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The published version has minor changes to a few words and the numbering of the figures. Table 1 in the attached is Figure 2 in the published version and the subsequent figures 2-15 in this manuscript are labelled 3-16 in the published version.

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Photofeature: Natural and anthropogenic halite karst subsidence in north Cheshire, UK; comparison of Rostherne Mere, Melchett Mere, Tatton Mere and their surroundings.

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Abstract: Most of the north Cheshire - Knutsford Group - of meres (lakes) in the UK formed naturally by dissolution of Triassic halite after the Devensian glaciation. Anthropogenic brine extraction in the 19th and 20th Centuries produced further subsidence that enlarged some meres and formed the new lake of Melchett Mere. The characteristic features of three meres, Rostherne, Melchett and Tatton are compared here by historical surveys, maps, photographs and LiDAR interpretations. These illustrate the similarities of the natural and anthropogenic subsidence features, which can only be separated by temporal evidence of their formation. Rostherne Mere and Tatton Mere are mainly natural, though deepened or made larger by anthropogenic salt dissolution; Melchett Mere is completely anthropogenic and mainly formed between 1927 and 2003. All three meres are surrounded by landslip scars related to the subsidence. Former brine pumping at Northwich, Plumley and possibly Agden is implicated in the formation of Melchett Mere and the reactivation of natural subsidence at Rostherne and Tatton meres plus The Mere along with Tabley, Pickmere and Budworth meres to the south west. The brine run linkages between these abstraction areas and the subsidence crosses the route of the proposed HS2 railway.

Introduction

Salt dissolution subsidence has affected the areas with Triassic salt in Cheshire for a considerable time, especially during and since the last (Devensian) glaciation and most likely during earlier glaciation. The dissolution subsidence has resulted in the formation of numerous meres (lakes) such as Rostherne Mere and Tatton Mere (described here), plus The Mere, Tabley Mere, Pickmere and Budworth Mere (the Knutsford Group of Reynolds,1979) along with mosses (peat bogs) that postdate the Devensian glacial deposits. Sporadic isolated ground collapses have also been noted in historical times. During the 19th and 20th centuries salt mining and more importantly wild brine abstraction has led to additional widespread subsidence in the salt areas, especially around Northwich and farther east to Plumley and Knutsford (Calvert 1915; Cooper 2020). This anthropogenic dissolution and subsidence have partially utilised existing dissolution features, commonly referred to as brine runs, causing further subsidence to existing features and the generation of numerous subsidence lakes, mostly called flashes to the south of Northwich and one named as Melchett Mere north of Knutsford (Fig. 1). Recent work on the route of the HS2 railway highlights the importance of understanding the geohazards, including salt subsidence, that affect the route and the usefulness of LiDAR studies in mapping the landscape features (Eccles and Ferley 2018; Moore *et al.* 2022).

Geological setting, salt dissolution and subsidence

Cheshire has extensive salt deposits of Triassic age present in two units: the lower, the Northwich Halite Member and the upper, the Wilkesley Halite Member. The regional stratigraphy with past and current nomenclature is shown in Table 1. The lower part of the sequence, below the Byley Mudstone Member is present in north Cheshire and salt dissolution related to the Northwich Halite Member is responsible for the meres and subsidence in the area described here.

The natural surface subsidence features relate mainly to peripheral water flow and natural halite dissolution induced by the advance and retreat of the Devensian ice, followed by the establishment of the natural pre-anthropogenic hydrogeological regime. Natural dissolution and groundwater flow caused brine movement towards low areas where brine springs, locally called wiches, developed - a name reiterated in the local place names (Cooper 2020). The dissolution has been shown to largely occur at the top of the halite deposits and the collapsed insoluble residues remain along with collapse breccia and collapsed strata; where this overlies the halite it has long been referred to as 'wet rockhead' (Cooper, 2020 and references therein). While 'wet rockhead' corresponds with the basal contact of a superficial deposit breccia over halite, the associated term of 'dry rockhead' was introduced by salt drillers and used by geologists to describe the dry contact between the halite and overlying dry mudstone (Fig. 2).

<table>
<tr><th>Group</th><th>Original name (Pugh 1960)</th><th>Intermediate name (Earp and Taylor 1986)</th><th colspan="2">Present formation and member name - BGS 2021 online Lexicon; (Ambrose et al. 2014)</th><th>Typical lithology (Eccles and Ferley 2018)</th></tr>
<tr><td rowspan="7">Mercia Mudstone Group (Formerly Keuper Marl)</td><td>Upper Keuper Marl</td><td>Brooks Mill Mudstone Formation</td><td colspan="2">Branscombe Mudstone Formation</td><td>Red-brown mudstone with some gypsum/anhydrite beds and nodules</td></tr>
<tr><td>Upper Keuper Saliferous Beds</td><td>Wilkesley Halite Formation</td><td>Wilkesley Halite Member</td><td rowspan="5">Sidmouth Formation</td><td>Thick rocksalt (halite) with red-brown blocky mudstones</td></tr>
<tr><td rowspan="2">Middle Keuper Marl</td><td>Wych Mudstone Formation</td><td>Wych Mudstone Member</td><td>Blocky mudstone with gypsum/anhydrite nodules and thin rocksalt beds at base</td></tr>
<tr><td>Byley Mudstone Formation</td><td>Byley Mudstone Member</td><td>Poorly laminated and blocky red-brown mudstone</td></tr>
<tr><td>Lower Keuper Saliferous Beds</td><td>Northwich Halite Formation</td><td>Northwich Halite Member</td><td>Rocksalt (halite) with thin beds of laminated mudstone</td></tr>
<tr><td>Lower Keuper Marl</td><td>Bollin Mudstone Formation</td><td>Bollin Mudstone Member</td><td>Interlaminated red-brown and green-grey mudstones with some thin dolomitic siltstone laminae plus thin gypsum veins</td></tr>
<tr><td>Keuper Waterstones</td><td>Tarporley Siltstone Formation</td><td colspan="2">Tarporley Siltstone Formation</td><td>Interlaminated and interbedded red-brown with green-grey mottled siltstones, mudstones and sandstones</td></tr>
<tr><td>Sherwood Sandstone Group. (Formerly Bunter Sandstone)</td><td>Keuper Sandstone</td><td>Helsby Sandstone Formation</td><td colspan="2">Helsby Sandstone Formation</td><td>Sandstone with pebble beds and siltstone</td></tr>
</table>

Table 1. Nomenclature and classification of the Triassic strata of the Cheshire salt field.

