Catfield Fen Investigation

Final Report

10 August 2012

AMEC Environment & Infrastructure UK Limited

Third-Party Disclaimer

Document Revisions

No.	Details	Date
1	Initial Draft Report	16 January 2012
2	Final Draft Report	10 February 2012
3	Draft Final Report	5 April 2012
4	Final Report	22 June 2012
5	Final Report	10 August 2012

Catfield Fen Investigation

Final Report

10 August 2012

AMEC Environment & Infrastructure
UK Limited

Report for

Ursula Buss
Environment Agency
Anglian Region
Kingfisher House
Goldhay Way
Orton Goldhay
Peterborough PE2 0ZR

Main Contributors

Dr Geoff Mason

Issued by

pp ....
Dr Geoff Mason

Approved by

....
Dr Tim Haines

AMEC Environment & Infrastructure UK Limited

Canon Court, Abbey Lawn, Abbey Foregate,
Shrewsbury SY2 5DE, United Kingdom
Tel +44 (0) 1743 342 000
Fax +44 (0) 1743 342 010

h:\projects\30321 catfield fen data evaluation & reporting\docs\final report june 2012\rr019i5.doc

Executive Summary

Following concerns being expressed by Natural England and the landowners of Catfield Hall Estate about the drying out of Catfield Fen, the Environment Agency has engaged AMEC to carry out an independent study of the Fen's hydrology and hydrogeology. This has included an initial consultation with interested parties inviting their comments. These interested parties have comprised Mr and Mrs T Harris of Catfield Hall, local licensed abstractors, the water company, the Environment Agency, Natural England, the Broads Authority and Professor David Gilvear of Stirling University who has previously studied the Fen and who has been engaged by Mr and Mrs Harris to act as an independent consultant. The consultation resulted in a visit to the Fen and surrounding area for discussions with the landowner (Mrs Harris) and a local abstractor (Mr Alston). Data have been received from Mr and Mrs Harris, Mr Alston, the water company and the Environment Agency. Following the issue of a Final Draft Report, a discussion of its contents was held with the various interested parties in Norwich. Their comments were incorporated into a Draft Final Report which was issued on the 5 April 2012 and further discussions followed at a meeting on the 23 April 2012. Following that meeting all interested parties were invited to submit any comments details are given in Section 9 of this report and the comments themselves are reproduced in Appendix L. and these are acknowledged with thanks. More detailed discussions have also been held with Professor Gilvear and he has provided specific comments on various sections of the previous version of this report and these have been reproduced in this Final Report. Notes from the more detailed discussions with Prof Gilvear are provided in Section 9.

This report has been produced for the purpose of addressing the following three key objectives identified by the Environment Agency:

- To assess how the Fen functions hydrologically and hydrogeologically;
- To assess the Fen's sensitivity to water abstraction;
- To comment on possible causes for the site drying out.

Catfield Fen comprises an 'internal drainage system', which is bounded to the west and south by the Commissioners' Rond and to the north and east by "uplands", and Great Fen which lies to the west of the Commissioners' Rond, outside the north-western part of the internal system. Great Fen is part of the 'external drainage system' which occurs between the Commissioners' Rond and Barton Broad and is regarded as having free access for river/Broad water via a system of dykes. The internal system is also crossed by a dyke system which is believed to be unimpeded without any retaining structures within it.

Within the Rond, there are two structures, one in the north and one towards the south of the Fen, which are potential routes by which water can move between the external and internal systems. Another potential water transfer route, one which has not previously been formally recognised, is via a low-lying bund at the southern end of Catfield Fen, just to the east of the Commissioners' Rond.

The Fen is underlain by peat to depths of almost 7 m in the south-east parts, and the peat is in turn underlain in most places by a clay layer which overlies the Crag. The Crag underlies the whole of the Fen at depth and forms the lower slopes of the uplands which surround the Fen on its northern and eastern sides. A basal clay layer underlying the fen peat is widespread, but appears to be absent at the fen margins, in places near to the margins (e.g. in parts of North Marsh) and in the bottom of some dykes where they have been cut down into the Crag.

