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Hydrogeomorphic control on tree growth responses in the Elton area of the Cheshire Saltfield, UK

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Abstract

Increment cores were sampled from oak (*Quercus robur*) and ash (*Fraxinus excelsior*) growing at Elton, an area of the Cheshire Saltfield that has experienced significant subsidence and damage to the natural and built environments in the latter part of the twentieth century. Ring-width measurements for Elton trees permitted the construction of one main site chronology (Elton) and four sub chronologies (Elton A, Elton B, Elton C, Elton ASH). Ring-width difference between these and a control chronology identified periods of sustained growth reduction in oak trees commencing in AD 1859/1861, 1886 and 1934. Growth reductions after 1934 are related to watertable draw down caused by brine pumping from a concentration of nine boreholes at Elton, up to 2 km from tree sampling locations. Growth reductions in 1859/1861 and 1886 are likely to be the result of earlier phases of brine pumping in the Wheelock Valley, up to 5 km to the east of Elton, and these reductions correlate well with historic records of subsidence and pumping activity. Cessation of pumping in 1977 led to a lagged growth recovery in oak trees between 1981 and 1986, indicating that an artificial drought had been imposed on the Elton area for a period in excess off 100-y. This research demonstrates a hydrological separation of surface water and groundwater in an area where salt beds are overlain by till and that ring-width records of *Q. robur* can be used to reconstruct watertable variability and also the spatial impact of solution mining.

Keywords: Dendrochronology; Tree ring-width; *Quercus robur*; *Fraxinus excelsior*; Brine pumping; Subsidence

1. Introduction

Salt has long been a valuable resource for humans, as a preservative and more recently as a raw material in the chemical industry. Evidence of salt exploitation from the Iron Age in the UK (Lane, 2005; Nevell, 2005), but earlier usage is probable where there were naturally-occurring brine springs.

In recent years a series of archaeological discoveries in the UK have demonstrated that brine exploitation technologies had become relatively sophisticated by Roman times (Connelly and Power, 2005; Dodds, 2005; Garner, 2005; Penny and Shotter, 1996) and between the Saxon period and the Middle Ages, salt was a major industry in towns such as Droitwich, Worcestershire (Hurst, 1991), and Nantwich, Cheshire (McNeil, 1980, 1983; Leah, 2003).

Salt production efficiency was enhanced from as early as the late eighteenth century, particularly in the nationally important Cheshire Saltfield, with the introduction of steam pumps that led to the practice of

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"wild" (using natural brine — at Elton) and "bastard" (water injection — Northwich area only) brine pumping. The resulting development of large underground caverns gave rise to widespread, and before 1977 uncontrolled, subsidence in Cheshire, notably in the Northwich area. These geographical impacts often exceeded those of other types of mining from the solubility of the mineral and the long distances over which brine flowed to the pumping shafts (Wallwork, 1956).

Depending on site location, tree-ring growth increments can reflect not only climatic variables, the basis for dendrochronology (cf. Schweingruber, 1988; Baillie, 1995), but also disturbance events that cause significant environmental disruption. Pioneering research in the field of dendrogeomorphology was published by Alestalo (1971) and elaborated further in many other studies since (cf. Shroder, 1980; Shroder and Bishop, 1995, Fantucci, 1999, 2007). Few investigations however can be directly linked to mining activities. Schweingruber (1996) used a range of case studies to illustrate the effects of tectonic and volcanic activity on trees, and Kaiser (1993) demonstrated the effects of ground displacement on tree growth in the Gulf of Alaska following a major earthquake, a natural phenomenon that may have parallels to the effects of mining-related subsidence. Dendrochronological dating has been used to document phases of mining activity (Hattori and Thompson, 1987; Lavier and Lambert, 1996; Rom et al., 1999) and dendrochemical studies are thought to reveal the pollution legacies of mining (Guyette et al., 1991; Watmough and Hutchinson, 1996; Watmough, 1999).

Trees also react to changing water levels (cf. Stockton and Fritts, 1973; Yanosky, 1982, 1983, 1984; Sloan et al., 2001; Yanosky and Jarrett, 2002), and trees growing on bogs have been shown to clearly document drainage events and other human interventions (cf. Schulthess, 1990). Currently, however, the effects of mining activity on water tables as documented by tree-rings have also received limited attention, with the exception of Yanosky and Kappel (1997), although this study focused on the incursion of saline surface waters and is therefore not directly comparable to the research reported here.

This research focuses on Elton, SW of Sandbach in Cheshire, as this area has experienced significant brine-related subsidence (particularly during the twentieth century) that has affected housing, agricultural land, water courses (Fielding and Fielding, 2006), and the Crewe to Manchester railway line (Wardell and Partners, no date). Tree ring-width series of oak (*Quercus robur*) and ash (*Fraxinus excelsior*) are compared to precisely-dated records of brine exploitation in order to assess tree growth-responses to water table fluctuations.

2. Location and historical background

The Elton area lies generally between 40 and 50 m a.s.l. on the generally flat/gently undulating topography of the Cheshire Plain. Superficial deposits comprise glacial tills and fluvioglacial meltwater deposits (Worsley, 2001), and due to the spatial variability in the clay content in these, the depth of the local "perched" watertables can vary significantly over short distances (M. Leah, Cheshire County Council, personal communication, 2005). In areas where glacial till predominates, such as at Elton, surface waters can accumulate independently of groundwater for similar reasons.

Elton is also located within the solid geology of the Cheshire Saltfield (Fig. 1), which lies within a Triassic syncline that covers large areas in the centre and the north of England. Rock salt was formed circa 200 million years ago in England, then located much closer to the Equator, by the evaporation of sea water from shallow basins. Today underground salt beds range from a few centimetres to hundreds of metres in thickness and can contain more than 90% NaCL (Fielding and Fielding, 2005). At Elton the salt beds are oriented horizontally and "natural brine" forms due to the incursion of groundwater where the top salt bed is overlain by till.

The first indication that salt may have been exploited in the Elton area emerged from the discovery of Iron Age artefacts (circa 500 BCE — 1 CE) (Twigg, 1994). Later historical evidence of brine use has emerged from the study of field names. "Brine Pit" and "Wich House" fields have been noted on eighteenth and nineteenth century maps relating to salt production in the adjacent valley of the River Wheelock (Twigg, 1994). "Wich" or "wic" is derived from the Latin vicus meaning place, but it was commonly associated with salt working by the eleventh century (cf. the Cheshire salt — producing sites/towns of Dirtwich, Nantwich, Middlewich, and Northwich).