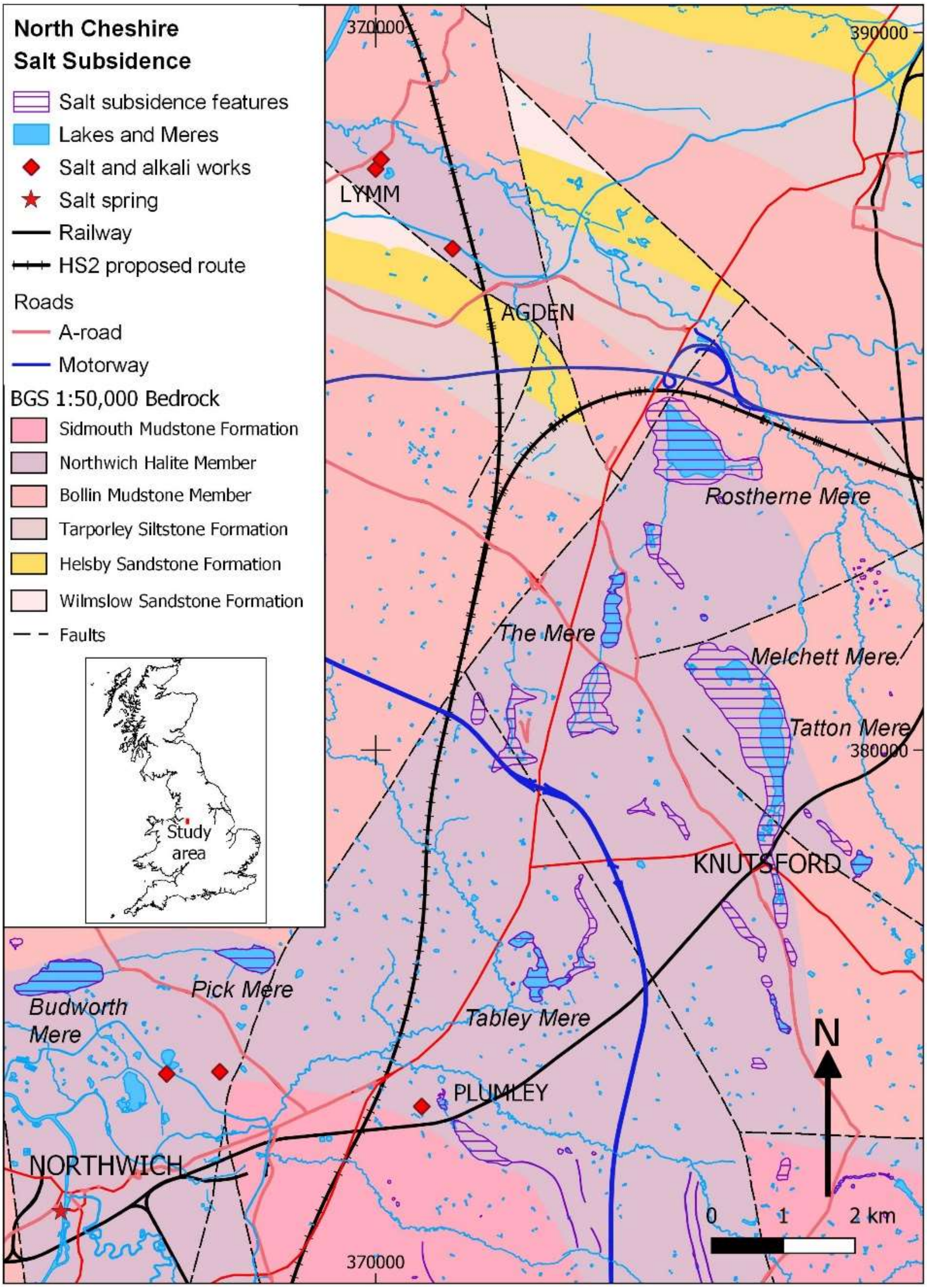

Figure 1. North Cheshire, location, geology, subsidence features and meres BGS © UKRI. Contains British Geological Survey materials ©BGS UKRI 2022; Contains OS data © Crown copyright 2022.

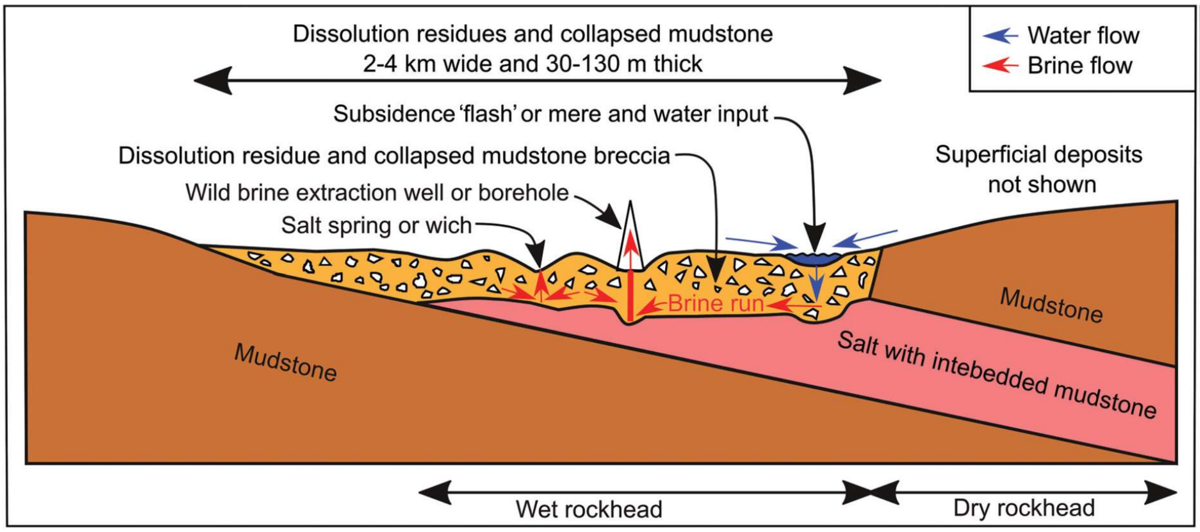

Figure 2. Relationship between 'wet rockhead' and 'dry rockhead' BGS © UKRI (after Cooper, 2020).

The mechanism of salt subsidence due to salt dissolution and brine removal (Fig. 3) has been likened to that of long-wall coal mining subsidence (Evans et al., 1968). The salt removal results in a depression with extension at the margins and compression in the main subsided part, especially concentrated around the margins. The higher parts of the marginal monoclines show cambering, slip scars and open fissures with subsidence blocks stepping down towards the low area. The flexure at the bottoms of the monoclines and to a lesser extent the floor of the subsidence depression can develop compression ridges (Fig. 3). As the subsidence develops the subsidence wave around the subsiding land goes from extension to compression and fractures that are initially camber gulls and subsidence slip scars can be reactivated into compression features with the intervening areas pushed up in the opposite direction, such as those described later for Melchett Mere (Fig. 10). The association of subsidence and compression features in the subsided areas formed by brine extraction is described by Vassileva et al (2021).