This investigation has shown that Catfield Fen, comprising both internal and external drainage systems, is a complex hydrological system. There is some groundwater input to dykes near the eastern margin, rainfall input to the fen compartments as well as a mixture of rainwater and groundwater entering the compartments laterally from the dykes in some places in the west, and possibly flow in the opposite direction from the compartments to the dykes in the east where the ground surface may be slightly higher (though has yet to be verified). The dyke water levels are also subject to the ability of the internal system to retain water. At times water flows over the low bund at the southern end of the internal system, and this will affect the amount of water stored within the internal drainage system.

The possible reasons for the Fen drying out are varied and may involve several factors which are acting in combination to produce the effects described by the Compendium (Natural England et al., 2011). These might include the effects of groundwater abstraction, overflow of dyke water over the low-lying bund at the southern end of the internal system, leakage through sluices, changes in water management, and the process of terrestrialisation which could lead both to the infilling of former pond areas and to the general rise in the ground surface. These will be addressed below.

Water level data from the Fen show evidence of winter dyke water levels becoming progressively lower in recent years since 2007. However this trend appears to be related to regional trends in Crag groundwater levels. These show an overall rise in response to major recharge events, as in 2001 and 2007, and then gradually decline in subsequent years. This is a trend that is also seen in the Barton Broad water levels.

Water chemistry data indicate that the dykes on the eastern side of the Fen have a significant groundwater input, and from dyke water level data on the western side of the internal system it appears that dyke water levels are maintained by the Crag. However, the dyke water chemistry in the west does not show the predominance of groundwater input seen in the east, but a mixture of groundwater and surface waters. The groundwater influence on dyke water levels in the west may not therefore be due to direct groundwater input, but to a maintenance of levels that is linked by the unimpeded dyke network to the dykes on the eastern side of the Fen which are more directly influenced by groundwater heads due to the clay separating the Crag from peat being absent. Since the dyke waters are affected by Crag groundwater levels, they also a similar water level variation. It is of note that the lowest Crag groundwater levels at least since the 1970’s, and possibly since the 1950’s, probably occurred during the drought periods of 1989-1992. It was at this time that Mr MacDougall, a former owner of Catfield Hall, raised concerns about the Fen drying out, though he also noted concerns about the lowering of water levels over the previous 25 years.

The water levels within the fen compartments of Great Fen in the external system seem to be largely affected by water levels in the Broad. In the internal system, investigations of peat water flow and water chemistry indicate that rainwater is the major water source, and in Sedge Marshes water level data also suggest the significance of rainfall influences, though dyke waters also have an influence at least for part of the winter. Further to the east, there are indications that the ground level may be slightly higher than to the west, though this has still to be confirmed by a topographic survey. If this is so, rainfall-fed peat water within the compartments may well be higher than water levels in adjacent dykes, and therefore there could be flow towards the dykes. This would be greatest in winter when the head differential would be greatest. In such circumstances any lowering of dyke water level, or raising of the ground surface, could lead to increased drainage of water from the compartments to the adjacent dykes and this could lower the water table relative to ground level.

The lowering of dyke water levels, other than by the normal influences of increasing temperature and evapotranspiration, could be a result of several factors including groundwater abstraction, overflow via the low-lying bund at the southern end of the internal system, and by leakage through the sluices. Any lowering of winter water levels would mean there would be less water stored within the internal system, and less available to sustain the fen in the spring and summer periods.