In the twentieth century, a series of larger salt works were built to the S of Sandbach (Sheffield Works, established before 1919; British Soda 'Glacier' Works, 1920; Palmer Mann 'Sifta' Works, 1923). These represented the first concentration of solution mining specifically in the Elton area, and they used open pan and vacuum production techniques. In the late 1960s and early 1970s, these works were demolished as their companies were subsumed within British Salt. The brine from Elton, was then pumped further-a-field to

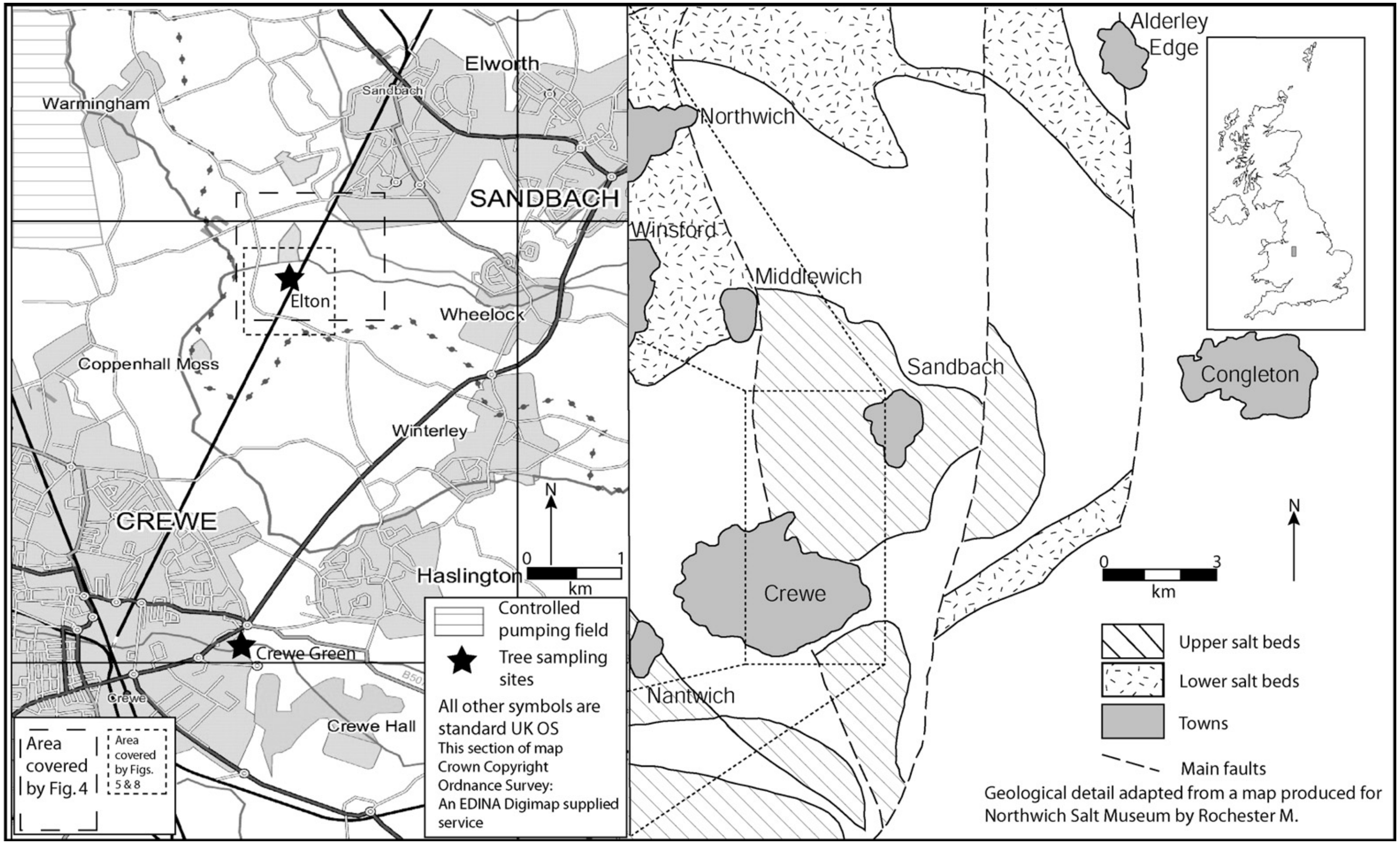

Fig. 1. The locations of the main study site at Elton, control site at Crewe Green, and the modern controlled pumping field to the west of the village of Warmingham, and their locations relative to the solid geology of central and south Cheshire (adapted from Rochester M — Salt Museum, Northwich — and using Ordnance Survey data: Crown copyright Ordnance Survey. An EDINA Digimap/JISC supplied service).

Fig. 2. Image of oak RC03 located at the edge of a subsidence-induced lake (a flash), image taken in July 2004. Note subsidence scar forming the shoreline.

the British Salt works at Cledford (5.5 km N of Elton). Brine from Elton was last used in 1977, although there was a period of reduced pumping from 1974–1975 to 1977, as brine from the new controlled pumping field came up to strength (G.D. Twigg, retired Industrial Chemist, personal communication, 2005).

3. Subsidence and water table variations

Subsidence is thought to be a natural, gradual process in the Sandbach area, but the effects of accelerated human-related subsidence were first noticed in the 1890s, probably caused by pumping of brine at the Wheelock Salt and Chemical Works 2.5 km to the E of Elton (Wallwork, 1960). A further acceleration in surface subsidence at Elton was noted from the 1920s (G.D. Twigg, personal communication, 2007) in the area surrounding the Crewe to Manchester railway, as underground cavities were enlarged and subsequently collapsed or subsided after brine removal.

As elsewhere in the Cheshire Saltfield, brine pumping has resulted in a range of subsidence-related geomorphological features (erosion scars, depressions, and lakes known locally as “flashes” that developed in the late twentieth century (Fig. 2)) and also in damage to the built environment. Accelerated pumping between 1969 and 1974 (Fig. 3) coincides with the period of and the most rapid subsidence (11 cm per annum between 1950 and 1975) documented at Elton by Wardell and Partners (no date) (Fig. 4).

After 1977, a controlled pumping field (filling of underground cavities of a predetermined size using water and waste material — technique first employed at Holford, Cheshire in 1934) was developed in a new area near the village of Warmingham, N of Sandbach (Fig. 1). To date, no subsidence has been noted in this area; but despite the cessation of brine pumping in the Elton area, problems related to subsidence and the older brine pumping techniques persist to the present day.