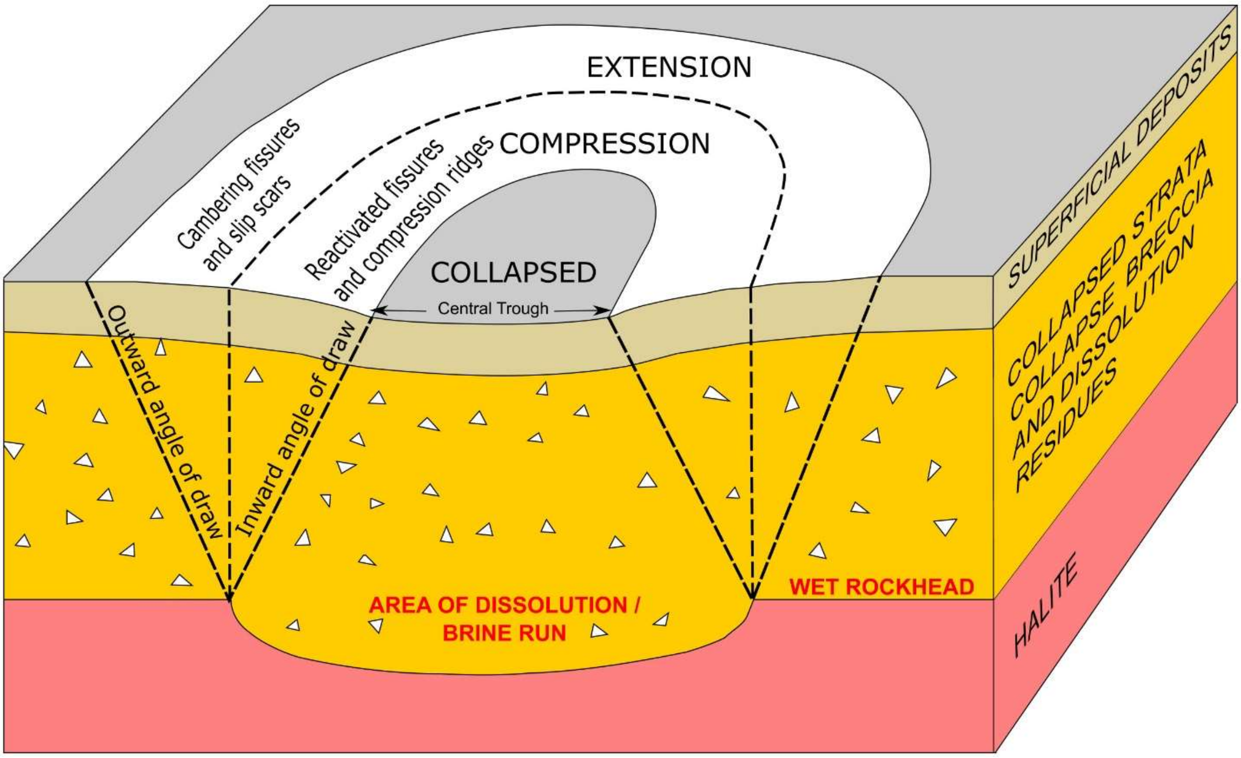

Figure 3. The features of subsidence due to brine extraction/salt dissolution, which are similar to long-wall coal mining subsidence. The monoclinal subsidence zone transitions from extension to compression as the subsidence expands before settling in the collapsed position BGS © UKRI.

Rostherne Mere

Morphology bathymetry and changes with time

Located about 3 km north of Knutsford, Rostherne Mere (Fig. 1) has a surface area of about 48.7 ha and a water level of about 21 m AOD (Fig. 4D). It is up to 31 m deep and lies in a subsidence depression that reaches between 40 and 50 m below the level of the surrounding terrain (Figs 4, A-D). The sides of the depression slope in at 5 degrees, but are steeper along the southern flank (below the churchyard), where the geomorphology and topography is influenced by fluvioglacial sand deposits. The main inflow is of fresh water from Rostherne Brook in the south west corner outflowing via Blackburn's Brook in the south-east corner draining to Birkin Brook, a tributary of the River Bollin. A small contribution of water also comes from Harper's Bank Spring in the woods west of the mere (Ryves *et al.* 2020). This spring water, sampled on 14/09/2010, had a very slightly elevated Na level of 21.21 mg/l compared with an average for the mere of 17.07 mg/l); Cl was not analysed, but the Na level could indicate a small amount of NaCl in the water (David Ryves pers. comm. 09/11/2021), however, it is definitely not a brine spring. Reynolds (1979) recorded similar NaCl levels for the mere with 0.69 meq/l-1 (about 15 mg/l) of Na and 0.68 meq1/l-1 of Cl (about 24mg/l) suggesting little change since then.

The first published depth soundings of Rostherne Mere were made by Mr Kenyon, Gamekeeper at the Tatton Park Estate. Reported by Newton in *The Fishing Gazette* of March 30th 1907, the depths were considered accurate reaching a maximum of 105 feet (32 m), but the positioning was poor; two deep water samples were also collected and found not to be salty.

The first accurate (rope and weight) bathymetric survey of the mere was in 1912-13 by Tattersall and Coward (1914). Their contours, metricated in Figure 4A, show a deep 'cup-shaped' depression with a relatively steep profile, most notably in the south-west part. A maximum depth of around 30 m was recorded slightly south of the centre of the mere. Towards its northern end a shallow ridge/plateau of lake bed was recorded about 6 m deep, lined with peat and interpreted by them as a former shoreline.

Woof and Wall (1984) surveyed Rostherne Mere with sonar equipment and recorded a maximum water depth of 31 m with a bathymetric profile (Fig. 4B) broadly similar to that of Tattersall and Coward (1914). However, significant differences were identified along the south and south-east shores, where a larger area of shallow water was recorded, coincident with the main inflow of Rostherne Brook (Fig. 4). They considered this to relate to an increase in surface area of the mere and sediment accretion between the two survey dates (Woof and Wall, 1984). More recently, Scott (2014) presented the results of a bathymetric survey undertaken in 2010, employing a dual beam sonar transducer and built in GPS; a profile broadly similar to that presented by Woof and Wall (1984) was obtained (Fig. 4 C)

The bathymetric surveys suggest that in 1912-13 the deepest part was just over 30 m with a 25 m deep area towards the south-west and a shallow area in the south-east. On the later surveys by Woof and Wall (1984) and Scott (2014) the mere appears to have become deeper in these areas. There may be some errors in the contouring due to the small number of depths recorded by Tattersall and Coward, but they did have a plumbed depth over their 25 m location. Differences in these surveys suggest some deepening of the mere by up to about 5 m between 1914 and 1984. Between 1920 and 2020, there has also been sedimentation in the deeper parts of the mere with up to 0.6 m of sediment deposited over 100 years equating to about 0.6 cm of sediment per year (David Ryves pers. comm. 21/12/2021). The surface area of the mere varies seasonally and with climatic variations as water levels fluctuate by around 1 m (Ryves et al., 2020). Some sediment accretion is also to be anticipated around the inflow of Rostherne Brook into the mere.