The groundwater abstractions that could affect shallow Crag groundwater levels at the Fen are those from the Ludham PWS source and from the Ludham Road borehole which is used for spray irrigation purposes. The effect of the Plumsgate Road abstraction on the Fen has been investigated and it is considered that it does not have an impact. The impact from the PWS source may however be relatively widespread since it has been abstracting continuously since 1973, and the amount of drawdown could be several centimetres. However, any such changes have not been clear from the water level data observed since 1996, and might not be expected to be seen since the PWS abstraction has been fairly constant over this period. The Ludham Road abstraction is considered to have only a small localised effect on groundwater levels near to Church Wood, the estimated drawdown being less than 5 cm, and when abstraction ceases groundwater levels return rapidly to the level that would have occurred without the abstraction. Observed data do not show any effect on water levels within the Fen. It would seem unlikely that this localised effect on groundwater levels could have a widespread effect on Fen water levels, particularly as dykes with groundwater input also occur further north near Middle Marsh where groundwater levels would not be lowered by the Ludham Road abstraction. However, whether there is an impact or not on the Fen cannot be determined with any certainty until the form of water level variation within the catchwater drain at Church Wood is known, the connectivity of the dyke system and of changes in levels within it is better established, and there is better knowledge of the relationship throughout the year between water table levels within eastern compartments and adjacent water levels in dykes.

Professor Gilvear has undertaken a separate assessment of the possible effect of abstraction on the water flux (or water budget) affecting the fen and how this may affect water levels. This has been termed the “stockade theory” and his calculations indicate a possible maximum change in groundwater levels (based on 30 days of pumping at the full licensed abstraction rates) of about 4cm from the spray irrigation abstractions and a similar amount from the AWS Ludham abstraction i.e. 4-9cm in total. The potential effect of this change on the water levels across the fen will be dependent upon hydrological pathways and characteristics of the fen deposits.

A known factor in reducing water levels in the dyke system is overflow over the low-lying bund at the southern end of the Fen. Overflow through a breach in the bund was seen at this location in early March 2012 when dyke water levels were at 0.55 m AOD. These levels are not unusual in winter periods. Since any breach in a soft embankment will tend to get larger over time, it may be that the amount of water lost from the internal system has also increased over time. It may be a contributing factor to the fen drying out.

Leakage through the northern sluice is also known to occur, and may also occur at the southern sluice. The size of these losses is not known, but the sluices are believed to be in reasonably good condition, so the losses may not be significant.

The changed management in terms of sluice opening regime warrants consideration. Prior to the 1990s, when water levels within the internal system were low in the summer, water was allowed to enter it from the external system. This is a practice that no longer takes place. Sluice management is now much more controlled with the sluice only being opened for a few days in some, not all, winters in order to let water out of the internal system. The reason keeping the sluices largely closed is to prevent Broad water from entering the internal system, but it was clearly an adopted practice prior to 1984 (Giller & Wheeler, 1986a) and possibly up until the 1990s. The change in water management practice means that less water is introduced into the internal system, and there is therefore less available within storage to maintain water levels at higher levels than would otherwise be the case.

It should also be recognised that the reduction in area of shallow open water referred to in the Compendium (Natural England et al., 2011) may be due not only to increased drainage, as described above, but also to the process of terrestrialisation. The terrestrialisation of turf ponds can occur at a faster rate than might be supposed and though quoted rates of 30 cm peat growth in 20 years may be under conditions that are more optimal for growth than currently exist at Catfield Fen, it does indicate that turf ponds can be infilled within a timescale that might be considered relatively short.

The process of terrestrialisation does not only occur in turf ponds and it is clear that past fen management practices recognised this and took steps through “turfing out” to reduce its effects. The turfed-out peat was dried and sold for fuel. It is understood that the Catfield Hall Estate stripped some peat off part of North Marsh in the 1990s. The effects of both turfing-out and not doing so warrants further investigation.

The complex nature of Catfield Fen and the many factors that may influence its wetness is thus apparent.

Contents

1. Introduction

Catfield Fen is part of Ant Broads & Marshes SSSI, and a component of the Broads Special Area of Conservation, and is the subject of concerns regarding its drying out. Following the recent production of a Compendium of ecological and eco-hydrological evidence from Catfield Fen (Natural England et al., 2011), Natural England stated "The evidence presented demonstrates a long-term trend of drying on this site which appears to be accelerating. There is evidence of vegetation change consistent with drying of the wetland habitat" (letter of 7 April 2011 to the Environment Agency).

