Hydrogeology of Saltersley Moss Peat Extraction Area

Transition Wilmslow

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1.0 Introduction

1.1 Background

1.1.1 Enzygo Ltd was commissioned by Transition Wilmslow to review the hydrogeology of Lindow Moss, focused on the peat extraction area on Saltersley Moss (Wilmslow Peat Farm) and its adjacent unworked areas. The peat extraction area is now worked out and is to be restored by stopping up the artificial drainage network to control the discharge of water and enable peat formation to begin again.

1.2 Scope

1.2.1 This report describes the baseline environment of the site (geology, hydrology, hydrogeology) and then specifically assesses:

- The magnitude and extent of lowering of the water table in the peat; and estimate of net loss of water from the peat aquifer by volume.
- The consequences of desiccation of the peat on shrinkage and oxidation, including carbon dioxide lost to the atmosphere.
- The effect of continuing inaction on the long-term prospects for ecological restoration.
- The potential benefits and practicality of mitigation measures to control the discharge of water, and the likely timeframe for the recovery of the peat aquifer once the discharge is controlled.

1.3 Documents Reviewed

Document	Authors	Date	Reference
Review of old mineral permissions Revised submission (second revision)	Terraqueous Ltd for Messrs A.P. Rowland & R.L. Bond	November 1999	Application 5/97/07581 Cheshire County Council This report **Appendix 5**
Planning Decision Notice Application No 5/97/0758P	Cheshire County Council	31 March 2003	This report **Appendix 6**
Revised settling pond and sluice scheme	Terraqueous Ltd for Croghan Peat Industries Ltd	July 2007	Application 5/97/0758P Cheshire East Council
Results of a Ground Investigation at Newgate kennels Ltd, Newgate Wilmslow	Subsoil Surveys Ltd Manchester	2012	Report no 2012/001-001-FAC-REV0
Response by Transition Wilmslow to Cheshire East Council on Planning Application 15/0064M for variation of planning conditions and restoration of Lindow Moss peat extraction site	Transition Wilmslow	Feb 2015	Application 15/0064M Cheshire East Council
Lindow Moss:	Hafren Water	8th February 2016	Project Ref 2081 This report **Appendix 1**

Supplementary information relating to the planning application for residential development			
Technical review of Hafren Water 8 Feb 2016 response to Environment Agency feedback on groundwater investigation reporting supporting a house application (briefing note)	Ecus Ltd for Newgate Kennels Ltd	2016	Project briefing note: Hafren Water review by ECUS This report **Appendix 1**
Causal link and critical review of Peat extraction from Lindow Moss and the issues of subsidence at Newgate Kennels	Ecus Ltd for Newgate Kennels Ltd	2016	Project briefing note: Causal Link Review This report **Appendix 4**
Restoration Scheme Version 4 to Accompany a Section 73 Application 15/0064M to Cheshire East Council	Terraqueous Ltd for Messrs A.P. Rowland & R.L. Bond	August 2018	This report **Appendix 7**
Newgate Kennels, Lindow Moss Peat Extraction Area & Adjacent Property: Hydrogeological Assessment	Enzygo Ltd for Newgate Kennels Ltd Report No SHF.1633.001	July 2019	Information and photographs from the report is used in this report with kind permission of Newgate Kennels Ltd
The Potential of Peat: An investigation into the influence of a peat dam on carbon stocks at Saltersley Moss, Cheshire.	Durham University BSc. Geography Dissertation 2019 Z0969739	July 2019	

2.0 Baseline Soils, Geology, Hydrology and Hydrogeology of Saltersley Moss

2.1 Location

2.1.1 Lindow Moss is 4.4km^2 of north east Cheshire dominated by peat soils developed in two large hollows within varied superficial glacial deposits (Till, sands, and gravels)[1]. The superficial peat deposit extents on the online BGS geological map (extract in Figure 1) delimit the Moss.

2.1.2 Peat is a partly- decomposed mass of semi-carbonized vegetation which has accumulated under waterlogged, anaerobic conditions.

2.1.3 The area north of Newgate as far north as Mobberley Road was extensively worked for its peat, sands, and gravels during the 20th Century (a disused small gravel pit is shown on the 6-inch Ordnance Survey map of 1897) and the workings were part-restored by landfilling and by allowing the workings to flood forming Rossmere, a lake used for fishing (shown on Figure 1 and shown/named on Figure 2). The approximate centre of Rossmere is located at national grid reference (NGR) 382060,381121. The area of peat south of Newgate extends south to Moor Lane, east almost to Lindow Common and thins to the west to Mobberley golf course (Figure 1) with its limit at NGR 380974,380700.

2.1.4 This report focuses on Saltersley Moss ('the Site') the 0.33 km^2 (33ha) of Lindow Moss south of Newgate and in/around Rotherwood Road with its centre at NGR 382360,380798 where peat extraction has occurred (the Wilmslow Peat Farm) and was unrestored at the time of this report (Figure 2).

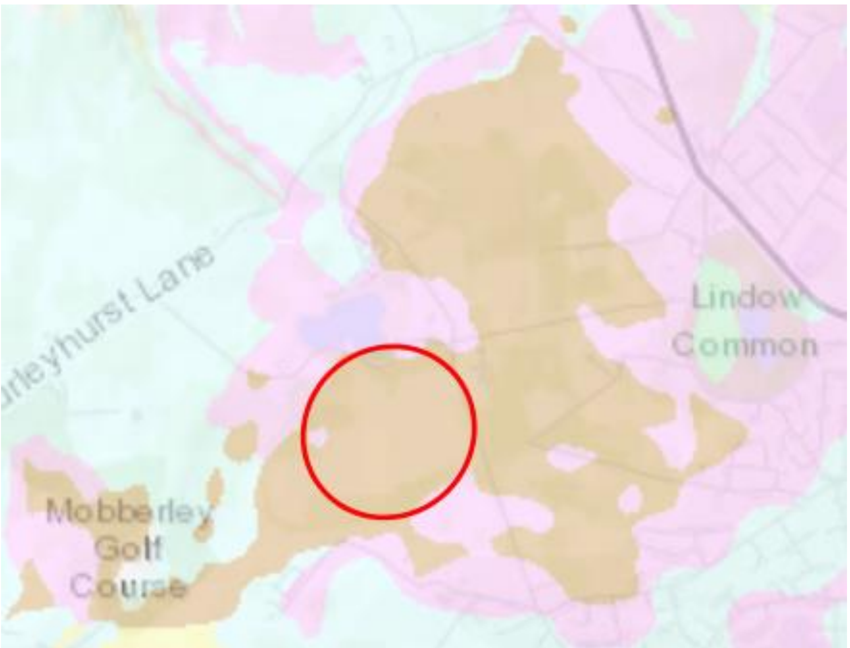


Figure 1 Peat Extent, Lindow Moss with sub area of Saltersley Moss marked *Image © BGS 2020*

[1] Leah M D, Wells C E Appleby C and Huckerby E 1997 *The Wetlands of Cheshire.* North West Wetlands Survey 4, Lancaster Imprints

Figure 2 Wilmslow Peat Farm, Saltersley Moss in 2005 *Image © 2020 Infoterra Ltd & Bluesky*

2.2 Soils

2.2.1 The natural soils of the district including the peat extraction area cover 1.9 km^2 and are described as peaty, naturally wet fen peat soils supporting wet fen and carr woodland habitats[2]. Much of the soils have been removed from the peat extraction area but remain below undeveloped land elsewhere, for example the block of woodland east of Rotherwood Road and the kennels and cattery property to its north owned by Newgate Kennels Ltd.

2.3 Bedrock Geology

2.3.1 The bedrock is Triassic-aged Mercia Mudstone Group Bollin Mudstone Member. This is locally extensive but does not crop out anywhere in the vicinity and on BGS borehole record evidence (British Geological Survey (BGS) Reference SJ88SW3, extract of log included in Appendix 2) is over 34m below the north east corner of the Site.

2.3.2 A north-south regional bedrock fault passes to the east of the Site (Figure 3).

[2] 'Soilscapes 27' - NSRI Soilscapes viewer July 2020

2.4 Superficial Geology

From Geological mapping

2.4.1 The superficial geology is mapped as Holocene to Recent lowland organic peat deposits. These appear to be underlain and bounded by Quaternary-aged glaciofluvial mineral deposits (Figure 3).