Further evidence of sediment accumulation is presented by the Physical Geography Departments of Royal Holloway College, London, UK and the University of Utrecht, Netherlands (QuatSciBlog 2015). In the deepest part of the lake they cored 13.85 m of lake sediment resting on probable glacial till (diamict). Rostherne Mere is located around 19 km north of the last (Devensian) glacial maximum ice advance in the UK. The climate began to warm circa 17,000 years BP and Rostherne would therefore have been one of the first areas to become free of ice and sediment accumulation probably commenced around 15,000-12,500 BP (Reynolds, 1979) suggesting a deposition rate of around 0.9 cm per year. The 13.85 m of sediment recorded and the relative inflow and outflow levels of the mere suggest overall there has been a maximum of around 44 m of salt dissolution subsidence here since the end of the glaciation.

Subsidence (slip) scars and LiDAR interpretation

The flanks of the subsidence depression occupied by Rostherne Mere are cambered and interrupted by dormant partially degraded tension (slip) scars, developed in the surface superficial deposits (Fig. 4). The features were recorded by Worsley (1967) who noted a greater concentration of slip scars on the north and eastern flanks of the mere. Such slip scar features have been described as analogous to the morphology of subsidence features associated with the long-wall mining of coal and brine-related subsidence. The vertical displacement along the scars is typically less than 1.0 m (Fig. 5) and they are still relatively well preserved.

Airborne LiDAR (Light Detection And Ranging) data for the area (Fig. 4 D) provides more recent high-resolution information about the subsidence depression and tension (slip) scars. The LiDAR derived Digital Terrain Model (DTM) also reveals details obscured by vegetation and not visible on aerial photographs, such as the wooded area of Mere Covert when Worsley (1967) published his survey. The slip scars were digitised from the 2006-2009 LiDAR DTM information (Fig. 4D). More features were recognised than were recorded by Worsley (1967), but the increase most likely relates to the ease with which the DTM displays them, rather than a large increase in their number. This information does not preclude that some movement may have occurred between 1967 and 2006-2009. However, the lack of subsidence damage to the mid-18th to late 19th century St Mary's Church, located near the south-west edge of Rostherne Mere, indicates a relatively long period of stability just outside of the slip scar area.

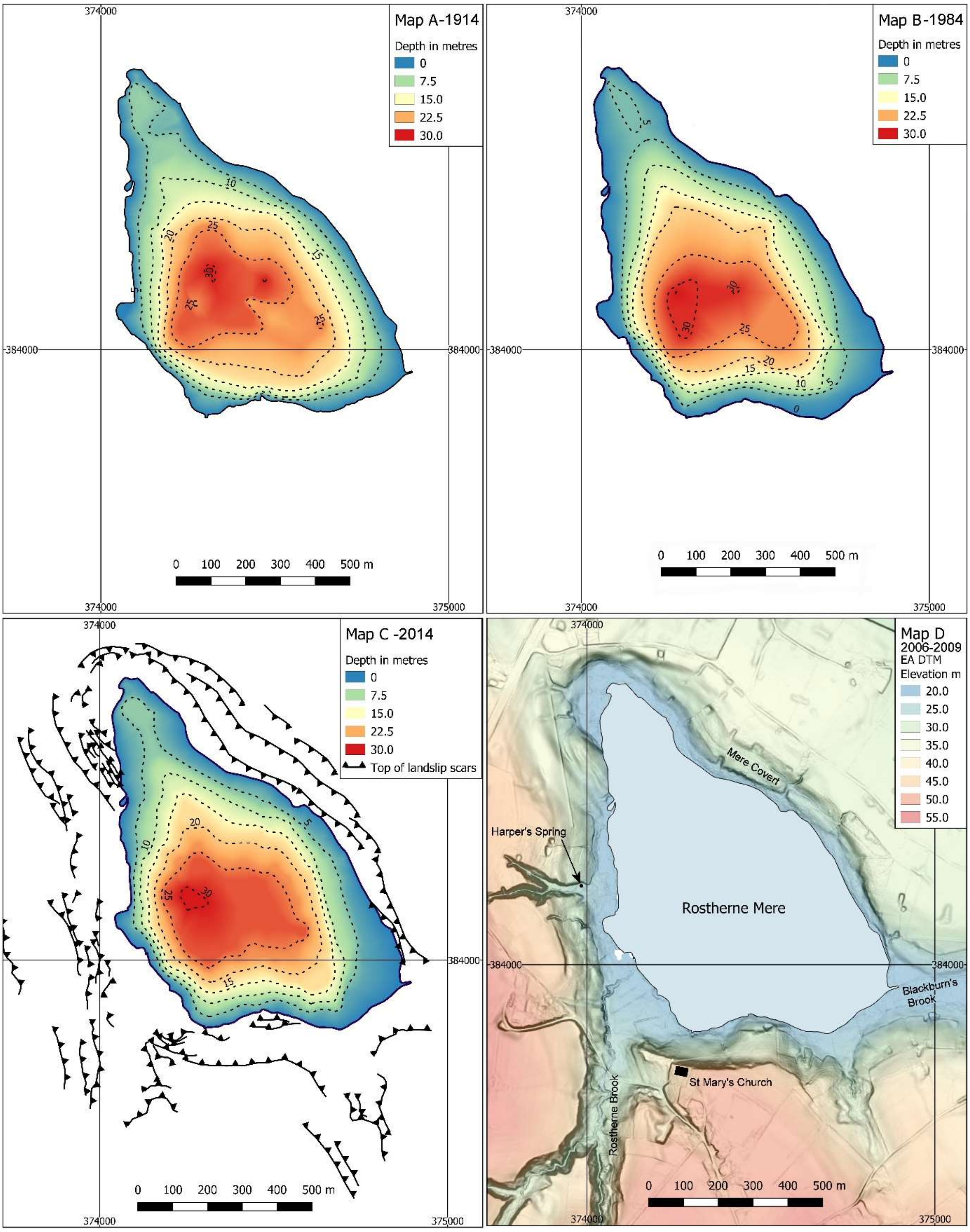

Figure 4. Rostherne Mere: A. Bathymetric survey after Tattersall and Coward, 1914 (depths converted to metres); B, Bathymetric Survey, after Woof and Wall, 1984; C, Bathymetric Survey May 2010, (after Scott, 2014) with landslip scars digitised from EA 2006-2009 1m Lidar BGS © UKRI; D. EA 1m Lidar 2006-2009 processed in QGIS with hillshade and coloured elevation © Environment Agency copyright and/or database right 2021. All rights reserved.

Figure 5: Partially degraded (dormant) slip scars (looking north west) around northern perimeter of Rostherne Mere, adjacent to Gale Bog (left of picture) – photo Colin Serridge.