As a consequence, the Environment Agency has engaged AMEC to undertake an independent study of the Fen's hydrology and hydrogeology. This study has included an initial consultation with interested parties inviting their comments. These interested parties have comprised Mr and Mrs T Harris of Catfield Hall, local licensed abstractors, the water company, the Environment Agency, Natural England, the Broads Authority, and Professor David Gilvear of Stirling University who has previously studied the Fen and who has been engaged by Mr and Mrs Harris to act as an independent consultant. The consultation resulted in a visit to the Fen and surrounding area for discussions with the landowner (Mrs Harris) and a local abstractor (Mr Alston). Data have been received from Mr and Mrs Harris, Mr Alston, the water company and the Environment Agency. Following the issue of a Final Draft Report, a discussion of its contents was held with the various interested parties in Norwich. Their comments were incorporated into a Draft Final Report which was issued on the 5 April 2012 and further discussions followed at a meeting on the 23 April 2012. Following that meeting all interested parties were invited to submit any comments and details are given in Section 9 of this report and the comments themselves are reproduced in Appendix L and these are acknowledged with thanks. More detailed discussions have also been held with Professor Gilvear and he has provided specific comments on various sections of the previous version of this report and these have been reproduced in this Final Report. Notes from the more detailed discussions with Prof Gilvear are provided in Section 9.

This report has been produced for the purpose of addressing the following three key objectives identified by the Environment Agency:

- To assess how the Fen functions hydrologically and hydrogeologically;
- To assess the Fen's sensitivity to water abstraction;
- To comment on possible causes for the site drying out.

In addition, the Environment Agency has requested that all data and reports considered in this report be identified at the outset. These are detailed Section 2.

An overview of Catfield Fen and of its setting, both geographically and within the context of groundwater abstraction in the area, will be briefly described in Section 3, after which the geology, hydrogeology and hydrology will be discussed in Section 4 and 5. These sections will conclude with an assessment of how the Fen functions hydrologically and hydrogeologically.

The licensed abstraction in the area will then be described in Section 6 and their impact on the Fen considered in Section 7. Possible reasons for the Fen drying out are considered in Section 8 and finally, before providing a brief summary and conclusions comments form third parties are referenced in Section 9.

This report builds upon on an earlier investigation into the monitoring at Catfield Fen (Entec 2010). This considered all the installations, both those that had loggers installed and those that were only monitored monthly and made recommendations for further monitoring. Since then, there have been no new installations added to the monitoring network, though loggers have been added to some existing installations. Furthermore, following a review of monitoring by the Environment Agency, many of the installations that were formerly only monitored manually have been removed from the regular monitoring round. This report will therefore mainly only consider the current monitoring, not past monitoring of existing installations which are no longer monitored and which were considered by Entec (2010). As the current monitoring is largely based on loggers, which monitor water levels at intervals of an hour or less, there is the potential for recording changes which may result from any changes in impacts from external sources.

2. Data Considered in this Report

The Environment Agency has requested that all data and reports considered in this report be identified at the outset. A list of reports is presented in the Bibliography and References (Section 10). The data are summarised below.

2.1 Water Levels

Comprising:

- Surface water levels and groundwater levels recorded in previous studies;
- All manual data and logger data where available for the installations currently monitored as listed below.

2.1.1 Surface Water

- o Data collected by the Environment Agency at the following installations:

NTG3261G1

NTG3261G2

NTG3261G3

TG32/710 (also known as GB-A or the “Ballscroft gaugeboard”)

TG32/711

TG31/790 (at Sharp Street Fens, also known as Boardman’s Marsh)

TG31/697c (at Reedham Marshes on a dyke connected to the River Ant)

Barton Broad T.S. (Station No. T340903)

Hickling Broad (Station No. T341001)

- Data collected by Catfield Hall Estate for the TG32/710 (also known as GB-A or the “Ballscroft gaugeboard”);
- Gaugeboard data from a Natural England file covering the period 1967-1978 (provided by Clive Doarks, 6 July 2010).