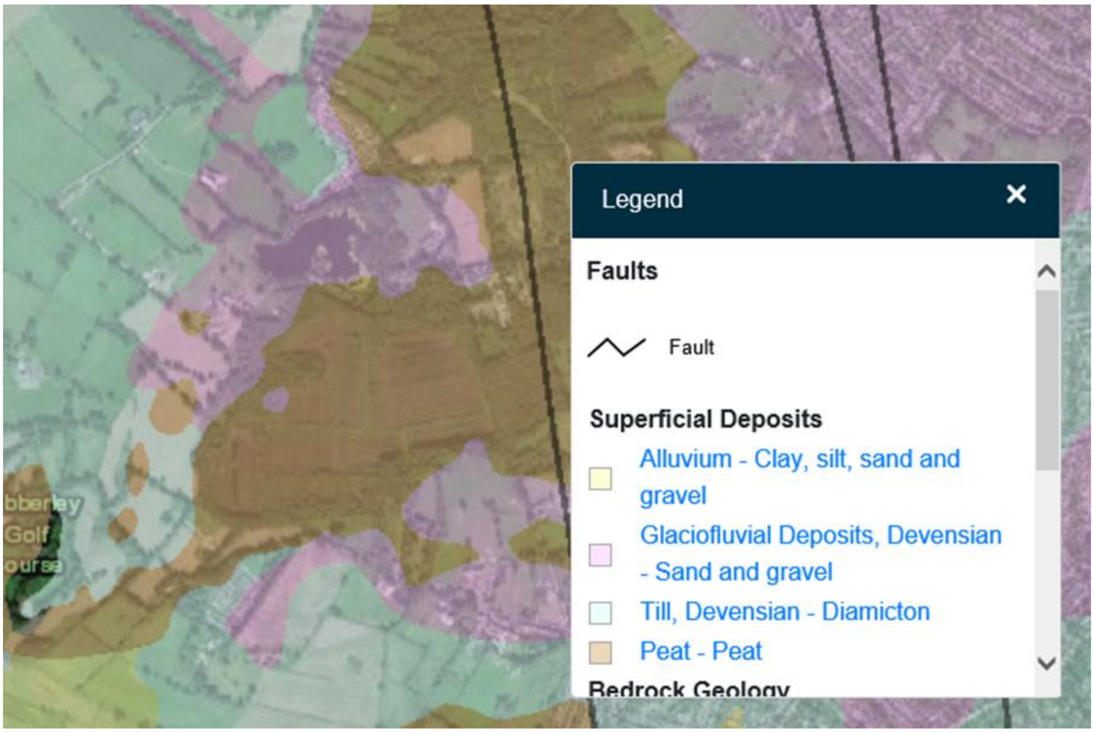


Figure 3 Superficial deposits and bedrock faults *Contains British Geological Survey materials © NERC [2020]*

From Site Investigations

2.4.2 Figure 4 summarises the locations and results of various intrusive investigations and site observations of the superficial deposits.

2.4.3 Peat was recorded as present during the drilling and construction of groundwater monitoring wells (P01/07, P02/07, P03/07, P04/07, P05/07, P06/07, and P07/07) around the peat workings (locations in Figure 8) in April 2007 (See Table 2, and Appendix 2 spreadsheet data in Appendix 1 Hafren Water Report). However, there are no published borehole records.

2.4.4 Much of the top layer of peat was removed from the footprint of the peat extraction area. In the north-east corner the drainage ditches installed to lower the peat water table and enable peat extraction breached sands directly below the peat, visible along the eastern boundary with Rotherwood Road (Figure 5).

2.4.5 Recorded mineral deposits directly below the peat of the peat extraction area vary from clays and silty clays to sands. Sand was recorded directly below the peat in the north and south of the site but as the focus of the investigation was on the peat deposits[3], the coring stopped on reaching mineral at the base of the peat, or when the ground became too stiff to penetrate

[3] Leah M D, Wells C E Appleby C and Huckerby E 1997 *The Wetlands of Cheshire.* North West Wetlands Survey 4, Lancaster Imprints

with the corer. Consequently, there is no direct proof of sand below much of the south west of the peat excavation area although it is likely to be present.

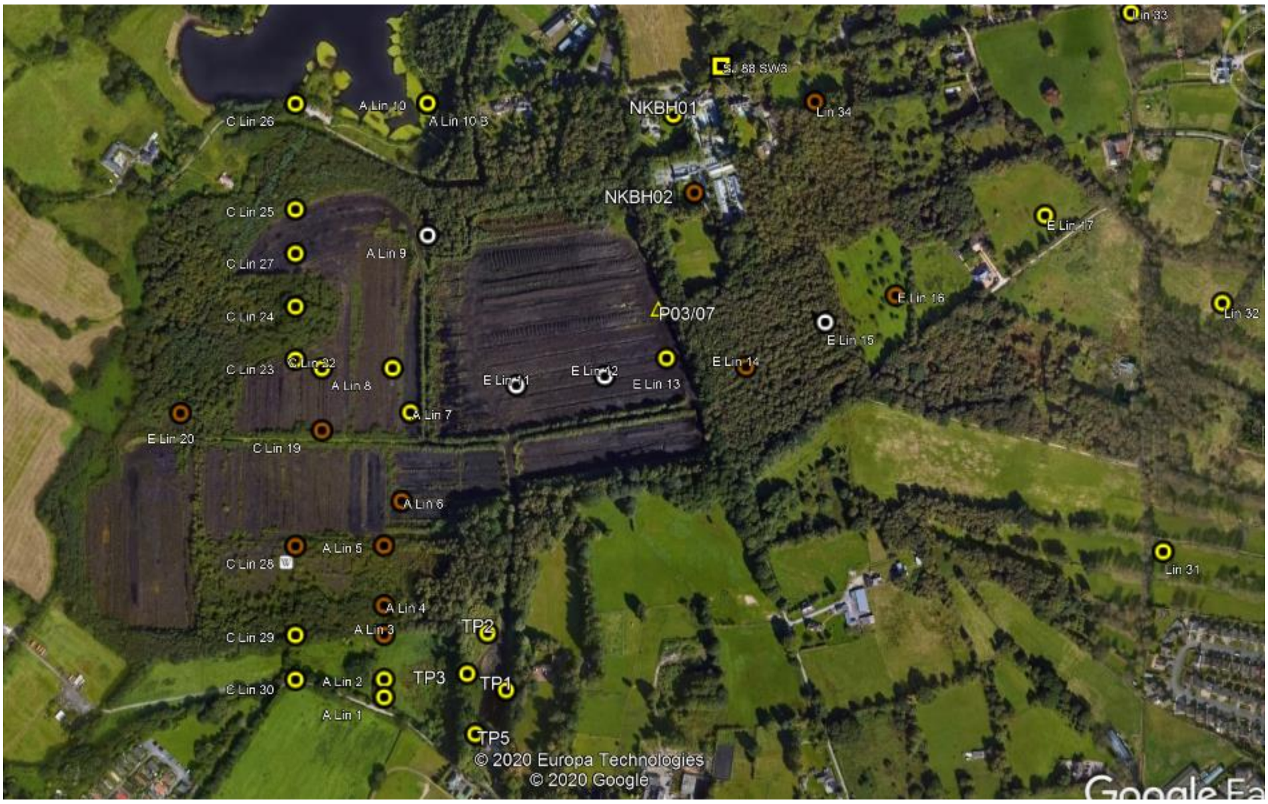


Figure 4 Proven superficial mineral geology compiled from intrusive site investigations.

Yellow icons – sand, Brown circle - silty clays. White circle - not recorded

Figure 5 Exposed and eroding sand deposits below peat in the north east corner of peat extraction area (photo taken January 2015 reproduced from report No SHF.1633.001 with permission of Newgate Kennels Ltd)

2.4.6 A 2016 report by Hafren Water consultants for a proposed housing development on the former peat preparation and storage area to the south of the excavation area (Appendix 1) stated that the bounding western and eastern ditches are excavated in sand from their examination of photographs and logs from nearby trial pits (TP1, TP2, TP3, and TP5 on Figure 4).

2.4.7 Consequently, the thickness and base of the sand across most of the site is not known. The only deep borehole in the vicinity (British Geological Survey (BGS) Reference SJ88SW3 marked on Figure 4) proved 12 m of sand. An extract of the borehole log is included in Appendix 2 and shows 8 feet (2.44m) of made ground underlain by 12 feet (3.66m) of peat underlain in turn by 40 feet (12.19m) of fine-grained 'running' sand, slightly argillaceous (clayey) in the bottom 8m. The sands are followed by 51 feet (15.54m) of boulder clay (glacial till) and 12.5 feet (3.81 m of sands/gravelly sands and clays over mudstone bedrock at 113.6 feet (34.6m below ground level (mbgl)).

2.4.8 Two site investigation boreholes constructed as part of a ground investigation in the Newgate Kennels Ltd Site in 2012 are marked as NKBH01 and NKBH02 on Figure 4. NKBH01 encountered 0.2m of topsoil over 1.6m of Clay with subordinate sand and gravel over 10.05 m of mostly fine to medium grained sand which was described as very loose to loose between 5.95m and 10.05 m depth.

2.4.9 Borehole NKBH02 encountered topsoil/peat to a depth of 6.6m over 0.3m of clay.

Summary

2.4.10 The peat of the site is likely to be underlain by several meters of permeable sand. However, other than off-site borehole SJ88SW3 there is no information on sand thickness and extent below the peat extraction area in any previous site investigation.

2.5 Hydrology

Rainfall

2.5.1 The Standard Average Annual Rainfall (SAAR) for the site is 826mm (Appendix 10).

Runoff

2.5.2 The peat extraction area (Figure 6) is drained by a network of man-made ditches that discharge by uncontrolled gravity drainage into Sugar Brook, a tributary of the River Bollin located approximately 2.5 km northeast of the site. Sugar Brook is a main watercourse below Moss Lane (the responsibility of the Environment Agency) and a minor watercourse upstream of Moss Lane and at the peat workings (and so the responsibility of riparian owners and/ or Cheshire East Council as Lead Local Flood Authority (LLFA)).

2.5.3 It is important to estimate the 'greenfield' runoff from the former undeveloped site, as changes or modifications to the site will either increase the runoff (installation of a drainage network) or decrease it (selective lowering of parts of the site by peat extraction thereby creating 'reservoirs' for storage of rainfall). The runoff will also change over time as the former peat workings are restored by stopping up the internal drainage network. Changes in runoff rates and volumes will also impact on Sugar Brook by changes in the watercourse morphology (erosion causing channel bed and or bank changes) or reduced flows causing channel aggradation.