3.1. Brine pumping

The scale of brine pumping at Elton and in the Cheshire region as a whole is illustrated by the data in Fig. 3 spanning the years A.D. 1953–1974. Brine pumping at Elton caused a significant depression of the water table, sometimes referred to locally as the brine level. Generally, the salt bearing strata underlie circa 30–50 m of glacial till and associated deposits. At Elton, more detailed data are available from the 1960s during the period of accelerated brine pumping. British Salt records (T. Cowles, British Salt, personal communication, 2005) show that the “top [salt] bed” ranged from 12.6 to 31.9 m below mean sea level, whilst the “bottom bed” ranged from −47.2 to −54.9 m. Where the top salt bed was −31.9 m, the brine level was at −24.2 m.

In a brine pumping test in October 1944, two adjacent pumps at the Brooks Lane shaft near Middlewich, 7 km to the NW of Elton, working at a rate of $155-159\times10^3$ l/h, caused the brine level to fall by 11.6 m (Murgatroyd’s Salt and Chemical Company Ltd, unpublished data, G.D Twigg, personal communication, 2005).

Following the cessation of brine pumping at Brooks Lane (Middlewich), the brine level rose from 22 to 14 m below ground surface between 14 April 1977 and 13 September 1977 (G.D Twigg, personal communication, 2005) and there are reports that the water table in the Elton area rose by as much as 18 m after 1977 (A. Savage, formerly Crewe and Alsager College, personal communication, 2005).

4. Material and methods

Sampling sites at Elton were chosen in 2001 (Newcombe, 2002) (also in 2004) adjacent to and at varying distances away from the area known to have experienced the most significant subsidence. A road bridge located in this area was closed due to the subsidence, leading to the re-routing of the road and construction of a new railway bridge (Fig. 5). Trees sampled were located in areas to the east and west of the railway line running between Crewe and Manchester (Fig. 5).

Sample trees were growing along field boundaries, within hedgerows, or in isolated locations within fields under pasture. Increment cores were removed from 22 oak trees (*Q. robur*) and four ash trees (*Fraxinus excelsior*) using a 5-mm diameter Pressler-type borer. Trees were chosen to provide useful samples for dendrochronology, and also to be old enough to span/pre-date, where possible, the start of concentrated solution mining at Elton

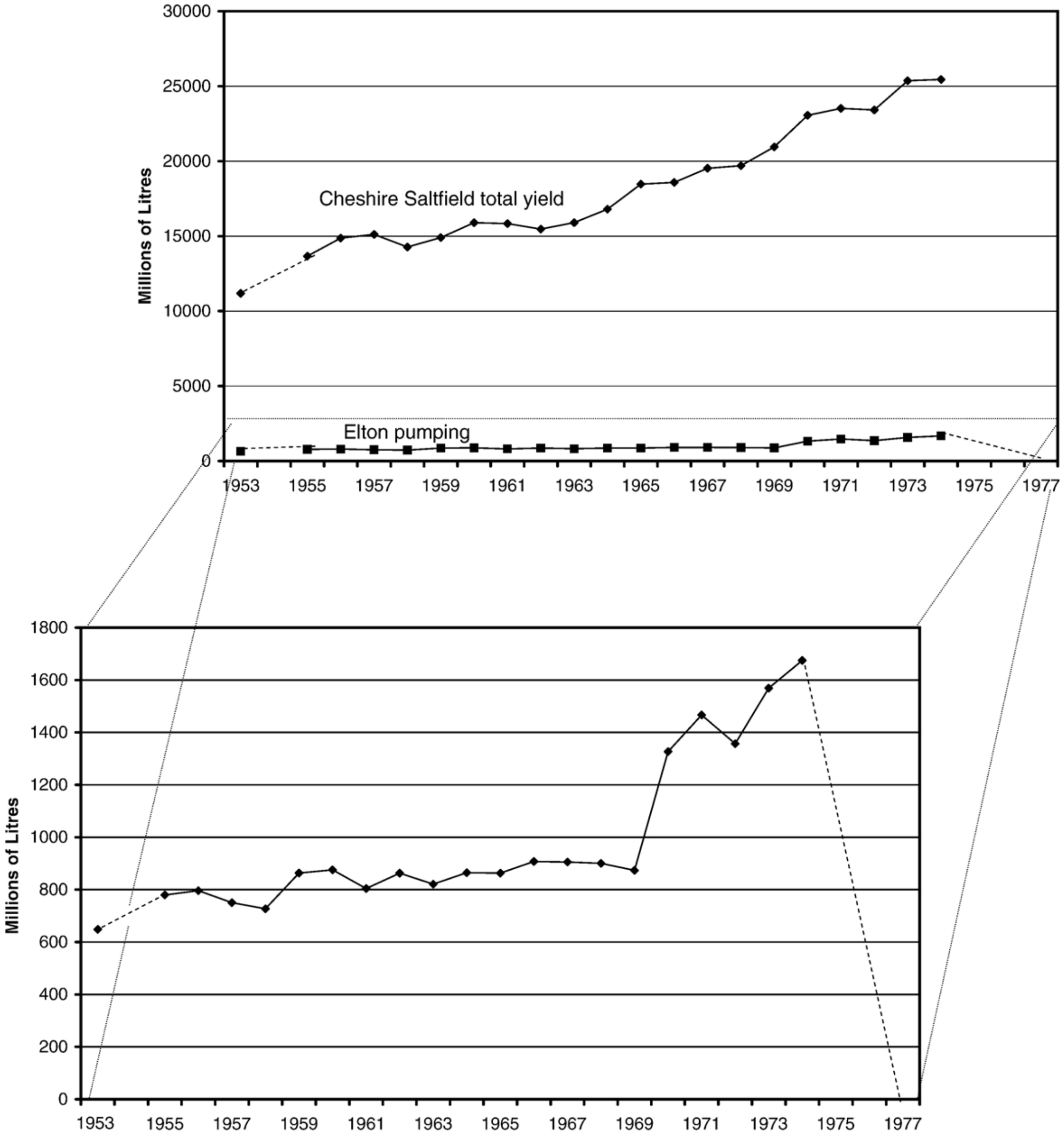

Fig. 3. Records of brine pumped between AD 1953 and 1977 from the Cheshire Saltfield (including Elton) and specifically the Elton area (Data courtesy of G.D. Twigg). Detailed pumping records were kept for the first time by all sites in Cheshire following the 1952 Brine Subsidence Act legislation.