2.1.2 Groundwater

Data collected by the Environment Agency, Anglian Water Services and Mr Alston at the dipwells and boreholes in the vicinity of Catfield Fen noted below:

TG32/617	TG32/605c	TG32/815	TG31/791a
TG32/617a	TG32/606	TG32/815a	Alston Obs “Plumsgate Road 3.5m”
TG32/617b	TG32/616d	TG32/815b	Alston Obs “Plumsgate Road 15m”
TG32/616a	NTG3261P1	TG32/815c	AWS P1 Sharp Street
TG32/616b	NTG3261P2	TG32/815d	AWS P2 Sharp Street
TG32/605	NTG3261P3	TG32/805 (“Alston Obs 1”)	AWS P3 Sharp Street
TG32/605a	NTG3270P4	TG32/801 (“Alston Obs 2”)	AWS P5 Ludham
TG32/605b	NTG3270P5	TG31/791	

Environment Agency data from regional observation boreholes:

TG13/320B near Itteringham, to the north of Aylsham

TG32/914 to the east of the village of Catfield

TG32/760 to the north of Stalham

TG32/913 at North Walsham

Also Environment Agency data from some dipwells located remote from Catfield Fen, namely:

TG32/536 at Barton Fen (Ant Broads & Marshes)

TG32/608 at Hall Fen (Ant Broads & Marshes)

TG32/639 at Little Bog (Ant Broads & Marshes)

TG32/737a at Sutton Broad (Ant Broads & Marshes)

TG42/016a at Mrs Myhill’s Marsh (Upper Thurne Broads & Marshes)

TG42/217 at White Slea Marshes (Upper Thurne Broads & Marshes)

2.2 Water Chemistry

Comprising:

- Water chemistry data of surface waters and groundwaters recorded in previous studies given in Section 10;
- Water electrical conductivity (EC) data and related surface water level data collected by the Environment Agency from the following installations:

NTG3261G1

TG32/711

TG31/790 (at Sharp Street Fens, also known as Boardman's Marsh)

TG31/697c (at Reedham Marshes on a dyke connected to the River Ant)

TG30/270 (on River Yare near Brundall Marina. Data used for comparison with the Ant valley locations)

- Water chemistry data of pumped borehole water provided by Anglian Water Services;
- Water chemistry data provided by Mr Alston;
- Water temperature data provided by the Environment Agency.

2.3 Meteorological Data

Covering at least the same period as surface water and groundwater levels, and including the following data provided by the Environment Agency:

- Daily rainfall totals from Barton Hall, Ormesby St Michael and Buxton Dudwick Cottage rain gauges;
- Weekly MORECS evapotranspiration data (provided by the Environment Agency);
- Weekly rainfall totals from the Catfield Hall Estate rain gauge provided by Mr Harris.

2.4 Abstraction Records

Abstraction records as available from the Environment Agency for the following licences (and any predecessors) as follows:

- Daily abstraction quantities for the two Alston licences 7/34/10/*G/0141C (Ludham Road) and 7/34/09/*G/0144B (Plumsgate Road) (with some very recent data also provided by Mr Alston). (Note, the most recent licence numbers for these two licences are AN/034/0009/009 and AN/034/0009/008 respectively. However, the older form of licence number is still the one most commonly used, and therefore will be used in this report)
- Daily abstraction quantities for Catfield Broad surface water abstraction licence 7/34/09/*S/0084;
- Daily abstraction quantities for the Overton licence 7/34/10/*G/0111;
- Daily abstraction quantities for the Anglian Water Services (AWS) Ludham licence 7/34/09/*G/0091;
- Annual abstraction quantities for the above licences.

2.5 Borehole Records

Including all records (lithological logs and construction records) for the installations listed in Section 2.1.2 and for the abstraction boreholes of the licences listed in Section 2.4 as available from the Environment Agency, Mr Alston, and from reports given in Section 10.