2.5.4 Runoff from the site is not measured and there are no historic flow records in the public domain.

Runoff Estimate, Peat Extraction area

2.5.5 The HOST class for "Undrained lowland peat soils waterlogged by groundwater" is 12, producing a standard percentage runoff (SPR) of 0.6 (60% of rain falling on the Site will occur as runoff to the receiving watercourse).

2.5.6 Using the Wallingford greenfield runoff rate estimation tool (results in Appendix 10) the estimated mean annual greenfield peak flow from the 33ha site is:

- Qbar 269.76 l/s

Greenfield runoff rates (excluding any allowance for climate change) are estimated as:

- 1 in 1-year 234.69 l/s
- 1 in 30-year 458.59 l/s
- 1 in 100-year 561.09 l/s

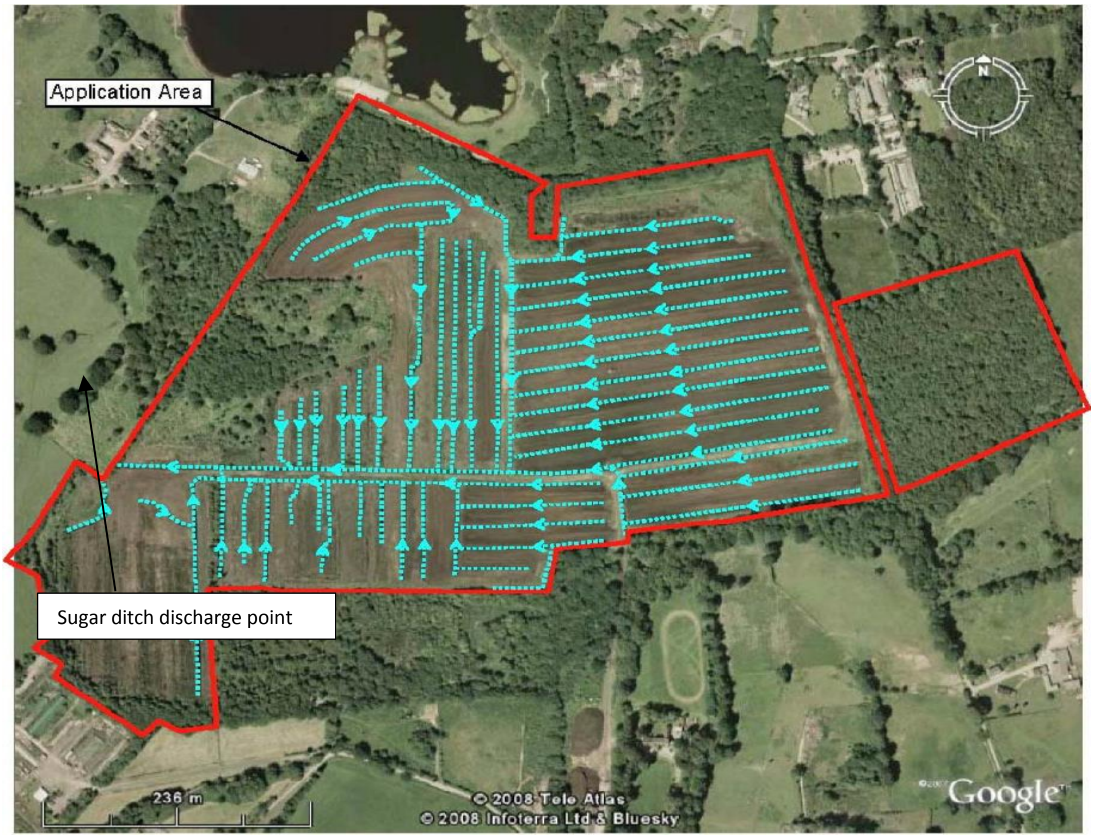


Figure 6 Drainage network of peat workings *(Modified ex Figure 4.1 Application 15/0064M)*

2.5.7 Part of the eastern end of the drainage system was stopped up during 2016 (Figure 7) using a peat 'plug' or dam with the aim of raising the water table in the peat to the east of it (Z0969739, 2019). The reason for doing this is not clear.

2.5.8 The dam is around 1m high and extends across the width of the drain thereby backing up water in the upstream drains to the east by up to 1m at the upstream side of the dam.

2.5.9 Several local drains in and around the peat extraction area appear to be unconnected with the drainage network of the peat workings. Rossmere Lake 500 m to the north of the application site (NGR SJ 820 811) is a flooded former sand and gravel quarry used as a fishing lake. It is not connected to any of the drainage ditches within the peat extraction area but may be hydraulically connected with sands and gravels.

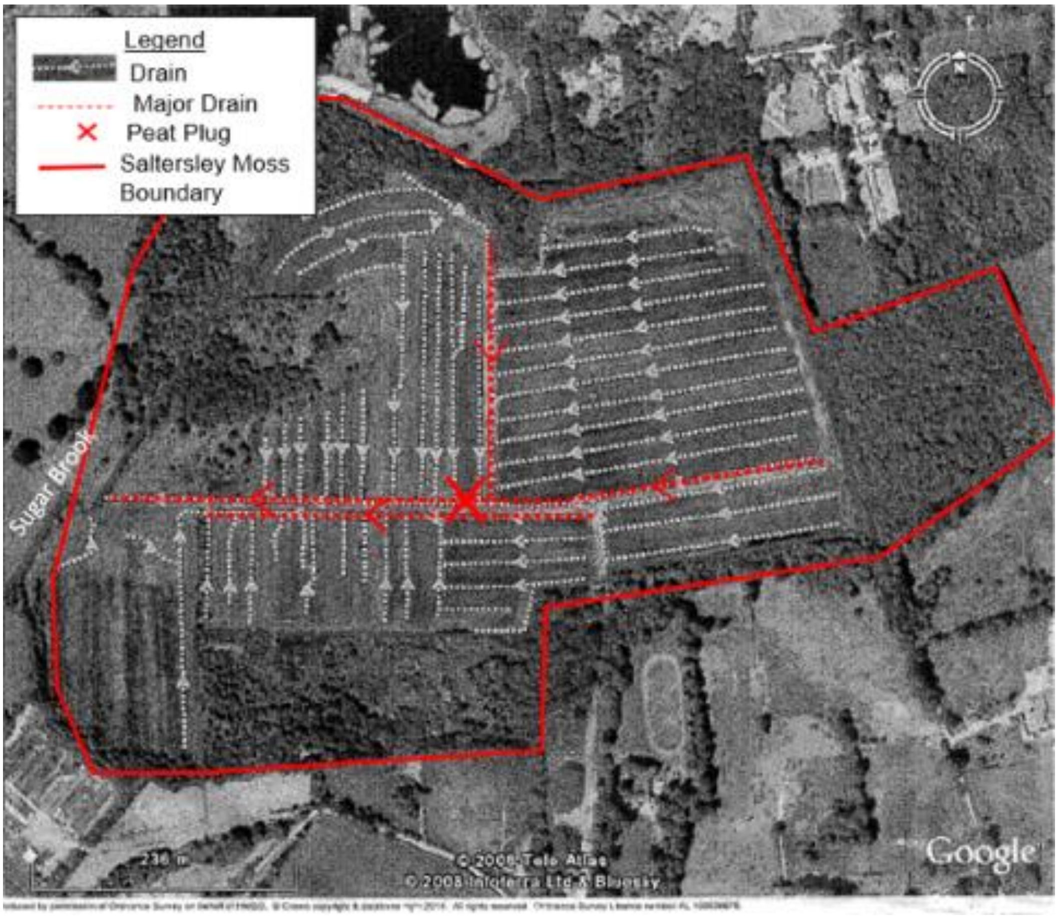


Figure 7 Location (**X**) of stopped up drainage ditch (University of Durham Z0969739, 2019)

2.6 Hydrogeology

2.6.1 Saltersley Moss is a raised bog where the peat was formed in deep hollows in the glacial till. The peat consists of an upper layer- the Acrotelm where the peat is low density and primarily aerobic and so where the peat is most subject to decay and loss, and the deeper Catotelm where the peat is saturated, is under anaerobic conditions, and has a higher density due to compression and compaction. So, the hydraulic conductivity generally decreases with depth.

2.6.2 The mean water content percentage of the peat as measured by Z0969739 (University of Durham 2019[4]) was 81%-86% with the top layer drier than deeper layers. There are no data on hydraulic conductivity for the peat. However, literature values (Table 1) are in the range 10^{-5} to 10^{-7} m/second (3.15-315 m/year) and so may vary by orders of magnitude.