Melchett Mere

Morphology, bathymetry and changes with time

Melchett Mere is of anthropogenic origin having formed by subsidence mainly between 1927 and 2003 as a result of brine extraction; it was named by Lord Egerton of Tatton, after Lord Melchett (formerly Sir Alfred Mond), the then Chairman of the brine extraction company that he considered responsible for the subsidence. It is located in Tatton Park about 750 m south-east of the house (Tatton Hall) and 3 km south of Rostherne Mere (Figs 1 and 6). The mere has a surface area of around 8 ha and lies within a shallow linear dissolution depression.

The mere first started to form in 1927 and its development was recorded by the former Tatton Estate (Figs 7, 8 and 9). Their records at the Cheshire County Records Office note that in 1929 the maximum depth was around 4.8 m and that by 1937 this had increased to around 6.0 m (Fig. 8). At the same time the surface area of the mere increased at a rate of around 0.20 ha per year. Adjacent surveys showed that the centre of Carriage Drive (now Knutsford Drive) on the eastern side of Melchett Mere subsided by around 3.9 m between 1934 and 1945 (Fig. 9). Much later, Bennion et al. (2010) recorded a maximum lake depth of 11.6 m (at NGR 375080, 381147) and noted that diatoms in their core indicated that prior to about 1950 the mere was shallow, but after that it became deep. The continued growth of the mere in the 1950's is illustrated by the 1951 picture of the submerged boat house (Figs. 10 and 11).

Anderson representing the Tatton Estate in 1952 presented evidence to the Brine Subsidence Compensation Board (Cheshire Archives: DET 2389). This recorded that during 1928-29 land drains were showing subsidence problems, dry land was sinking and the drains had filled with water. To utilize the new lake a boat house was constructed in July 1931, but by 1938 it had become surrounded by water and had to be moved to a new position. Continued subsidence meant that by March 1939 it needed extending and a plank was needed for access. More subsidence required more modifications in the 1940's and by 1949 it was unusable. Subsidence also engulfed Long Wood and Crow Wood requiring iron fencing to be moved and reinstalled clear of the water. Areas of trees had to be felled when the water encroached - the extent of the two former wooded areas is shown in Figure 8. Trees being engulfed by on-going subsidence and the submerged boat house at Melchett Mere are shown in Figures 10 and 11 while slip scars and tilted trees are notable in Figures 11, 12 and 13.

Numerous datasets allow the formation history of Melchett Mere and its surroundings to be elaborated. The earliest map of Tatton Park by Hussey in 1773 (Cheshire Archives DET 3229/152) shows Turn Mere a small (subsidence generated) lake near the house with fields shown in the area that became Melchett Mere. Turn Mere is also shown on a map by Earl from 1787 (Cheshire Archives: DET/3299/153). Records from Historic England (1985), document the landscape changes here noting 'Turn Mere, nearer the Hall, was drained in 1816 under the direction of John Webb, who in 1818 was credited with 'improvements' at Tatton.' The landscaped gardens occupying what was Turn Mere and parkland to the south-east in what was to become Melchett Mere are shown on the c. 1848 Tithe map (Cheshire Archives and Local Studies 2021). Subsequently the Ordnance Survey maps of 1882, 1899 and 1910 all show parkland in the area that became Melchett Mere. The historical records of Melchett Mere held by the Cheshire County Records Office, plus historical air photography from Google Earth and the Tithe Maps online website show the development with time of Melchett Mere. Figure 14 summarises the changes in the shape and area of Melchett Mere from the initial subsidence in 1927 in the south-east part to a larger subsidence to the north-west in what is now the deepest part of the mere. The mere developed rapidly in size to 1948, then grew less quickly to 2003. More recent images from 2010-2019 have shown only slight changes in area, some of which might be a function of water levels or marginal vegetation confusing the boundary (Fig. 14).

Subsidence (slip) and compression scars and LiDAR interpretation

The slip scars around Melchett Mere were first mapped in 1948 for the Tatton Park Estate (Fig. 9). While most of the features are tensional slip scars, compression ridges (probably reactivated slip scars) were clearly visible in 1951 on the north-eastern side of the mere (Fig. 11), their relationship to the subsidence area is illustrated in Figure 3. The subsidence scars are typically less than 1 m in height, but public access and grazing of livestock has led to some deterioration of these features, closest to the mere. Photographs from circa 2017 show that the scars were still visible, particularly on the eastern flanks of the subsidence depression (Fig. 12) while trees leaning towards the mere near the northern/north-eastern shoreline (Fig. 13) provide a visual record of recently active subsidence.

Jenkins (1983) studied Melchett Mere and Tatton Mere. He undertook fieldwork with map, historical record and photogeological interpretation at 1:10,000 and larger scales. He looked at various aspects of geomorphological terrain analysis to understand the genesis and development their subsidence landforms. He documented the main subsidence scar features and showed how they increased around Melchett Mere and reactivated around Tatton Mere between 1935 and 1978 (Fig. 9 and Jenkins thesis diagrams 63, 64 and 65). He interpreted this development as being associated with reactivation of the basal down-dip dissolution zone aligned with the pre-existing linear subsidence feature.

The LiDAR imagery (Fig. 6) clearly shows the presence of the deep, connected subsidence features occupied by the former Turn Mere, Melchett Mere and Tatton Mere. They occupy a large linear subsidence feature, with slip scars clearly visible on the flanks. The slip scars are particularly sharp and marked to the west, east and north of Melchett Mere, but less distinct around the former Turn Mere, possibly reflecting its older age and garden landscaping.