2.6 Sluice Operation Records

Comprising all records available for sluice operation between the internal and the external system, provided by Mr Harris.

3. Overview of Catfield Fen and its Setting

Catfield Fen is located on the eastern side of Ant Broads & Marshes SSSI, between Barton Broad and the village of Catfield (Figure 3.1). It comprises both an "external" drainage system which is linked to the River Ant and Barton Broad, and an "internal" drainage system which is separated from the external system by a bank called the Commissioners' Rond. Though not precisely defined, the term "Catfield Fen" is generally applied to the internal system and to Great Fen in the external system to the west.

The boundary between the internal and external systems is shown in Figure A1 in Appendix A[1], and with more precision in the south, in Figure A2. The internal system can be connected to the external system by 2 sluices which allow flow through the Rond (Figure 3.1), but generally the current aim is to keep these sluices closed in order to maintain water levels in the internal system at a higher level than in the external system, and to prevent what is considered to be nutrient-rich river water from entering the internal system. The southerly sluice is generally kept closed, and the other is normally only opened for short periods, if at all, in the winter months in order to assist reed and sedge cutting.

The names assigned to different compartments within Catfield Fen are shown in Figures A2 and A3, as well as to some extent in Figure 3.1. Figure A3 includes that part of the Fen which is owned by Catfield Hall Estate, and Figure A2 includes the parts of the internal system to the west, these being managed by Butterfly Conservation. Great Fen, further to the west on the western side of the Commissioners' Rond in the external system, is managed by Norfolk Wildlife Trust.

The southern boundary of the Butterfly Conservation land is also marked by the Commissioners' Rond, following a sharp change of direction at the Rond's south-west corner, and further south, Little Fen and Irstead Holmes are understood to belong to Catfield Poors Trust. A meandering former course of the River Ant, along which the parish boundary runs, occurs within this area, though its form is changing with changes in dyke management over the past thirty years or so. This can be seen by comparing Figures A2 and 3.1. Furthermore, changes have taken place since the basemap for Figure 3.1 was produced, there now being a wide dyke extending along the entire southern side of Commissioners' Rond (to the south of gaugeboard TG32/711). This shown on the aerial photograph (Figure A4), dating from 1998. It was probably dug out during the period about 15 years ago when the dykes to the south of the Rond were cleared (Andy Hewitt, reed and sedge cutter, pers.comm).

ECUS (1997) note that the name Commissioners' Rond name is clearly associated with the Commissioners for Drainage, appointed at Inclosure, but it is not known if the Rond is related to these officials or preceded them. Nonetheless the purpose of the Rond was to assist with the drainage of the internal fens, but this appears not to have been successful. Giller and Wheeler (1986a) describe the Rond a "solid peat 'wall' about 5 m wide" and show it to be resting on the clay layer at a depth of about 0.8-1.5 m below the surrounding fen surface. This clay layer underlies the former course of the River Ant, which the Rond follows, and is underlain by further peat (Section 4.3). The Rond is lowest between Sedge Marshes and Great Fen, but its top is at a higher level further

[1] Where Figure or Table numbers are prefixed by a letter (e.g. A1), the letter refers to an Appendix (e.g. Appendix A).

south as a result of spoil from the cleaning out of dykes in Little Fen and Irstead Marshes having been placed upon it.

The Fen includes both areas of open fen and areas with taller scrub. The vegetation types and associated ecology have been described by many authors, including Giller and Wheeler (1978 to 1988), Wheeler and Shaw (2006), Norfolk and Norwich Naturalists' Society (NNNS)(2008), and Natural England et al. (2011). Giller and Wheeler (1986a) have identified extensive areas of the fen surface, accounting for about half its area, which were formerly shallow turf ponds, formed by peat digging to depths of 70-80cm apparently in the 19th century (Figure A5). Most of these areas have subsequently undergone re-vegetation and are now not necessarily evident in the field.