[4] The Potential of Peat: An investigation into the influence of a peat dam on carbon stocks at Saltersley Moss, Cheshire. Z0939739 Undergraduate Dissertation University of Durham 2019

Table 1 Literature values on peat permeability (hydraulic conductivity) from Wong et al 2009

Table 1: Values of natural water content, w_0, initial coefficient of vertical permeability, k_{vo} and c_α/C_c for peat deposits (Mesri *et al.*, 1997)

Peat	w_0 (%)	k_{vo} (m sec^{-1})	c_α/C_c	References
Fibrous peat	850	4×10^{-6}	0.06-0.10	Hanrahan (1954)
Peat	520	-	0.061-0.078	Lewis (1956)
Amorphous and fibrous peat	500-1500	10^{-7}-10^{-6}	0.035-0.083	Lea and Brawner (1963)
Canadian muskeg	200-600	10^{-5}	0.09-0.10	Adams (1965)
Amorphous to fibrous peat	705	-	0.073-0.091	Keene and Zawodniak (1968)
Peat	400-750	10^{-6}	0.075-0.085	Weber (1969)
Fibrous peat	605-1290	10^{-6}-10^{-5}	0.052-0.072	Samson and La Rochelle (1972)
Fibrous peat	613-886	10^{-6}	0.06-0.085	Berry and Vickers (1975)
Amorphous to fibrous peat	600	10^{-6}	0.042-0.083	Dhowian and Edil (1980)
Fibrous peat	600-1590	5×10^{-7}-5×10^{-5}	0.06	Lefebvre *et al.* (1984)
Dutch peat	370	-	0.06	Den Hann (1994)
Fibrous peat	610-850	6×10^{-8}-10^{-7}	0.052	Mesri *et al.* (1997)

Groundwater levels and hydraulic gradients

2.6.3 Nine boreholes in and around the adjacent peat excavation were completed as groundwater monitoring wells (OLD A, P01/07, P02/07, P03/07, P04/07, P05/07, P06/07, P07/07, P08/07). Other than drilled depth, length of response zone and indicative geology as indicated in the Excel spreadsheet dataset presented in Appendix 2 of the Hafren Water report (included here as Appendix 1, provided in electronic format as part of this reporting but under separate cover, and summarised here in Table 2) there is no information on monitoring well construction. The well locations (except OLD A which is shown on the included drawing) are shown on Figure 8. Borehole P05/07 is not at the location shown but is directly north of it on the east-west trackway across the peat excavation at the location marked on the topographic survey (copy in Appendix 3).

2.6.4 Water level dip and converted level data obtained between 2007 and 2015 on behalf of the operator was included as a printout of an Excel spreadsheet in Appendix 2 of the 2016 Hafren Water report.

2.6.5 The water level in the wells (depth from wellhead to water) would usually be measured by or for the site operator using an electronic dip meter. Readings from each well were taken at approximately 3 to 4- week intervals from August 2007 to October 2015. The data was converted to groundwater elevation metres Above Ordnance Datum (mAOD) as evident in the version of the dataset presented in Appendix 2 of the 2016 Hafren Water report included here as Appendix 1). Data was also obtained by Cheshire East Council during 2016/2019 and by Newgate Kennels Ltd for Enzygo Ltd during 2018/19 and for a short period in 2020.

Data limitations

2.6.6 Enzygo noted some serious and ongoing problems with the monitoring well installations during a site visit in 2018.

- No borehole logs to confirm the superficial geology.
- Ground lowering at some of the monitoring wells has resulted in a lowering of the well head casing (cemented into the ground) relative to the inner well liner by up to 150mm, such that at some indeterminate point the datum point used by the person carrying out the monitoring would have to change from the top of the well casing to the top of the inner well liner. This is particularly apparent at boreholes 8 and 5 (See section 3 and Figure 12).
- No marked datum point on any monitoring well casing.
- Poor maintenance.

2.6.7 In July 2020 part of the site was levelled by the site operator and borehole P05/07 was destroyed (personal comment Mr J. Millett. Newgate Kennels October 2020).

2.6.8 As there are no published records of the monitoring notes that should be taken during site monitoring visits it has to be assumed that the dip data and resulting groundwater level data set in metres above Ordnance Datum (to enable direct comparison of water table elevations between boreholes and hence hydraulic gradients) is accurate.

2.6.9 As part of a previous study for Newgate Kennels Ltd, Enzygo compiled the available groundwater level data onto a new Excel spreadsheet (copy provided under separate cover with permission of Newgate Kennels Ltd). The data set of peat water table levels across the peat extraction area is summarised in Table 2, and relative mean (50%ile) groundwater levels across the area are shown on Figure 8. In general, the hydraulic gradient is from east to west. However, the gradient in the monitored peat upper layers varies locally because much of the peat is heavily dissected by artificial drainage channels intended to lower groundwater levels in the proximal peats. So, the main flux of local groundwater flow is into the drainage channels from where it is conveyed west out of the system into Sugar Brook.

Table 2 Monitoring well construction information and groundwater level data Saltersley Moss Peat Extraction Area

Construction information				Summary of groundwater elevation sample data				
Monitoring well (response zone geology)	**Well depth mbgl**	**Response zone depth mbgl**	**Well Casing Top mAOD**	**N readings**	**Min mAOD**	**Max mAOD**	**Range m**	**50%ile mAOD**
OLD A ?	?	?	72.66	522	70.19	71.66	1.47	70.89
P01/07 (in peat)	3	2-3	68.88	533	65.98	67.86	1.88	66.88
P02/07 (in peat)	3	1.4-2.45	70.46	533	68.37	70.09	1.72	69.34
P04/07 (in peat)	3	1.5-3	73.88	531	72.26	73.63	1.37	73.12
P05/07 (in peat)	3	2-3	72.00	532	69.16	71.00	1.84	69.82
P06/07 (in peat)	3	1.5-3	69.14	533	67.47	68.56	1.09	68.11
P07/07 (in peat)	3	2-3	71.98	532	69.69	71.33	1.64	70.91
No 8 (P08/07) ?	?	?	73.62	533	70.67	71. 80	1.13	71.30
P03/07 (in sand)	8	5-8	73.57	533	70.29	71.98	1.69	71.00
Site discharge point	**-**	**-**	**Stage board Top /Bed level**	**N readings**	**Min mAOD**	**Max mAOD**	**Range m**	**50%ile mAOD**
Sugar Brook	-	-	67.308/ 66.05 *	527	66.51	66.79	0.28	66.65
*as recorded in the topographic Survey 20/06/2013 (copy in Appendix 3)								

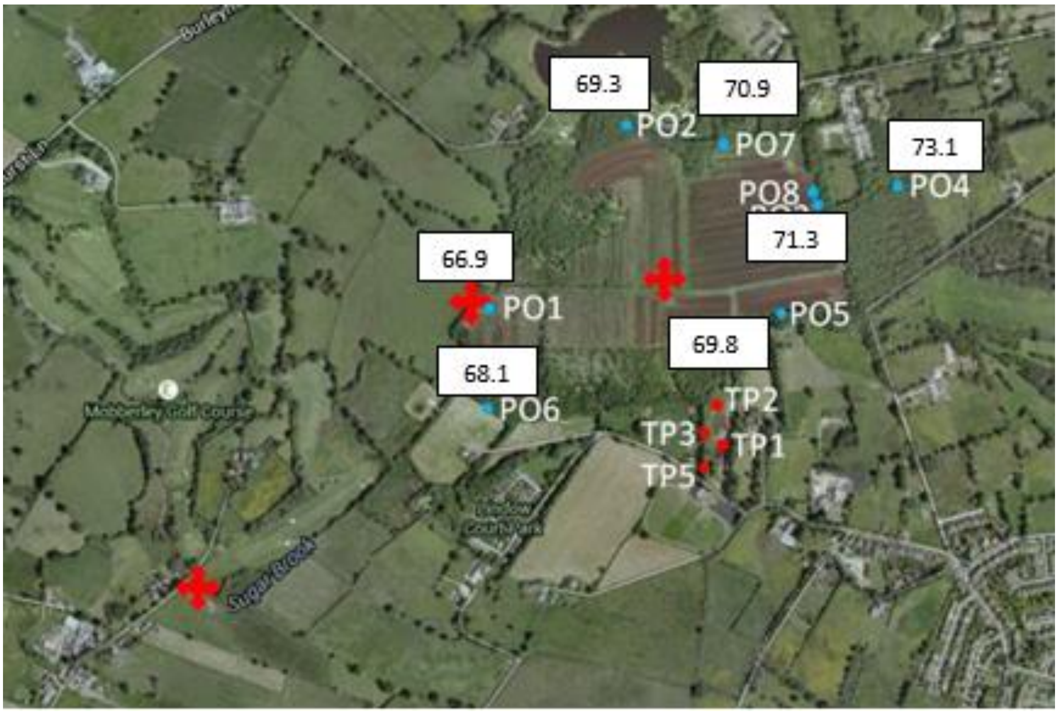


Figure 8 Mean groundwater levels in peat monitoring wells, Salters Moss peat extraction area 2007-2020

2.6.10 Enzygo consider that only P03/07 is monitoring the sand underlying the peat (based on its response zone at 5-8m as indicated in the original compiled data set (Appendix 2, Hafren Water 2016 report). Its location at the eastern end of the excavated peat area is shown on Figure 4.

Groundwater level variation

2.6.11 The mean groundwater level data in Table 2 and Figure 8 hide a considerable amount of seasonal and longer- term change in levels over time. A steep initial decline in groundwater levels in the record is apparent between 2007 and August 2011 when there is a clear step change in the data sets for several monitoring wells (See Appendix 9). The changes are summarised in Table 3.

2.6.12 The net effect of site operations to 2020 on peat groundwater levels appears marginal with a net 0.08m (8cm) fall across the 33ha site base shown by the monitoring well records. However, five of the seven peat monitoring wells are towards the edge of the site well away from areas disturbed by recent peat extraction and associated drainage works. So, they may be unrepresentative of what may be happening in the areas where peat extraction has been concentrated during the past 20 years.