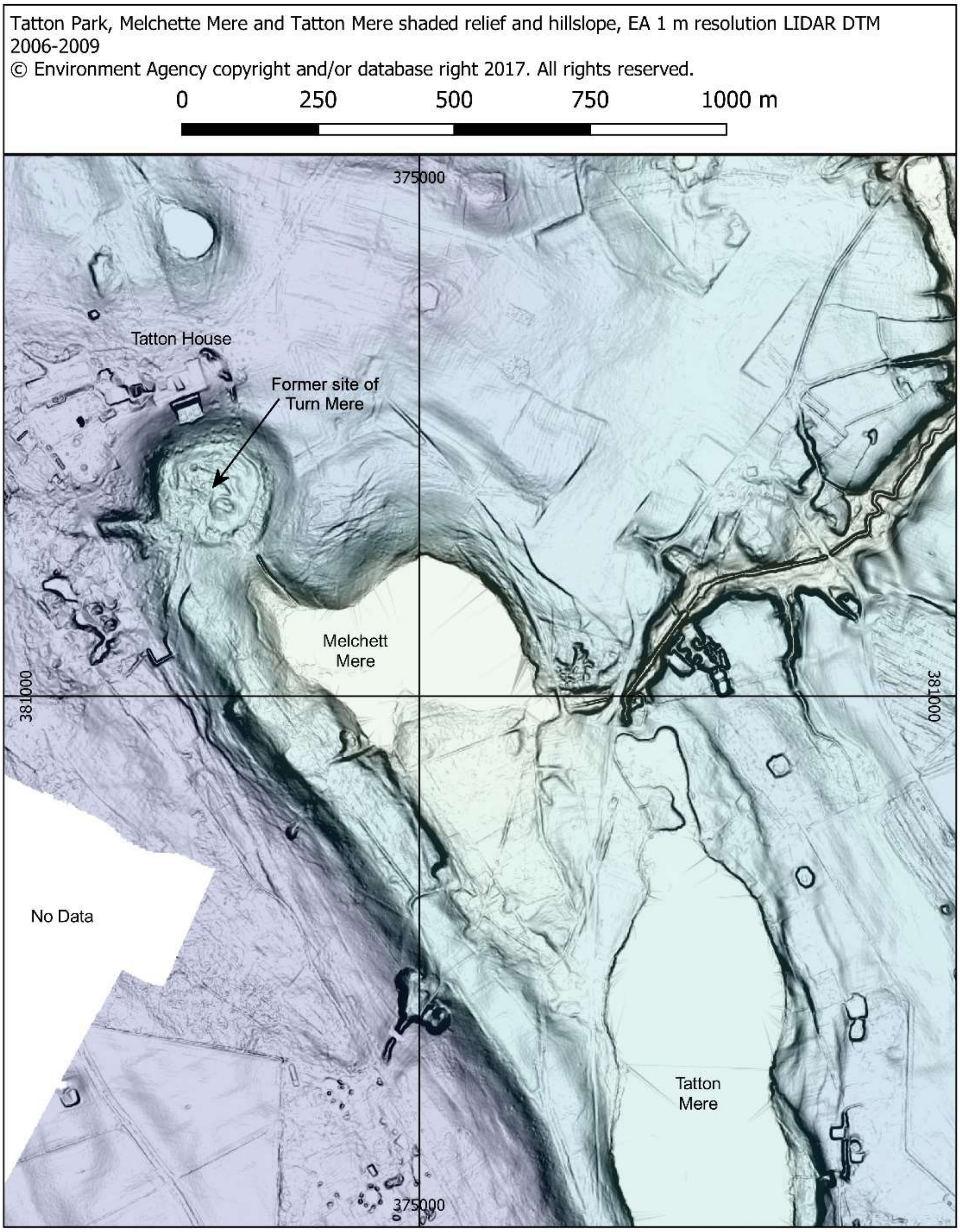

Figure 6: Lidar data for Melchett and Tatton Mere. The crater like depression between Melchett Mere and Tatton Hall (House) is the former Turn Mere, which is recorded as having been artificially infilled circa 1816. 1m Lidar 2006-2009 processed in QGIS with hillshade and coloured elevation © Environment Agency copyright and/or database right 2021. All rights reserved.

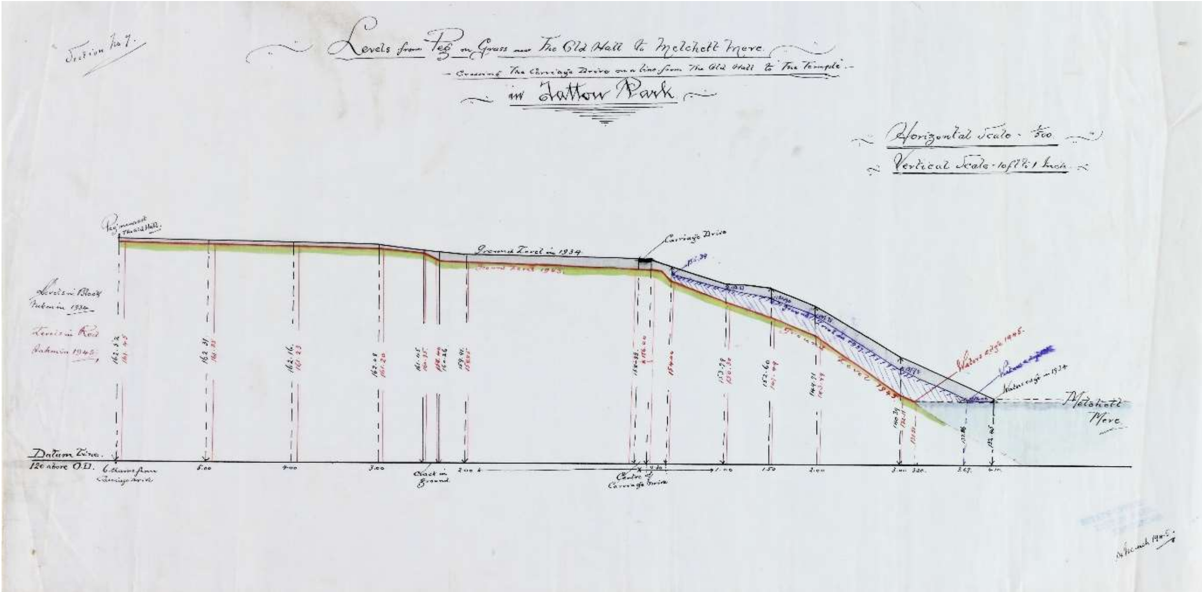

Figure 7: Recorded subsidence on eastern flanks of Melchett Mere: 1934 (black top line), 1937 (blue middle line) and 1945 (red bottom line); at the 1945 lakeside edge about 10ft (3m) of subsidence occurred between 1934 and 1945 - Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389.