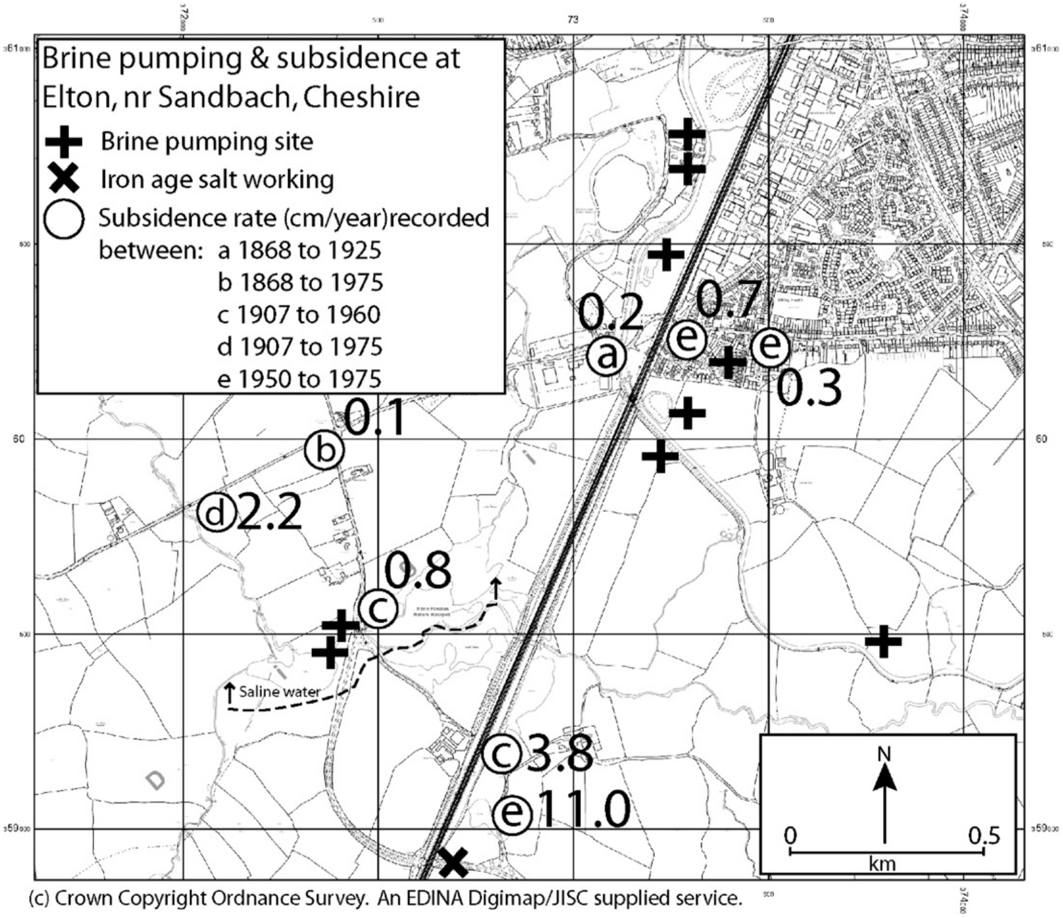

Fig. 4. Brine pumping sites at Elton and associated subsidence records from 1868–1975. Based on an annotated map (Ordnance Survey 1:2500 Cheshire Sheet XLIX.12 for 1909) courtesy of British Salt; subsidence data from Wardell and Partners (no date) and on Ordnance Survey data: Crown copyright Ordnance Survey. An EDINA Digimap/JISC supplied service.

in the 1920s and also the period of accelerated brine production in the mid to late twentieth century.

A further 18 oak trees were sampled at Crewe Green, 4 km S of Elton. Crewe Green was chosen as a control site, as it is located near to the main study area, but outside the Cheshire Saltfield. These trees were growing under similar climatic/environmental conditions to those at Elton (local atmospheric pollution from industry, such as the Crewe railway works may have influenced all trees sampled in this research), but had not been subjected to any salt-related subsidence.

Increment cores and sample disks were prepared using standard procedures (cf. Schweingruber, 1988), and ring widths were measured to 0.01-mm accuracy (cf. Lageard et al., 1999). Chronology building followed dendrochronological conventions (Schweingruber, 1988; Hillam, 1998) and used crossmatching programs based on Baillie and Pilcher (1973) and Munro (1984) (Tyers, 1999). *t* value correlations in excess of 4.5 were used as the basis for crossmatching.

Further analysis of the ring-width data involved use of the Crewe Green control chronology to make direct comparisons with the Elton chronology and with groups of trees from Elton which failed to crossmatch. As both oak and ash are noted in the British Isles for the consistency of their ring-width responses and their lack of missing or false rings (Pilcher et al. 1984; M.G.L. Baillie, Queens University Belfast, personal communication, 2007), data from unmatched Elton trees was averaged in four subgroups/chronologies (defined by groups of trees that exhibited a similar ring-width trend — section 5, Fig. 6)). The Elton chronology and each subgroup were plotted against the Crewe Green control, together with the ring-width difference between each pair of chronologies (Fig. 7A–E). Data from individual trees were also carefully examined.

5. Results

5.1. Ring width analyses

Mean ring-width measurements for 17 trees from the Crewe Green control site were combined after rigorous crossmatching (computer-assisted and verification using manual ring-width plots) to produce a 183-y tree ring-width chronology, Crewe Green, spanning the calendar years A.D. 1821 to 2003 (intra-site *t* value correlations ranged from 4.57 to 8.76). Trees sampled at Elton, however, exhibited less uniformity in their ring-width responses, and only 5 of the 26 ring-width patterns could easily be crossmatched forming the Elton chronology (A.D. 1802 to 2004; intra site *t* values: 5.24 to 8.5). Comparison of the Crewe Green control chronology and Elton site chronology revealed good statistical (*t* 7.75) and visual correlations (Fig. 7A).

Ring-width difference was used to identify periods when ring-width response differed from the local norm in areas unaffected by subsidence (Crewe Green control chronology). In the case of the Elton chronology, its five trees grew better than the control in an initial period from AD 1821, but there were a series of sustained checks on tree growth commencing in A.D 1861, 1886 and 1934 (Fig. 7A). Ring-width difference also identified a significant growth recovery between AD 1981 and 1985 after an initial growth release trend that commenced after 1975. There is also a marked downturn in the ring-width difference between the control and Elton chronology that commenced in 1998.