2.6.13 Conversely, well P05/07, located on the central track between Compartments 5 and 6B shows a greater level of peat dewatering and so arguably is more indicative of the effects of peat extraction. However, it is less than 1m from the edge of the peat excavation and is considered to represent an example of very localised drawdown or dewatering of the local peat.

2.6.14 The mean peat water table in P05/07 lowered by over 1m between 2007 – 2016 (Figure 9) but there is a clear reversal in decline from August 2016 (Figure 10) coincidental with the insertion of a peat plug in the main drain (see Figure 7). So, conversely P05/07 shows the local drain-side benefit to peat groundwater levels by raising adjacent drainage ditch water levels which appears to have caused a partial recovery in the local water table.

Table 3 Summary groundwater level change 2007-2011-2020 Saltersley Moss Peat Extraction Area

Monitoring point	Geology	2007 mean level mAOD	Change +/- m	2011 mean level mAOD	Change +/- m	2020 mean level mAOD	Overall change in mean level 2007-2020 +/- m
P01/07	Peat	66.70	+0.02	66.72	+0.43	67.15	+0.45
P02/07	Peat	69.45	-0.20	69.25	0.00	69.25	-0.02
P04/07	Peat	73.18	-0.18	73.00	+0.20	73.20	+0.02
P05/07	Peat	70.25	-0.25	70.00	-0.30	69.70	-0.55
P06/07	Peat	68.20	-0.25	67.95	+0.25	68.20	0.00
P07/07	Peat	71.05	-0.29	70.76	+0.04	70.80	-0.25
P08/07	Peat	71.42	-0.22	71.20	0.00	71.20	-0.22
P03/07	Sand	71.48	-0.33	71.15	-0.80	70.35	-1.13
OLD A	-	71.10	-0.50	70.60	+0.20	70.8	-0.30
Sugar Ditch	-	66.57	+0.01	66.58	+0.20	66.78	+0.21
Overall change in peat groundwater levels							-0.08

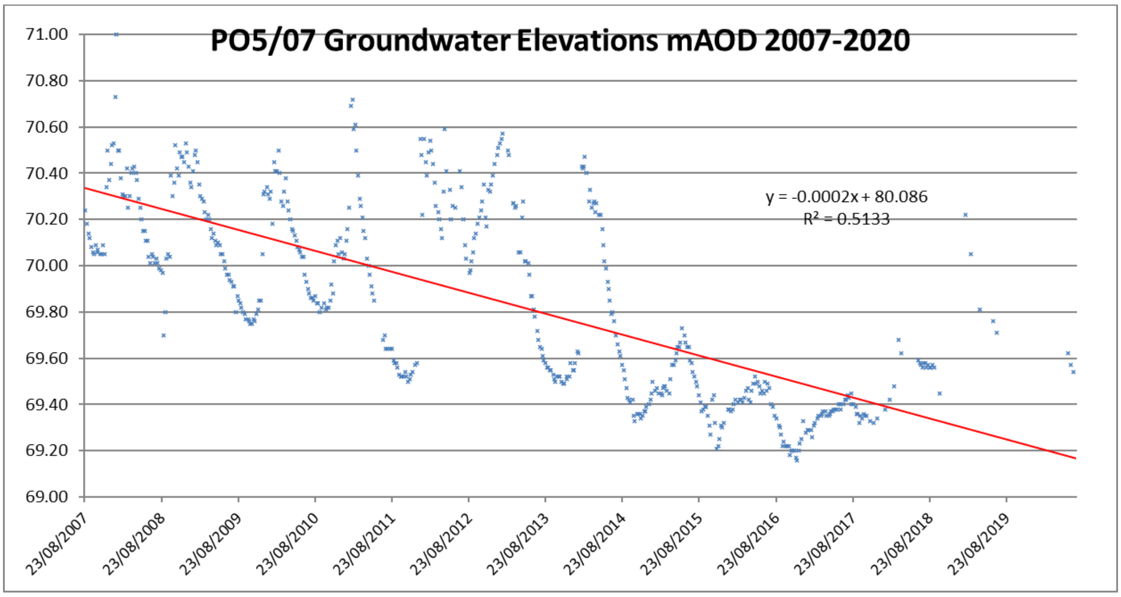


Figure 9

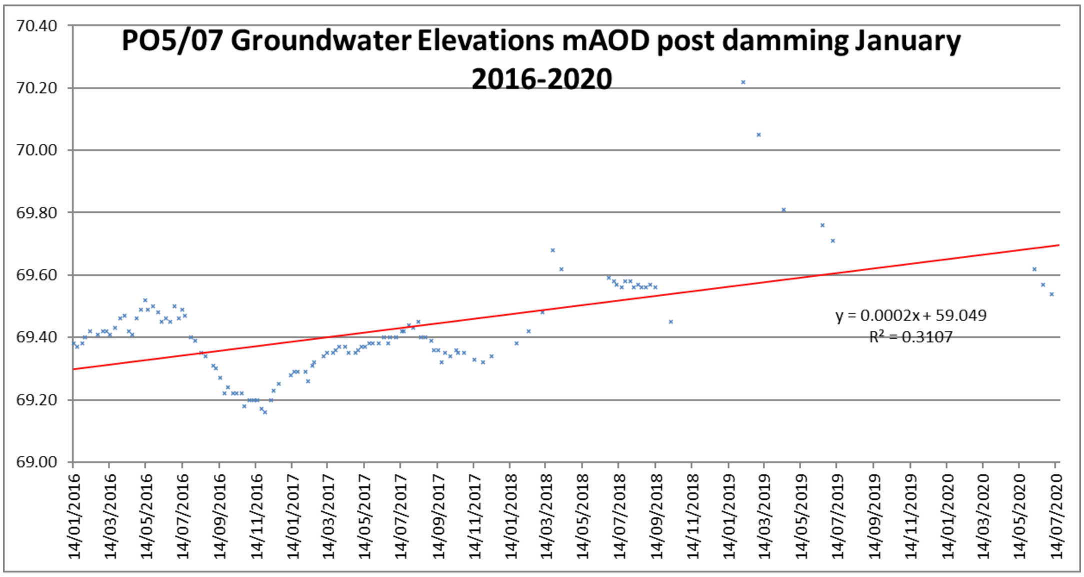


Figure 10

Magnitude and extent of lowering of the water table in the peat; and indicative estimate of net loss of water from the peat aquifer by volume.

33 ha Site-wide Estimate

2.6.15 Assuming a mean water content in the peat of 81-86% (Section 2.6.2 and using the average site-wide groundwater level data, the volume of groundwater storage created (and conversely volume of groundwater lost assuming the result of groundwater table lowering is not compaction by the overlying peat mass) is estimated from:

depth x area = volume x 81% or x 86%

0.08m x (33 x 100 x100)m^2 = 26,400 m^3

26,400 m^3 x 81% = 21,384 m^3

26,400 m^3 x 86% = 22,704 m^3

6.7 ha Eastern area Estimate

2.6.16 Assuming a mean water content in the peat of 81-86% (Section 2.6.2) and using groundwater lowering data from borehole P05/07, the volume of groundwater storage created (and conversely volume of groundwater lost assuming the result of groundwater table lowering is not compaction by the overlying peat mass) is estimated from:

depth x area = volume x 81% or x 86%

0.55m x (6.71 x 100 x100)m^2 = 36,905 m^3

36,905m^3 x 81% = 29,893 m^3

36,905m^3 x 86% = 31,738 m^3

Figure 11 Eastern end of peat working area (~6.7 ha)

Summary

2.6.17 Across the site some 21,384 m^3 to 31,708 m^3 of groundwater storage may have been lost due to drainage of the peat area, most of the losses occurring at the eastern end of the site (assuming groundwater levels at monitoring Well P05 are representative).

2.6.18 Most of the water being conveyed by the drainage system is therefore direct rainfall on the extraction area running off the peat surface.

Effects on the sand aquifer

2.6.19 P03/07 and P08/07 are co-located at the north east boundary of the peat extraction area (locations shown on Figures 4 and 8 respectively). Removal of the peat cover from the underlying sand has led to natural deepening of the drainage ditches post- construction at that location since 2010 (Figure 2) by erosion of the sand by flowing water (Figure 5). Consequently, the water table in the sand has lowered relative to the water table in the overlying peat (Figure 12) and the drainage ditches are dewatering the underlying sand. The removed sand is likely to be washed through the drainage system into Sugar Brook and could explain why water levels at Sugar Brook and groundwater levels at adjacent P01/07 are rising if the aggrading sand is raising the bed level. There is anecdotal evidence of considerable sediment accretion along Sugar Brook below the site.

