and gravels	Mudstone, siltstone, shale, sandstone, faults and fissures, accumulation of hazardous gases, shallow mine workings	Coal, clay	Secondary B	Secondary A		SuDS is highly compatible for 16% of the area
Trafford	Glaciofluvial deposits, Peat, Alluvium Till	Wilmslow Sandstone Fm, Mercia Mudstone Group, Sherwood Sandstone Group	Sands and gravels	Mudstone, presence of halite, may be swelling and shrinkage, faults and fissures, accumulation gases		Secondary A	Principal, Secondary B	40% of the area has potential for gw flooding to occur at surface, 27% of the area for gw flooding of properties below ground level	
Wigan	Glaciofluvial, Peat, Alluvium, Glaciolacustrine deposits, Till	Manchester Marl, Middle, -Lower Coal Measures, Sherwood Sandstone Group, Collyhurst Sandstone, Wilmslow Sandstone Fm	Sands and gravels, peat	Mudstone, siltstone, shale, sandstone; faults and fissures, accumulation of hazardous gases, shallow mine workings	Coal, fireclay, limestone, clay	Secondary A, B	Principal, Secondary A	48% of the area has potential for gw flooding to occur at surface, 23% of the area for gw flooding of properties below ground level	

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