Tree ring series from Elton that failed to crossmatch were divided into four groups based on ring-width trends/patterns and species (Fig. 6). Elton A, Elton B and Elton C contained 10, 5 and 2 oak ring-width records respectively, and each group was averaged to

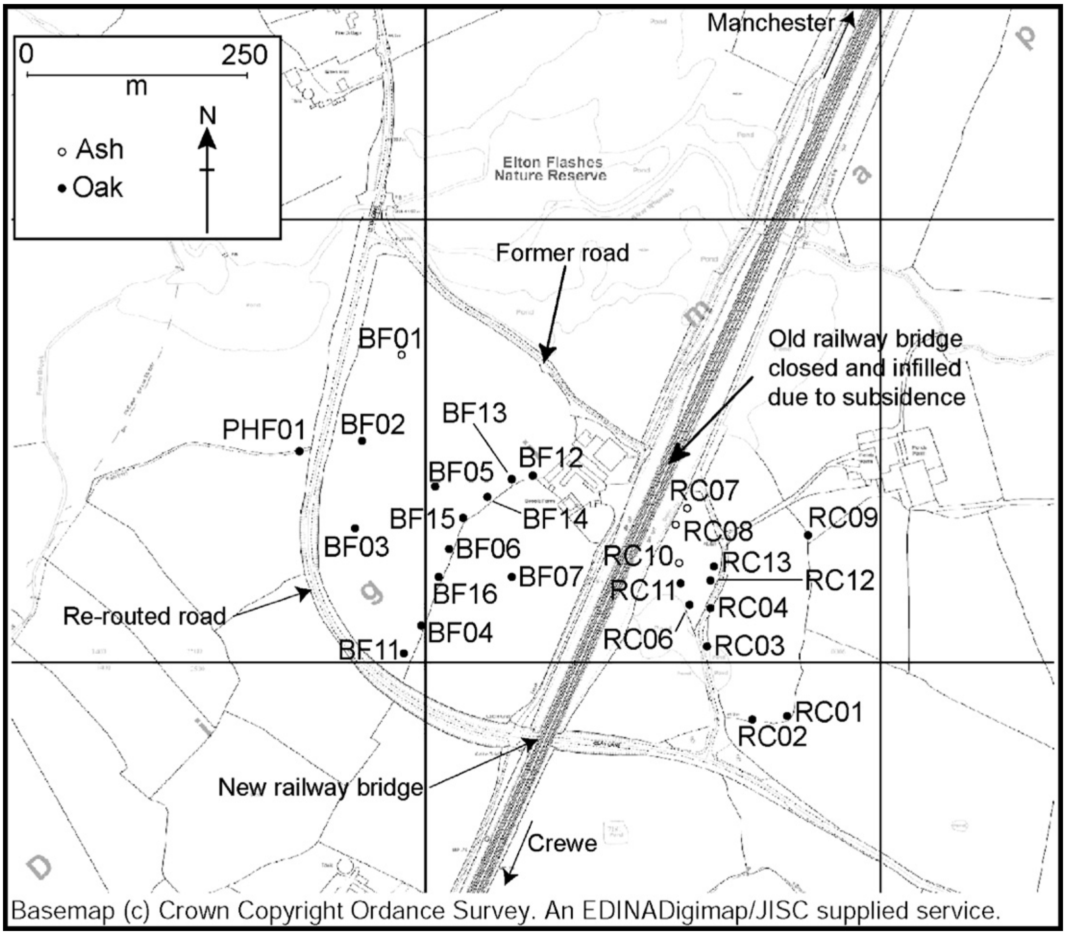

Fig. 5. Map of the Elton area showing the locations of trees sampled in this research and locations of key subsidence-related features in the built environment. Pumphouse Flash (PHF) and Brook Farm (BF) trees located to the west, and Railway Cottages (RC) trees to the east of the Crewe to Manchester railway (Map based on Ordnance Survey data: Crown copyright Ordnance Survey. An EDINA Digimap/JISC supplied service).

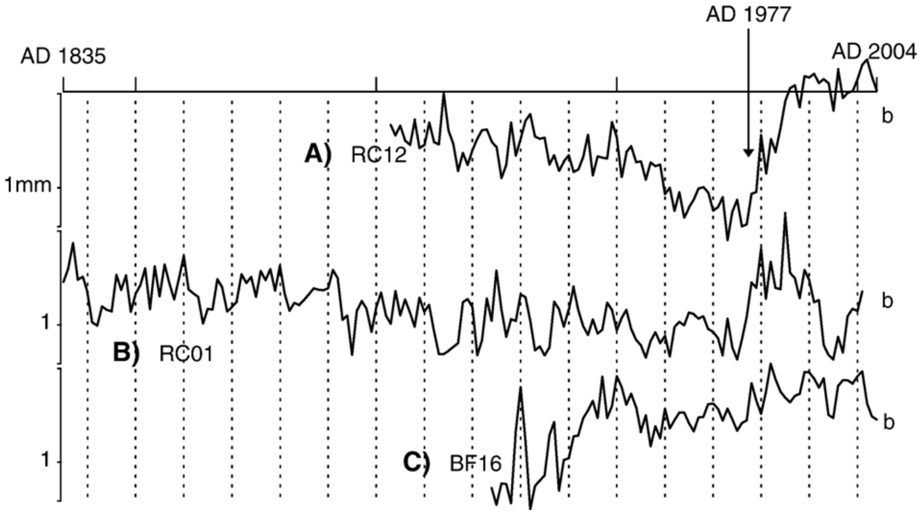

Fig. 6. Individual tree ring-width series selected to illustrate growth responses typical of chronologies Elton A — tree RC12: long-term declining ring-widths followed by sustained growth release (A); Elton B — tree RC01: long-term decline followed by episodic growth release (B) and Elton C — tree BF16: long-term trend of increasing ring-widths (C). b at the end of each ring-width curve denotes the presence of bark.

form separate site chronologies (Fig. 7B–D). Data from the four ash trees were combined using similar rationale to form Elton ASH (Fig. 7E). Subsequent crossmatching revealed that there was good agreement between the Elton chronology and both Elton A (*t* 6.52) and Elton C (*t* 8.22).

Comparison of the ring-width difference between Elton A and the control (Fig. 7B) reveals a pattern of tree growth similar to that noted in Fig. 7A, with growth reductions commencing in AD 1859, 1886 and 1934. This pattern is repeated in Elton B (growth reductions in A.D. 1859, 1886, 1934, 1986) (Fig. 7C). There is a trend in ring-width reductions up to 2004 in Elton and Elton B that indicate localised ground instability and hydrological modifications may still be occurring up to the present day.

Elton C (Fig. 7D) is the exception, with an upward trend in ring-widths since 1888. Elton C does however demonstrate growth reductions between 1898 and 1915 and the record of ring-width difference does mirror previous patterns of growth recovery post 1977. Ash ring-widths do not follow the patterns observed in the oak chronologies and cannot be related to the known records of solution mining (Fig. 7E).

Observation of the spatial distribution of trees in the Elton chronologies (Fig. 8) reveals that the five component trees of the Elton chronology describe an arc from RC01 in the SE to PHF01 in the W of the sampling area, all approximately 40 m a.s.l.. Further trees BF12, BF13, BF14, BF15, BF06, BF16, BF04 and BF11 follow a hedgerow boundary that rises up and leads away from the subsidence area in a SW direction. Elton C trees (BF16 and BF11) are located on a small hillock.