One feature that is not clear from the published maps is the presence of a low bund dam at the southern end of the internal system, adjacent to the Rond (Figure 3.1). This prevents water in the internal system from draining to the south along the dyke which leads to Mud Point, and thence to the Sharp Street Fens. The bund is about 30 m wide, from north to south, and is slightly raised over a 2-3 m width immediately adjacent to the internal dyke at the south end of Catfield Fen. Photographs of this bunded area taken during site visits in November 2011 and February 2012 are shown in Figures J7 to J9. Its top is at a lower level than the adjacent Commissioners' Rond and the presence of a muddy surface, with little if any low-lying vegetation, indicates this is a location where water is likely to overflow when fen water levels are high. Such overflow has been observed by Andy Hewitt and by Andrew Alston, and is shown in Figure J10 (see also Section 5.5.2).

The dykes within the internal system are about 3 m wide and clear of tall vegetation. Giller and Wheeler (1982) noted their water depth was about 1.5 m. In the external system in Irstead Marshes, the dykes tend to be wide and clear and have good connection with the River Ant. Great Fen is potentially connected to Barton Broad in the north near Wood End Staithe but this dyke is very overgrown and not cleared out in order to limit the influence of Broad water on the Fen (Andy Hewitt, pers. comm.) The main connection of Great Fen to the river is from the south, but flow is impeded by the vegetation growth within the dykes.

Water input to the internal system from the upland areas to the east occurs from a field drain which discharges to a drain at the eastern edge of North Marsh, and from surface watercourses in the Glebe area near Catfield School and in the south-east corner near NTG3270P4 and P5 (Figure 3.1). Mrs Middleditch of the Old Rectory (pers. comm.) has confirmed that there is a spring in the Glebe which has a small flow throughout the year. Runoff via a road drain into the ditch containing this spring is also understood to occur on some occasions. Mr and Mrs Harris also regard the Glebe area as being the location of a spring, and a former owner of Catfield Hall, Mr McDougall, thought there were springs not only in the Glebe but also in the North Marsh and Middle Marsh areas (Mrs. Harris, pers.comm.). Mr and Mrs Harris believe that the wetness of parts of Middle Marsh, with the associated presence of bogbean, may be indicative of such groundwater discharge.

Evidence of groundwater discharge near the eastern margin of the Fen is also indicated by the water chemistry of the catchwater drain in this area (Section 5.5.3) and by observed discharge on the southern edge of the low-lying bund at the southern end of the internal system (Figure J9).