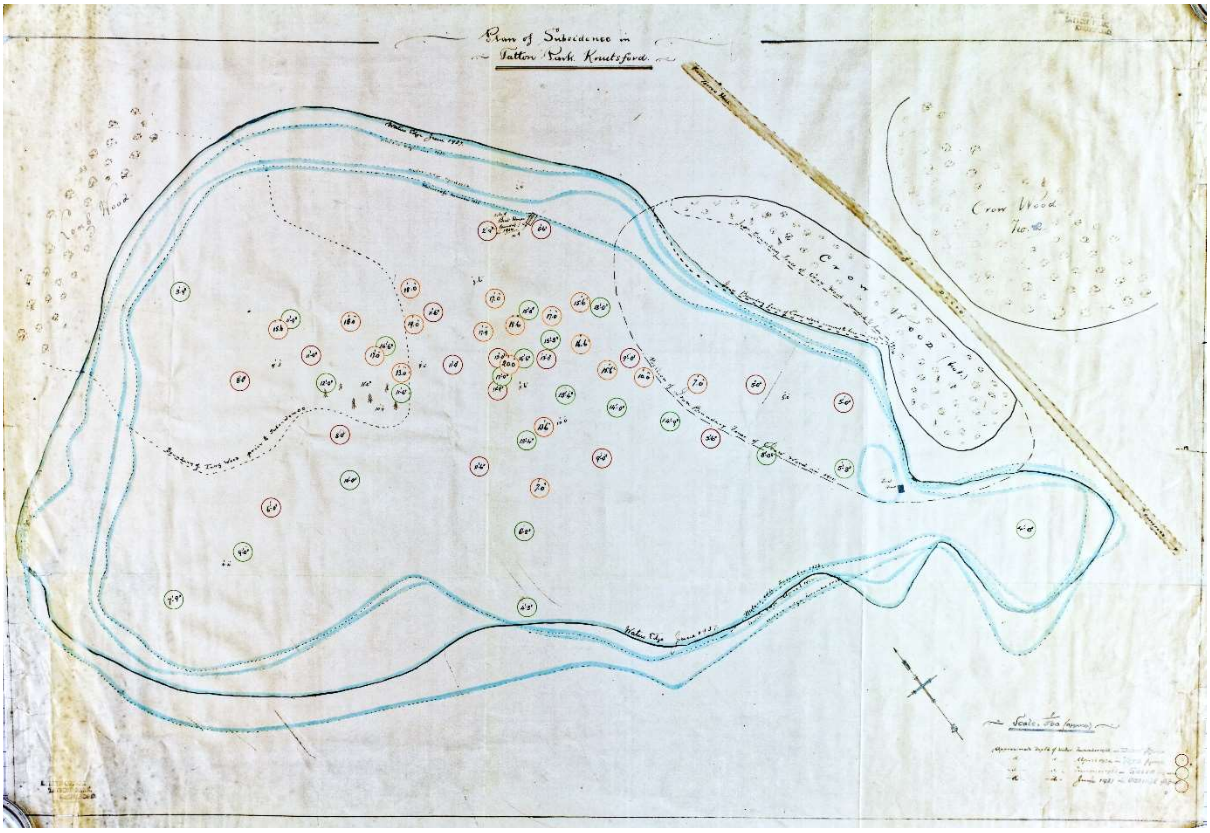

Figure 8: Outlines and depths in feet of Melchett Mere in November 1933, April 1934 (with red circled depths), November 1935 (with green circled depths) and June 1937 (with orange circled depths) - Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389.

Figure 9: Map extract of Melchett Mere and northern half of Tatton Mere dated 1948 showing associated slip scar development (red dashed lines), during on-going subsidence. The former position of the boat house near the island and the new boat house position at northern end of Tatton Mere are both arrowed - Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389).

Figure 10: Melchett Mere, loss, due to subsidence, of boat house and trees on west side of Crow Wood (middle of picture) and the southern end of Long Wood in the background, circa 1951. (Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389).

Figure 11: Compression scars and ridges on eastern flanks of Melchett mere, 1951. Submerged boat house and trees can also be clearly seen. (Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389).

Figure 12: Slip scars developed on the flanks of Melchett Mere during subsidence event. Vehicle provides an indication of scale. Photograph taken 2017 by Colin Serridge.

Figure 13: Leaning trees on north bank of Melchett Mere (edge of Long Wood), attributed to subsidence. Photograph taken 2017 by Colin Serridge.

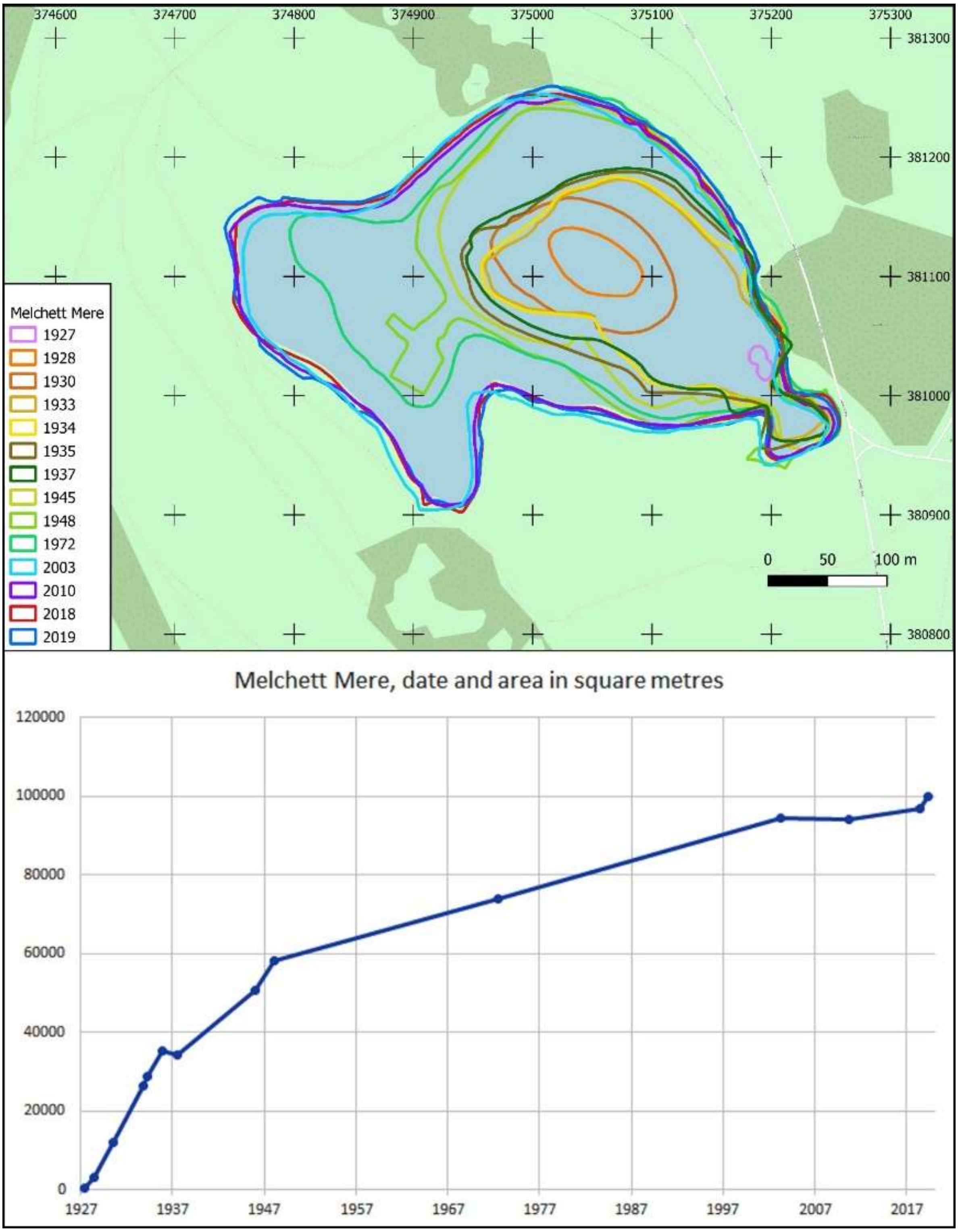

Figure 14: Interpreted growth in surface area of Melchett Mere 1927-2019, BGS © UKRI. Datasets used 1927-1937 and 1948 Tatton Park records (Cheshire Records Office; Figs 8 and 9); 1945 and 1972-2019 aerial photography from Google Earth or Tithe Maps online (https://maps.cheshireeast.gov.uk/tithemaps/) Contains OS data © Crown copyright 2022. Digitised in QGIS.