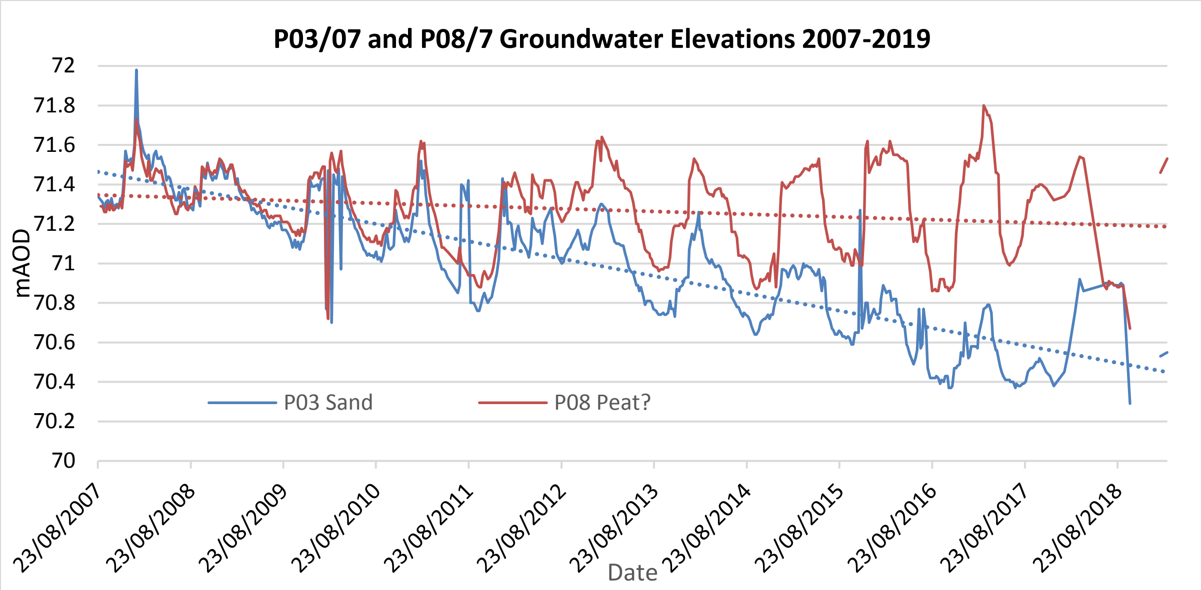


Figure 12 P03/07 (Sand) & PO8/07 (Peat) Groundwater levels (Ex Enzygo report SHF.1633.001, reproduced with the permission of Newgate Kennels Ltd)

Other Groundwater levels

2.6.20 Groundwater was not recorded in the log for BGS borehole SJ88SW3 north of the Newgate Kennels (Appendix 2).

2.6.21 During construction of borehole 1 of the 2012 ground investigation on the Kennel Site groundwater was struck in the sand at 2.5m depth, the level rising to 2.0m. Groundwater was also struck in the peat deposit during construction of borehole 2 at 4.5m depth, the groundwater level rising to 3.0m depth. The groundwater elevations (mAOD) are not known.

2.6.22 Some CEH borehole groundwater level data was submitted with the S73 Application for restoring the site (Appendix 8). However, there is no information on monitoring well construction.

***The consequences of desiccation of the peat on shrinkage and oxidation, including carbon dioxide lost to the atmosphere*.**

2.6.23 Drainage of the peat extraction site by installing and then deepening the on-site drainage ditches appears to have had only a marginal effect on groundwater levels in the peat as monitored by the current monitoring wells, which is explained by the low hydraulic conductivity of the peat mass (therefore requiring a high density of drainage ditches to ensure effective drawdown of the proximal peat groundwater table adjacent to the drainage ditches). Natural variation in groundwater levels and the small (0.08m) decrease in mean groundwater level across the site will have had minimal effect on shrinkage and oxidation.

2.6.24 As the water table is at depth (Table 4) there will be minimal effect on moisture contents at surface, on desiccation, and hence on oxidation and CO_2 generation by the change in mean groundwater table elevation.

Table 4 Groundwater Depth Variation (metres below ground level) Peat Extraction Area

	Units	A	P01/07	P02/07	P04/07	P05/07	P06/7	P07/07	P08/07	P03/07
min	m	1.00	1.02	0.37	0.25	1.00	0.58	0.65	1.82	1.59
max	m	2.47	2.90	2.09	1.62	2.84	1.67	2.29	2.95	3.28
50%ile	m	1.78	2.00	1.12	0.76	2.18	1.03	1.07	2.32	2.57
N		522	533	533	531	532	533	532	533	533
range	m	1.47	1.88	1.72	1.37	1.84	1.09	1.64	1.13	1.69

CO2 losses, 33 ha peat extraction site

2.6.25 Assuming a mean water content in the peat of 81%-86% (Section 2.6.2) and an affected volume of peat of 0.08m x (33 x 100 x 100)m^2 = 26,400m^3 the balance is organic matter i.e. between 26,400m^3 x 19% = 5,016m^3 and 26,400m^3 x 14% = 3,696 m^3

2.6.26 Assuming a high carbon content of 0.048 g cm^3 of carbon[5] (48 kg /m^3), some 48kg/m^3 x 3,696m^3 = 177,408kg as C to 48kg/m^3 x 5,016m^3 = 240,768kg as C is moved into the potential zone of desiccation and oxidation by a 0.08m average reduction in water table.

2.6.27 If oxidised this carbon would generate 582,912kg (583t) to 791,095kg (791t) of carbon dioxide emissions to the atmosphere.

CO2 losses, 6.7 ha Eastern area extraction site

2.6.28 Assuming a mean water content in the peat of 81-86% (Section 2.6.2) and an affected volume of peat of 0.55m x (6.71 x 100 x 100)m^2 = 36,905 m^3 the balance is organic matter i.e. between 36,905m^3 x 19% = 7,012 m^3 and 36,905 m^3 x 14% = 5,166 m^3

2.6.29 Assuming a high carbon content of 0.048 g cm^3 of carbon[6] (48 kg /m^3), some 48kg/m^3 x 5,166m^3 = 247,968 kg as C to 48kg/m^3 x 7,012m^3 = 336,576 kg as C is moved into the potential zone of desiccation and oxidation by a 0.55m average reduction in water table.

2.6.30 If oxidised this carbon would generate 814,752kg (814.7t) to 1,105,893kg (1.1Mt) of carbon dioxide emissions to the atmosphere.

Limitations on the use of previously obtained groundwater level data and on CO_2 estimates

2.6.31 Considerable caution must be exercised when attempting to extrapolate peat groundwater levels from individual monitoring wells to the wider peat deposits. This is because the monitoring wells are all less than 3m deep in a peat deposit that is variably affected by artificial drainage ditches designed to lower the peat water table to facilitate peat extraction. So, the groundwater levels are affected by:

- Proximity to drainage ditches: many of the boreholes are distant from the active drainage system, or conversely very close to the edge of peat excavations (e.g., BH05)

2.6.32 Similarly, CO_2 emissions will vary across the site depending on the degree of drying and oxidation of the peat mass. A clear seasonal response in several peat groundwater monitoring wells is evident and so in summer when groundwater levels are low and ground temperatures increase it is expected that drying of the uppermost peat will cause oxidation and losses of CO_2. Rewetting of the peats during the winter months together with reduced ground

[5,7] The Potential of Peat: An investigation into the influence of a peat dam on carbon stocks at Saltersley Moss, Cheshire. Z0939739 Undergraduate Dissertation University of Durham 2019

[6] The Potential of Peat: An investigation into the influence of a peat dam on carbon stocks at Saltersley Moss, Cheshire. Z0939739 Undergraduate Dissertation University of Durham 2019

temperatures will reduce CO_2 losses. It is also noted that considerable volumes of peat have also been removed for use off-site where it will also dry, oxidise and lose CO_2 to atmosphere.

2.6.33 Enzygo consider that both water and CO_2 losses will be greatest close to the edge of the drainage ditches and that groundwater levels in the centre of the peat blocks between drainage ditches will be relatively unchanged because of the low lateral and vertical permeability of the peat.

2.6.34 A more detailed examination of the effects of peat extraction and site drainage on CO_2 production is beyond the scope of this report and would require an improved site monitoring design. Moreover, the site is to be restored such that new peat forms and locks up CO_2. In our view a study of rates of deposition of biomass and hence rates of CO_2 storage would be much more pertinent.

3.0 Conceptual Model

Introduction

3.1.1 The conceptual hydrogeological model for the peat extraction site and adjacent property developed by Enzygo is that it is a dual aquifer system with a perched aquifer in the low hydraulic conductivity organic peat layer and a second perched aquifer in the underlying higher conductivity unconsolidated glaciofluvial sands. The sand aquifer is linked to the peat aquifer such that groundwater in the sand supports groundwater in the peat which in its absence could slowly cause water levels in the peat to lower by drainage into the sand (depending on the vertical hydraulic conductivity of the peat).

3.1.2 Variations in groundwater levels in either aquifer unit could have a significant effect on ground stability both singly and in combination. Variations in groundwater levels occur from natural changes in precipitation but there is an added complicating factor at this site caused by long-term lowering of the ground surface relative to the fixed monitoring well installations and by draining of the site to different depths in the drainage network at various times during the site phasing.

Effects of ground level change on measurement and monitoring of groundwater levels

3.1.3 None of the monitoring wells has a marked datum point. Good practice is to have a permanent datum point marked on the outer well head casing enabling the dip tape to be read off against the datum point. This is not the case at this site where there is no marked datum point. Otherwise, the dip tape would be read off against the top well head casing. This assumes that each well head casing is level and that its elevation is fixed such that it does not change over time. This is not the case with many of the site monitoring wells. The datum point has clearly lowered relative to the level when the well was constructed because the well head casing is attached to or sitting on the peat which due to drainage and shrinkage is now lower by several tens of centimetres. This is clearly shown in monitoring wells P08/07 and P05/07 in Figure 12, whereas the ground elevation around monitoring well P06/07 (also in Figure 12) in the west in an older worked area has not resulted in any apparent well casing lowering.