It is also interesting to note the sensitivities (high frequency variance cf. Kaennel and Schweingruber, 1995) of chronologies Elton, Elton A and Elton B. These are 0.18, 0.14 and 0.14 respectively, indicating a similar, reduced magnitude growth response of their component trees, when compared to Crewe Green (0.23). Elton C has a sensitivity of 0.22, indicating a much more dynamic response of these two particular trees, similar to trees from the control site.

Narrow ring series (defined here as six or more rings ≤1.5 mm), were also noted in each tree ring record from Elton (Fig. 9). Narrow ring series of seven trees end in 1976 or 1977, and 24 of the 26 Elton trees demonstrate growth release (five or more years with consecutive increases in ring widths) commencing between 1976 and 1978. Fourteen trees also demonstrate growth release between 1957 and 1962. Other significant growth release trends were observed in smaller numbers of trees commencing in or between: 1920–1924, 1934, 1937–1938, 1941–1944 1947, 1968, 1970–1973, and 1986.

6. Discussion

The Elton area of Cheshire has experienced significant subsidence since the 1950s related to brine extraction that amongst other impacts has led to the creation of lakes, or “flashes”, where previously there were fields. Today, trees with apparently normal growth forms, and some occasionally with forms that indicate sub-optimal growth conditions (Fig. 2), can be seen growing at Elton in areas adjacent to these water bodies.

At the outset of this research we hypothesised that downward displacement of the land surface from brine extraction would have resulted in tree growth suppression from waterlogging and insufficient uptake of oxygen by tree roots (cf. Yanosky, 1984; Astrade and Bégin, 1997; Bégin, 2000). Narrow tree rings formed in this way would be analogous to the narrow ring events and narrow ring series in subfossil oak described by Baillie (Baillie 1995, 1999, 2001) and Pilcher (1990), which are thought to be caused by increasing waterlogging of peat

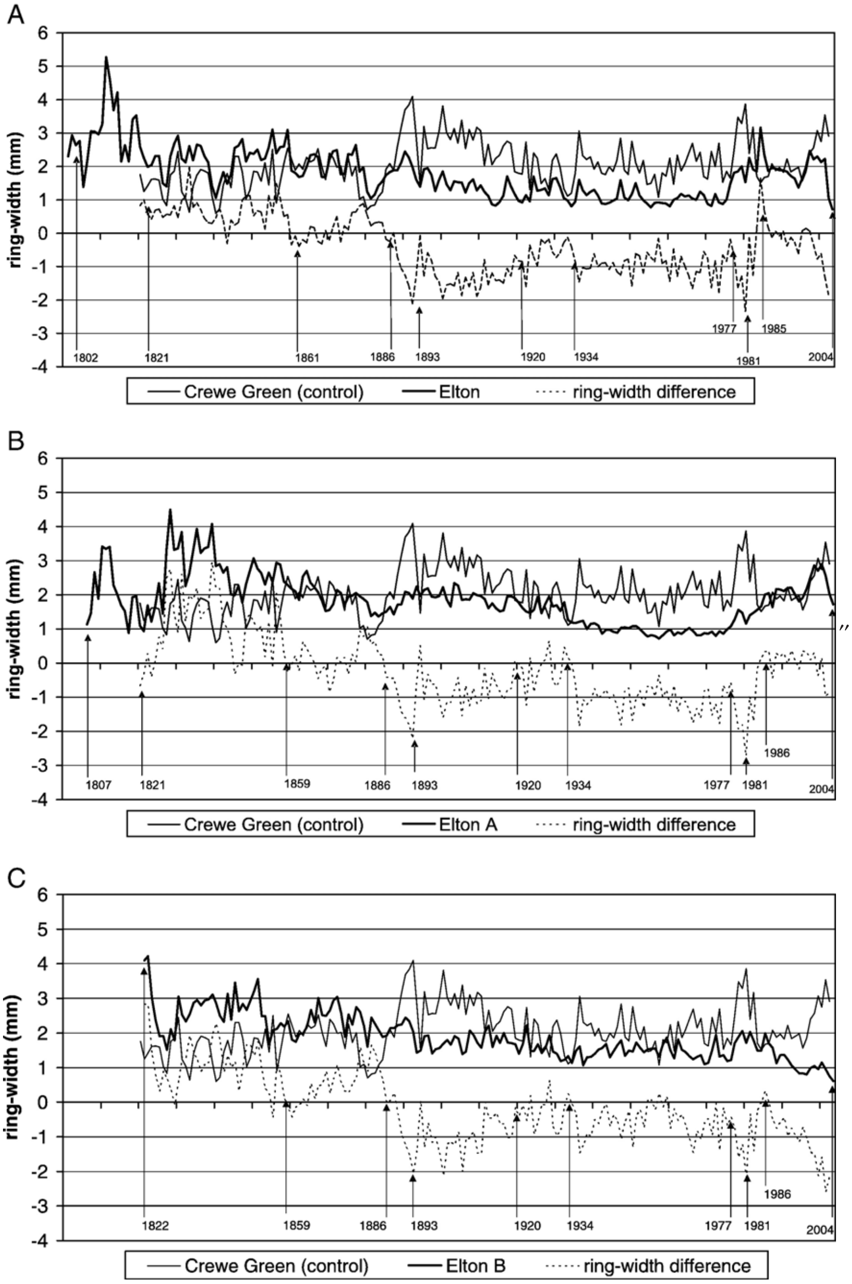

Fig. 7. Comparison of the Crewe Green control chronology and chronologies Elton (A), Elton A (B), Elton B (C), Elton C (D) and Elton ASH (E). Ring-width curves are shown by solid black lines and the ring-width difference between the two curves by the dotted line. Key calendar years are also indicated.