Tatton Mere

Morphology, bathymetry and changes with time

Tatton Mere is about 1.6 km long and extends over about 32 ha south from Tatton Park to near Knutsford. Surveyed in 2010 it had a maximum depth in the middle of about 12 m, a deep northern part reaching 10 m and was shallow in the most northern section and southern third (Scott, 2014).

Comparing the Ordnance Survey maps from 1910 with the aerial photography of 1948 (Google Earth) changes at the north end of Tatton Mere show subsidence and lake enlargement around the boat house. This sank as illustrated by the c. 1951 photograph (Fig. 15). These changes, increases in mere size, increases in boggy areas and increased numbers of subsidence scars around the lake were also noted by Jenkins (1983) who recorded differences between c.1935, c.1946 and c.1978 based on Tatton Park records, Ordnance Survey maps and aerial photography (Jenkins, 1983 thesis figures 63, 64 and 65). Other changes are also visible between the 1971-3 air photographs when a small island that was present then near the east bank (also shown on Fig. 9 from 1948) is not visible on the later images from 1999.

The southern part of Tatton Mere also shows considerable changes as noted by Jenkins (1983). These changes are seen on the Ordnance Survey maps and aerial photographs from 1875 to 2021. In this time the mere extended southwards and the fields of “The Moor” mapped in 1875 and 1898 included a small lake by 1910 with much larger water areas shown on the 1971 to 2021 maps and air photographs. In addition, Taylor et al. (1963) noted that “Southwards from Tatton Mere a zone of subsidence passes through Knutsford, where the Moor is affected and where houses on the side of the Mobberley Road at Cross Town have developed cracks.”

Subsidence (slip) scars and LiDAR interpretation

From the historical maps and aerial photographs for Tatton Mere Jenkins (1983) noted changes in the mere and in the surrounding slip scars from c.1935, c. 1946 and c. 1978. Dated information for the same area is also seen in Figure 9 for 1948 and Figure 6 highlighting the features shown in the LiDAR 2006-2009 DTM. There are no maps of the slip scars prior to 1935, but Ordnance Survey maps illustrate that Tatton Mere shows considerable changes in width and shape from 1875 to 2021. As slip scars were mapped later than 1935 it seems likely that earlier subsidence and enlargement of the mere would also be associated with slip scar movement around its margins. Many of the changes to Tatton Mere have occurred on a similar timescale to the formation of Melchett Mere and it is likely they relate to the same brine extraction events.

Both meres have similar superficial geology with glacial till to the east and glacio-fluvial sand and gravel deposits to the west (BGS superficial geology online). A 1946 borehole to investigate the subsidence (BGS SE77NE1; NGR 375529,379514) proved 39 m of superficial deposits (65% sand or sand and gravel with about 35% clay and gravelly clay) on very soft red and grey marl to 45.7 m. Such deposits can provide fresh water and localised pathways to the bedrock that facilitate water ingress and both natural or anthropogenic salt dissolution. Within the Tatton Park area Jenkins (1983) interpreted the main subsidence features as occurring over linear and down-dip dissolution zones following the strike of the salt beds and the sub-glacial channels, the orientation of these being described as almost identical, leading to the prominent sinuous dissolution zones which cut north-south to join Rostherne Mere. He described Tatton Mere (Figs. 1, 6 and 9) as an artificially enhanced water filled portion of a peat lined linear subsidence feature of post Devensian age, formed after the halite ‘rock head’ had been scoured by ice and blanketed with superficial deposits.

Figure 15: Submerged boat house (also submerged trees) at northern end of Tatton Mere, circa 1951 (Source: courtesy Cheshire Archives and Local Studies Ref: DET 2389).

Brine pumping and implications

The temporal Tatton Park records, plus maps, air photographs and LiDAR information show how the natural salt subsidence areas have enlarged over time; they have changed at a rate commensurate with features such as Melchett Mere that are demonstrably of anthropogenic origin as a result of brine pumping especially during the late 1920’s to 1940’s. The brine pumping took place to a large extent at Plumley 7.3 km from Melchett Mere (Historic England 2018) and Northwich 9-10 km to the south-west, most likely fed by brine runs along the wet rockhead (Figs. 1, 2 and 3). These pumping activities were also likely to be the cause of subsidence about 2km south-west of The Mere (Fig. 1) and structural damage around the same time to the old manor house/hall and church at Tabley Mere (Taylor *et al.* 1963, Historic England 2012). The likely brine runs are indicated by linking these low mapped subsidence areas, where brine runs pass beneath higher ground they probably do not show very well and their positions are speculative.

There is also a possibility that brine may have been drawn northwards via faults and sandstone formations towards the boreholes and salt factories at Agden an Lymm (Fig 1). Brine can be drawn and brine runs develop over distances of at least 9 km (such as between Crewe and Middlewich, Cooper, 2020) linking up via natural dissolution and subsidence features. The last wild brine extraction was near Northwich, some 9 km from Melchett Mere, and production there ceased on the closure of New Cheshire Salt in 2006. It is unclear exactly where this factory was drawing the brine from.

The question remains as to whether and where brine runs cross the route of the proposed HS2 railway and if potentially unstable ground exists along the route in this area. To the east, around Knutsford, Tatton Mere and Melchett Mere, the Brine Subsidence Compensation Board considers the surroundings of the two meres to be of concern and have a Brine Subsidence Consultation Area in place around them; other similar consultation areas include Northwich, Lymm, Winsford, Sandbach/Crew and Alsager (Cheshire Brine Subsidence Compensation Board 2021). The wild brine pumping may have ceased, but relict subsidence may occur and natural dissolution may continue to cause problems along the anthropogenically induced brine runs. Once dissolution has occurred, there is the possibility of metastable cavities being present in the subsurface. Activities that cause changes in surface water flow and infiltration (or disposal) of surface water to the ground can significantly modify the groundwater regime and possibly trigger subsidence. In addition, activities that cause vibration may also trigger the collapse of metastable cavities (Cooper, 2020).

Conclusions

Historic uncontrolled (wild) brine-pumping has clearly accentuated many of the natural subsidence features occupied by the north Cheshire meres. Most of the meres are natural and of post-glacial age, but Melchett Mere is completely anthropogenic. Although wild brine pumping ceased in 2006 there is still the possibility of continued natural dissolution and metastable cavities being present. The induced brine runs can be recognised in some places by subsidence damage and mere or lake enlargement, but without further study their precise routes remain unclear. The presence of potentially metastable ground along these brine runs has implications for infrastructure development.

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Conflict of interest

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