3.1.4 A lowering of the data point on the outer casing would result in an increase in groundwater levels if not corrected for. The datum point used by the operator's monitoring team and by Cheshire East Council is not known. Where the inner well liner sticks up above the well head casing. Enzygo's dip levels for affected wells were measured against the top of the stickup casing as its elevation is less likely to have changed. However, it is accepted that there are inevitable errors in the dip levels obtained.

Effects of extraction on peat aquifer levels

3.1.5 The shallow drains in the peat were intended to drain and remove any perched groundwater in it to facilitate peat extraction. The reduction in groundwater levels in the peat by draining it include drying, shrinkage and oxidation resulting in a thinning of the strata by loss of peat mass and loss of standing water on the ground surface to the adjacent drainage ditches. This is clearly shown in the extraction site by the photographs of the monitoring wells P08/07 and P05/07 in undisturbed peat in Figure 15, where the outer well-head casing cemented to the ground has lowered relative to the internal monitoring well liner which is more firmly anchored in the underlying deep peat. In the west of the extraction site where peat working was of shallow depth the effects on adjacent peat are less dramatic such that there is no discernible effect on long-term peat groundwater levels or a slight increase.

3.1.6 In summary there appears to be a small lowering in mean peat groundwater levels over the 13-year period 2007-2020 but some of the decrease could be attributed to changes in datum point elevation in the monitoring well infrastructure. The change in datum point elevation is could be either continuously variable or episodic and so is indeterminate.

Figure 13 Effects of ground lowering on monitoring well datum at 08/07, 05/07 and 06/07, Peat Extraction area

Effects of extraction on sand aquifer levels

3.1.7 At the eastern end of the site the site, the drains were over- deepened and have clearly breached the underlying sand leading to a lowering of the local water table in the sand aquifer. This is predictable (although paragraphs 34 and 35 of the proposed 2018 restoration scheme for the extraction site (included in Appendix 7) state that the mineral substrate is 'impermeable'). Conversely, the sand as monitored by well P3/07 is clearly permeable as it responds rapidly to rainfall and the water table has been lowered by excavation of the drainage ditches into the sand.

3.1.8 The Cheshire County Council planning decision notice for 5/97/0758P (included in Appendix 6) Condition 29 stated:

29. A minimum depth of in- situ peat of 0.5metres shall be retained unless otherwise agreed in writing with the Mineral Planning Authority. For the avoidance of doubt minimum depth shall mean minimum average depth measured on a field by field basis according to the annual levels monitoring scheme proposed by Terraqueous Ltd dated December 2002. For the avoidance of doubt the lowest levels to which peat has been extracted shall exclude drainage channels.

3.1.9 Thus, drainage channels were excluded from the minimum depth of peat. However, the drainage channel construction clearly conflicts with Condition 31:
31. No sand shall be dug, disturbed, or removed from the application site unless otherwise agreed in writing with the Mineral Planning Authority.

3.1.10 Exclusion of drainage channels from the minimum peat depth was recommended by the operator's consultant Terraqueous Ltd in its Review of Old Minerals Permissions (ROMP) Revised submission (second revision) for the extraction site as part of Application 5/97/07581 (This report Appendix 5, paragraph 5.6.3.2).

3.1.11 Had a proper ground investigation been undertaken before the site was developed, the operator's hydrogeological consultants should have advised that there is a dual shallow aquifer system and so that the groundwater monitoring infrastructure must include the underlying sand aquifer. Consequently, there is only one well (P03/07) monitoring the underlying sand aquifer and so the impacts of peat extraction on the sand aquifer have gone un-noticed until the data analysis in this and the previous Enzygo report, in particular the comparison between adjacent peat and sand groundwater levels evidenced in the extraction site operator's own data set shown in Figure 9 of this report but masked by the compressed Y scale of the groundwater level hydrograph drawing for P03/07 in the Hafren Water 2016 supplementary information report in Appendix 1.

Effects on off-site ground stability

3.1.12 The effects of groundwater lowering in unconsolidated sand long-known for its running nature (for example the information in the BGS borehole record in Appendix 2 has been available for many years) include extraction of sand by erosion from surface water and groundwater flows along the site drainage ditches, vertical erosion (downcutting) by flows along drainage ditches cut into the sand, and headward erosion from the heads of drainage ditches as the hydraulic pressure gradient changes to focus groundwater flows into the ditches. Any erosive flowlines can cause sub-surface erosion of unconsolidated fines by seepage-induced suffosion[7] of silt or sand with their removal along the flowline into the ditch watercourses. The overall effect on the aquifer materials is differential ground lowering from below, including where there are undisturbed overlying peats (where there would be a combined overall effect because of drying out).

3.1.13 The deepened ditch excavations at the east end of the extraction area will increase the water table hydraulic gradient in the sand aquifer from off-site into the excavated area. We consider that a combination of peat drying from lowering of the peat water table in combination with lowering of the sand water table is adversely impacting ground stability off site to the east of the extraction area by ground lowering / subsidence.

3.1.14 It is also possible that there is a buried glacial channel or similar feature at the north east end of the excavation that has focused the groundwater drainage, but the most likely cause of the focus is interception of the sand by the site drainage.

3.1.15 The extraction site and the Site appear to lie east and outside of the Cheshire Brine Subsidence Compensation District and so subsidence caused by brine extraction from deep halite beds is not considered to be relevant.

3.1.16 Newgate Kennels Ltd maintain that ground subsidence on its property has worsened in the past 20 years or so since peat extraction moved to the eastern side of the extraction area. Had a sluice network been installed to limit erosion losses and maintain groundwater levels in the

[7] The term 'suffosion' is recommended to describe the instability phenomenon whereby the transport of fine particles by seepage flow is accompanied by a collapse of the soil structure. Accordingly, this distinct internal instability phenomenon may be quantified by a mass loss, a volumetric contraction and a change in hydraulic conductivity. R. J. Fannin and P. Slangen 2014. *On the distinct phenomena of suffusion and suffosion* https://doi.org/10.1680/geolett.14.00051

peat workings, wetlands, and adjacent areas, then deformation rates on adjacent land should have been lower.

4.0 Mitigation of Hydrogeological Effects

The potential benefits and practicality of mitigation measures to control the discharge of water and the likely timeframe for the recovery of the peat aquifer once the discharge is controlled.

Monitoring network

4.1.1 ECUS findings in their causal link review of 2016 (in Appendix 4) were that the current groundwater monitoring wells are poorly- placed and constructed. The headworks of several have lowered relative to the inner well lining such that the datum point is uncertain.

4.1.2 Only one of the monitoring wells P03/07 is monitoring groundwater levels in the (assumed) extensive sand aquifer underlying the peat. However, there is no information on its construction such as length of screened section (response zone) other than overall borehole depth and what is observable at headworks.

4.1.3 A new monitoring network should include wells with response zones in the sand and should be installed by the operator as part of the restoration scheme to ensure there is sufficient baseline data to inform the restoration scheme and to judge the success or otherwise of it.

4.1.4 Typically, 12 months of data covering the groundwater year is required. The remaining old infrastructure should be retained and monitoring of groundwater levels should continue, to provide overlap with the data set of the new infrastructure and enable back- estimation of drainage levels in the parts of the site being newly monitored.

4.1.5 The monitoring wells and levels of all drainage ditches and control infrastructure should be surveyed to provide comparative elevations in mAOD.

4.1.6 Controlling the discharge of water from the site will have implications for the receiving watercourse and so the LLFA (Cheshire East Council) should be consulted as it is responsible for flood risk management of Sugar Brook as a minor watercourse. Other riparian rights owners on Sugar Brook should also be consulted due to the potential for their land to be affected. The EA should also be consulted as a downstream main watercourse would also be affected.

4.1.7 The site does not appear to have a discharge consent but any control on discharge might require a permit from the EA.

Restoration

4.1.8 Application 15/0064M by the operator to Cheshire East Council proposed variation of conditions of planning permission 5/97/0758P Restoration would be achieved through re-wetting of the site by raising of water levels by a series of dams and subsequent management of water levels by compartmentalisation of areas of the site to increase storage of incident rainfall. This scheme (August 2018 version 4) is included in Appendix 7.

4.1.9 The approved restoration scheme relies on passive control of drainage using peat bunds within the compartments and reinforced peat dams in the main drain. In our view this should be adequate but an active control, specifically a sluice on the main drain at the outfall to the Sugar Brook should also be included since this will enable a controllable rise in water levels in the Main Drain which the restoration proposals have committed to undertake (August 2018 para 164) despite current uncertainty on final topography. The installation of controls and so the ability to manage levels of the main drain prior to the commencement of works would also ensure that materials disturbed and entrained into site drains during the restoration reprofiling are retained within the site and not discharged from it into Sugar Brook.

4.1.10 Stopping up of the site drains at the north east end of the extraction site by backfilling with non-erosive low permeability material would prevent rapid erosive runoff of input rainfall and emergent groundwater along the ditch heads and should eventually restore the water table in the underlying sand to a level such that it would re-wet the peat deposits or at least prevent further desiccation and oxidation losses.

4.1.11 Stopping up of the site discharge to Sugar Brook to an appropriate level should ensure that eroded site materials are retained within the site as well as reducing the groundwater hydraulic gradient and reducing erosion rates.