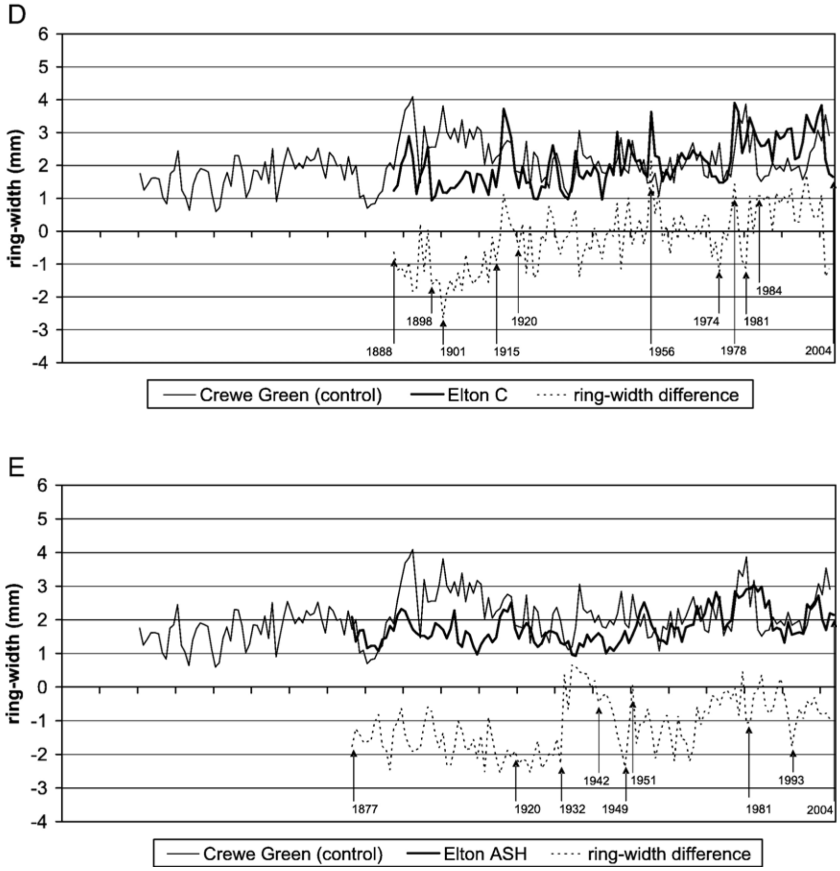

Fig. 7 (*continued*).

substrates brought on by climatic deterioration during the Holocene.

Boreholes used in water abstraction can however have a significant local draw down effect on the water table (Arnell, 2002). At Elton, brine production rose steadily from 650×10^6 l per annum in 1953 to 905×10^6 l in 1966, and this was followed by a period of accelerated pumping after 1969, with pumping reaching 1673×10^7 l in 1974 (Fig. 3). A concentration of nine boreholes at Elton (Fig. 4) would have had a significant areal impact on groundwater. This is exemplified by observations of water table recovery, by as much as 18 m following the end of pumping in 1977. It is therefore likely that soil moisture deficit rather than waterlogging suppressed the growth of trees sampled at Elton.

The appearance of subsidence-created flashes since the 1950s does at first sit a little uncomfortably alongside the assertion of an artificially-droughted landscape. Flashes occur where surface depressions are created from the collapse of underground cavities. These depressions form in glacial till deposits that blanket large areas of the Cheshire Plain (Worsley, 2001). Today, farmers frequently excavate fish ponds in these deposits without the requirement for any artificial lining, because of the high clay content of the soil. As pumping operations at Elton up to 1977 extracted brine from salt beds 12–55 m below the surface, the salt beds at Elton were largely independent of surface water and the groundwater at depth (and up to and including at least some of the tree root zone) could therefore be significantly depleted, whilst subsidence-related hollows on the surface filled with surface drainage waters. This is analogous to water within and on the surface of a bath sponge.

Reduced pumping from 1974 and its cessation in 1977 clearly had a significant effect on many trees in the form of sustained growth release (Figs. 7A, B and 9), but this response is complicated by a growth release of greater magnitude in trees forming the control chronology, Crewe Green. 1976 is a significant pointer year in many tree-ring records throughout Europe due to widespread "natural" drought conditions (Rolland et al., 2000; Ponton et al., 2001; Lebourgeois et al., 2005; Eilmann et al., 2006). Drought in 1976 must have put

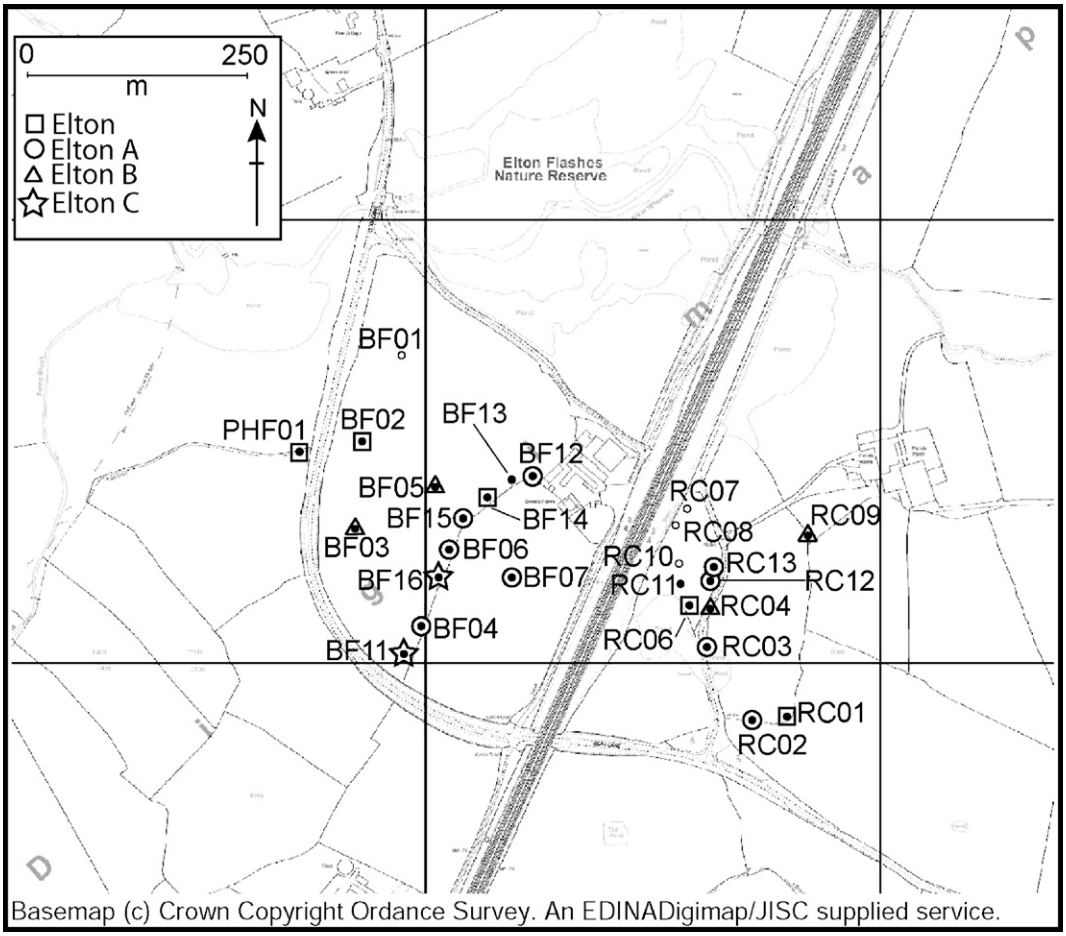

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Fig. 8. Location of trees comprising chronologies Elton, Elton A, Elton B and Elton C.

additional pressure on trees already stressed by the artificial drought imposed in the Elton area. This additional stress may account for unusually dramatic subsequent ring-width responses of Elton trees such as RC12 (Fig. 6A).

1976 may have been important for tree growth regionally, but for the Elton trees, stressed over a period exceeding 100 y, their overall response to elevating watertables after 1977 was lagged. This effect can be clearly seen when ring-width difference is plotted for comparisons between the Elton, Elton A and Elton B chronologies (Fig. 7A–C). For the Elton chronology the greatest difference between it and the control chronology is recorded in 1981, with a steep and stepped recovery between 1981 and 1985. This pattern is replicated precisely in Elton A and Elton B.

Tree-ring data (ring-width difference and narrow ring series) from Elton correlate well with data from the salt industry that records the end of solution mining in the immediate area. Further back in time three salt works were opened in the Elton area between circa 1910 and 1923 (Section 2) and the ring-width difference data clearly show significant and sustained growth suppressions between 1934 and 1981. The delay in growth suppression between 1923 and 1934 represents another lag effect, occurring as watertable draw down took place. The initial sudden growth declines in 1861, 1886 and 1934 indicate that some hydrological threshold may have been reached by previous/cumulative pumping activities.

Ring-width difference also indicates however that the Elton area had previously encountered the effects of brine pumping activities, from which the landscape was still probably recovering. Earlier growth suppressions occurred between 1886 and 1934 (subsidence in the Sandbach area noted in the 1890s (Wallwork, 1960)), and also between 1861 and 1876 (Fig. 7A–C). These data may well document responses to brine pumping

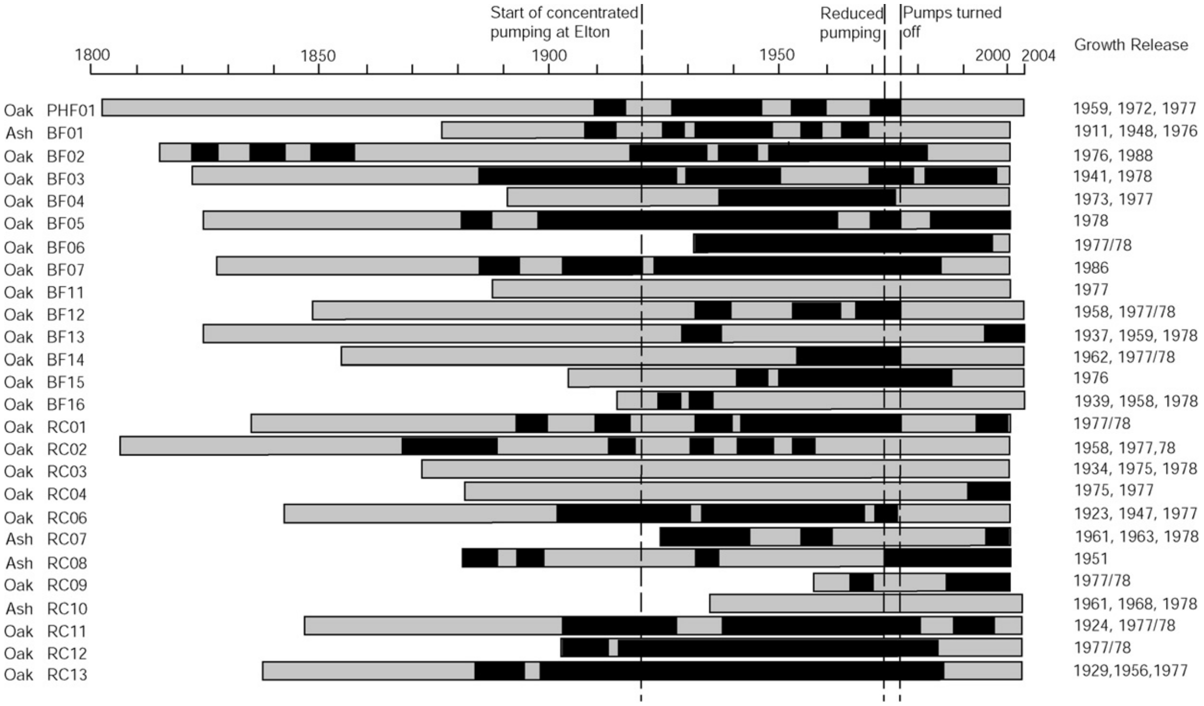

Fig. 9. Narrow ring series (six or more rings ≤ 1.5 mm) and the start years for periods of sustained growth release in ring-width records from oak and ash trees sampled at Elton. All dates are in calendar years A.D.

from other salt works up to 5 km from Elton. The river Wheelock flows into Elton from the east and a series of older salt works along its course can be implicated here, most notably the Wheelock Iron and Salt Co (1860–1888), Wheelock "Old" Works (c. 1851–1911) and the Canalside Works (c. 1775–1940s) (Twigg, 1994).

Data presented in this study suggest that an artificial and locally widespread lowering of the water table imposed drought conditions on trees within an area of at least 0.26 km^2 at Elton (Fig. 5) up to 2 km from the most distant borehole (Fig. 4). These data can also be used to speculate on the location of specific underground features associated with solution mining. The locations of the five trees that crossmatched to form the Elton chronology describe an arc of similar height a.s.l. (Fig. 8), indicating that these trees may be located close to, and also be responding to a "brine run" (an underground channel that develops due to brine pumping). The anomalous responses of only two of the Elton trees (BF06, BF11) can be explained by their more elevated location in relation to the area of known subsidence.

The lack of initial crossmatching amongst the Elton tree-ring records suggested that variations in local substrates and in their hydrological properties were important controls on tree growth, masking any coordinated tree-ring responses to solution mining. Analysis of unmatched trees has however demonstrated that at this location all oak tree-ring records do have annual resolution, and when combined can be used to reflect more widespread hydrological variation. This implies that artificial water-table draw down in areas where glacial tills predominate can be a relatively uniform process.

7. Conclusion

Comparison of dendrochronological records and historic data has shown that solution mining in the Elton area had a considerable spatial impact on groundwater up to at least 2 km, and possibly as far as 5 km, from boreholes/pumping sites. The onset of artificial drought conditions was probably a gradual process, and therefore the start of pumping activities did not have an immediate effect on tree growth. A lag effect is also noticeable following the end of pumping in 1977, as ring-width difference between the control chronology and the Elton trees shows a dramatic, stepped recovery between 1981 and 1985.

This research demonstrates for the first time that ring-width records from oak (*Q. robur*) can be used to demonstrate water table variability and also the areal impact of solution mining in areas where salt-bearing strata are overlain by till deposits.

Acknowledgments

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