4.1.12 The link between removal of erodible sands by the peat extraction drainage system and subsidence to third party land is circumstantial and not yet proven but is plausible. Removal of the erosion mechanism (flowing water) by stopping up drainage ditches and controlling water levels as restoration proceeds would be a prudent measure to prevent erosion of the sand aquifer.

4.1.13 Periodic monitoring of ground elevations and groundwater levels in the sand below third-party land is recommended before substantive works are carried out by the operator to prove or disprove any causal effect.

4.1.14 The water table restoration is dependent on lateral hydraulic conductivity rates, but on the basis that the central areas of peat between drainage ditches have remained wet, raising water levels in the ditches and retaining rainfall on the peat surface to enable infiltration will re-wet the limited areas of peat along the ditch banks and so the overall timescale may by relatively short: years to tens of years is our estimate based on the response of monitoring well P05/07 from 2016 following damming up of the adjacent drain (+0.4m in 4 years). Unfortunately, well P05/07 was destroyed during clearance operations by the site operator in summer 2020.

4.1.15 Regrowth of new peat deposits will depend on colonisation (natural or artificial) of peat forming flora and maintaining a suitable wet environment. However, estimating rates of regrowth are beyond the scope of this report.

The effect of continuing inaction on the long-term prospects for ecological restoration.

4.1.16 Restoration of groundwater levels by raising water levels in the ditch network should have a relatively rapid (decade timescale) effect, so continuing inaction should not prove too problematic.

5.0 Conclusions

5.1.1 The various regulatory bodies involved with the peat extraction site and the operator itself (and its hydrogeological consultants) have an incomplete understanding of the hydrogeology, in part because of a poorly- designed groundwater monitoring scheme focussed on monitoring groundwater levels in the peat layer but not the underlying permeable sand aquifer, which in the site restoration scheme the site operator's hydrogeological consultants maintain is impermeable. Contrary to their claims this may complicate groundwater management at this site. The peat groundwater levels are also not well understood due to the wide spacing between monitoring wells.

5.1.2 This incomplete understanding is a major failing since the sand and peat aquifer units extend off- site to the east beneath the adjacent Newgate Kennel and White House properties. Removal of the erodible silty sands by extraction site drainage and steepening of groundwater hydraulic gradients towards the peat extraction site would explain the differential ground subsidence experienced east of Rothermere Road. The sand aquifer may also be cut into by Sugar Brook in the west and so impact on flows in the watercourse.

5.1.3 There is anecdotal evidence of considerable clastic (sand) accreting against and affecting structures along Sugar Brook.

5.1.4 Drainage of the peat extraction site by installing and then deepening the on-site drainage ditches appears to have had only a marginal effect on groundwater levels overall across the peat in the past as monitored by the current monitoring wells, which could be explained by the low hydraulic conductivity of the peat mass (therefore requiring a high density of drainage ditches). We do not consider that one or two monitoring wells showing greater effects is representative of peat groundwater levels between drainage ditches.

5.1.5 Natural variation in groundwater levels and the small (0.08m) decrease in overall mean groundwater level will have had minimal effect on shrinkage and oxidation across the site.

5.1.6 As the peat water table is at depth there will be minimal effect on moisture contents at surface, on desiccation, and hence on oxidation and CO_2 generation by small changes in mean groundwater table elevation.

5.1.7 Restoration of the site by stopping up the ditches and raising the drainage ditch water levels will reduce the effectiveness of the site drainage network and so aims to re-wet the peat and enable colonisation by peatland vegetation. This is likely to be successful at decade timescales provided the interrelationship between peat groundwater levels, sand water levels ground subsidence and adjacent natural watercourses is much better understood.

6.0 Recommendations

Groundwater monitoring

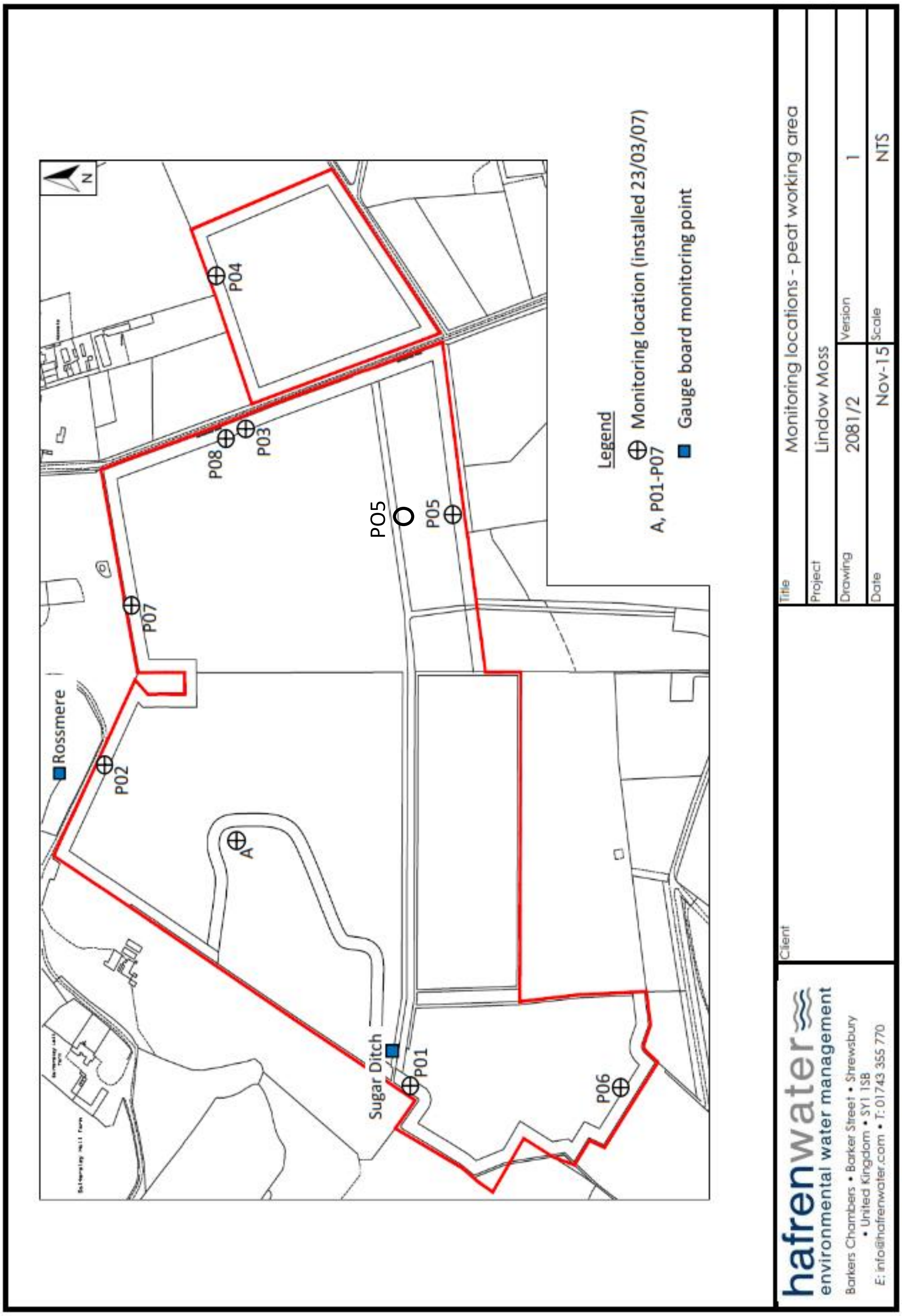
6.1.1 More extensive pre and post-restoration monitoring of groundwater levels in the sand aquifer east of the peat extraction area is required (around Newgate Kennels and the White House which have seen significant differential ground lowering or subsidence in the past 20 years), and in/around the peat extraction site must be carried out to determine the effects on hydraulic gradients in the sand aquifer and provide more information to determine whether or not peat extraction has caused or contributed to the demonstrated off-site ground subsidence and whether there might be an adverse effect of restoration of the peat extraction site.

Ground topographical levels and level change monitoring

6.1.2 Monitoring of current pre-extraction site restoration subsidence rates and the distribution of subsidence across the peat extraction site and the Newgate Kennels and White House property landholdings considered to have been impacted by the peat extraction site is essential to improve understanding of the relationship or otherwise between the sites. This would be achieved by periodic ground elevation surveys. Aerial drone or ground LiDAR surveys generating point cloud data would give rapid wide area coverage on areas of open ground in combination with traditional ground survey in areas of dense ground cover or woodland.

Additional requirements

6.1.3 A better understanding of the drainage network east of the site and groundwater levels/hydraulic gradients in both peat and sand is required as part of the site restoration scheme.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Rossmere
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Sugar Ditch
P01
P06
Legend
A, P01-P07 Monitoring location (installed 23/03/07)
Gauge board monitoring point
Title
Monitoring locations - peat working area
Project
Lindow Moss
Drawing
2081/2
Version
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Scale
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Appendix 1 – Hafren Water information & ECUS Review

Appendix 2 – BGS Borehole Record

Appendix 3 – Peat Extraction Area Topographic Survey

Appendix 4 – ECUS Causal Link Review

Appendix 5 – ROMP Submission

Appendix 6 – Planning Decision Notice

Appendix 7 – 2017 Proposed Restoration Scheme V3

Appendix 8 – CEH Borehole information

Appendix 9 –Site monitoring well levels 2007-2020

Appendix 10 –Greenfield runoff estimation

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