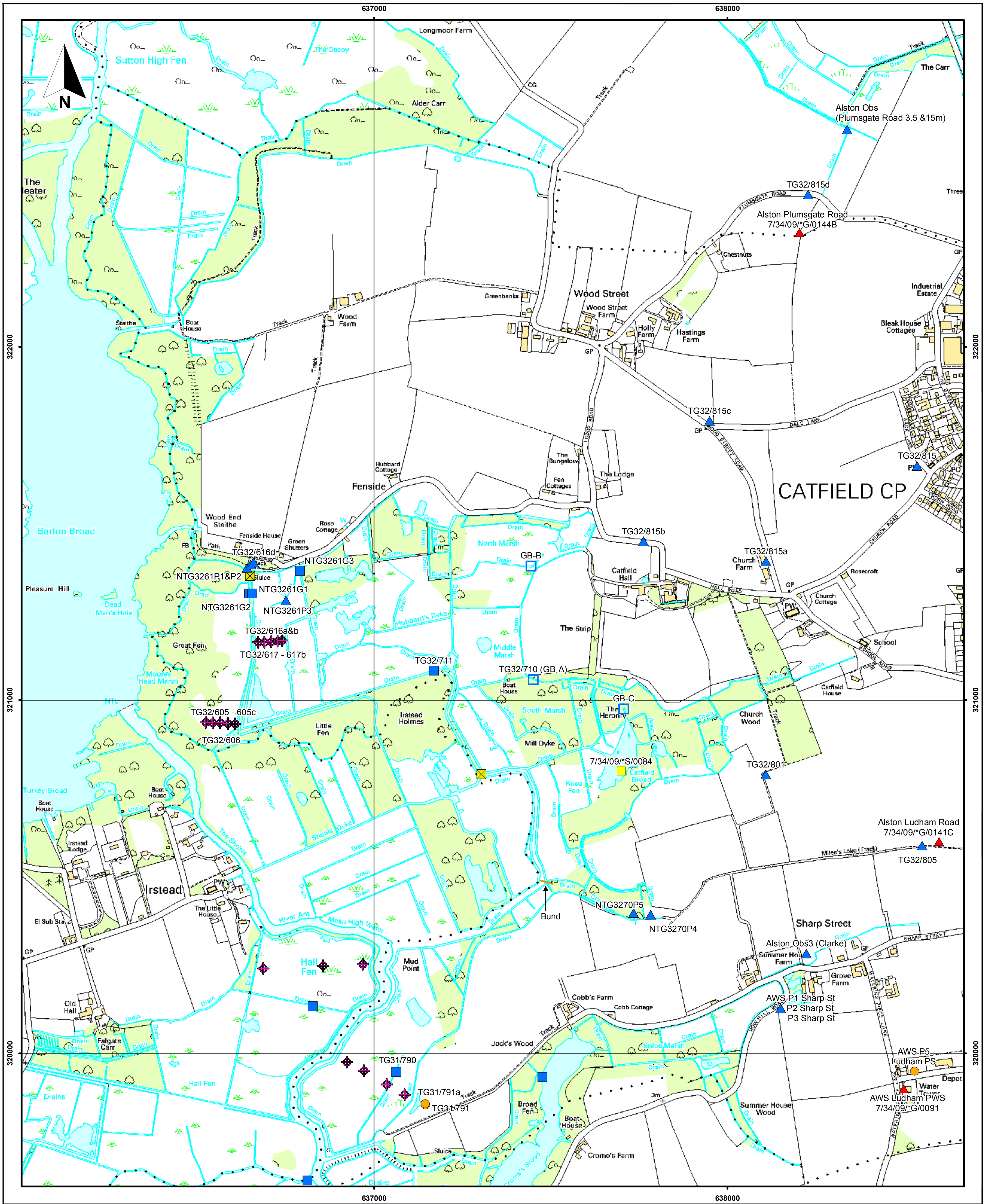
Topographic data for Catfield Fen were collected as part of studies by the University of Birmingham (Figure A6). These show the surface to be relatively flat with levels in the internal system generally ranging from

0.5-0.75 mAOD with no clear trend in any particular direction, whereas levels in Great Fen (external system) generally range from 0.25-0.55 mAOD. Some recent topographic data suggest slight differences in these levels but the University of Birmingham data give the most extensive coverage which can be used to give a broad overview (see Section 5.3). However, though survey data are not available to support this, field evidence suggests that the ground surface may rise towards the east across the Fen. This is based on the observed height of the compartments above the dyke water levels, since it appears that some of the western compartments such as Sedge Marshes are at a lower level compared to the dyke water level than are some other compartments to the east (e.g. Long Marsh).

The Fen is bounded on its northern and eastern sides by marginal catchwater drains, beyond which the land gently rises 5-7 mAOD over distances of 200-500 m. Beyond the boundaries of the Catfield Hall estate, this gently rising land is largely arable.

It is within the upland areas that groundwater abstraction occurs, taking water from the underlying Crag. The locations of these licensed abstractions are shown in Figure 3.2, together with a map of the geology of the area. The potential impact of these abstractions will be considered in Section 7.

Photographs of the Fen near to Commissioners' Rond are shown in Appendix J.



Key:

Existing Installations

- Agency Gaugeboard
- Catfield Hall Gaugeboard
- Dipwell
- Piezometer
- Borehole
- Licensed Groundwater Abstraction
- Licensed Surface Water Abstraction
- Water Control Structure/ Sluice
- Bund

0 100 200 300 400 500 Metres

1:10000 @ A3

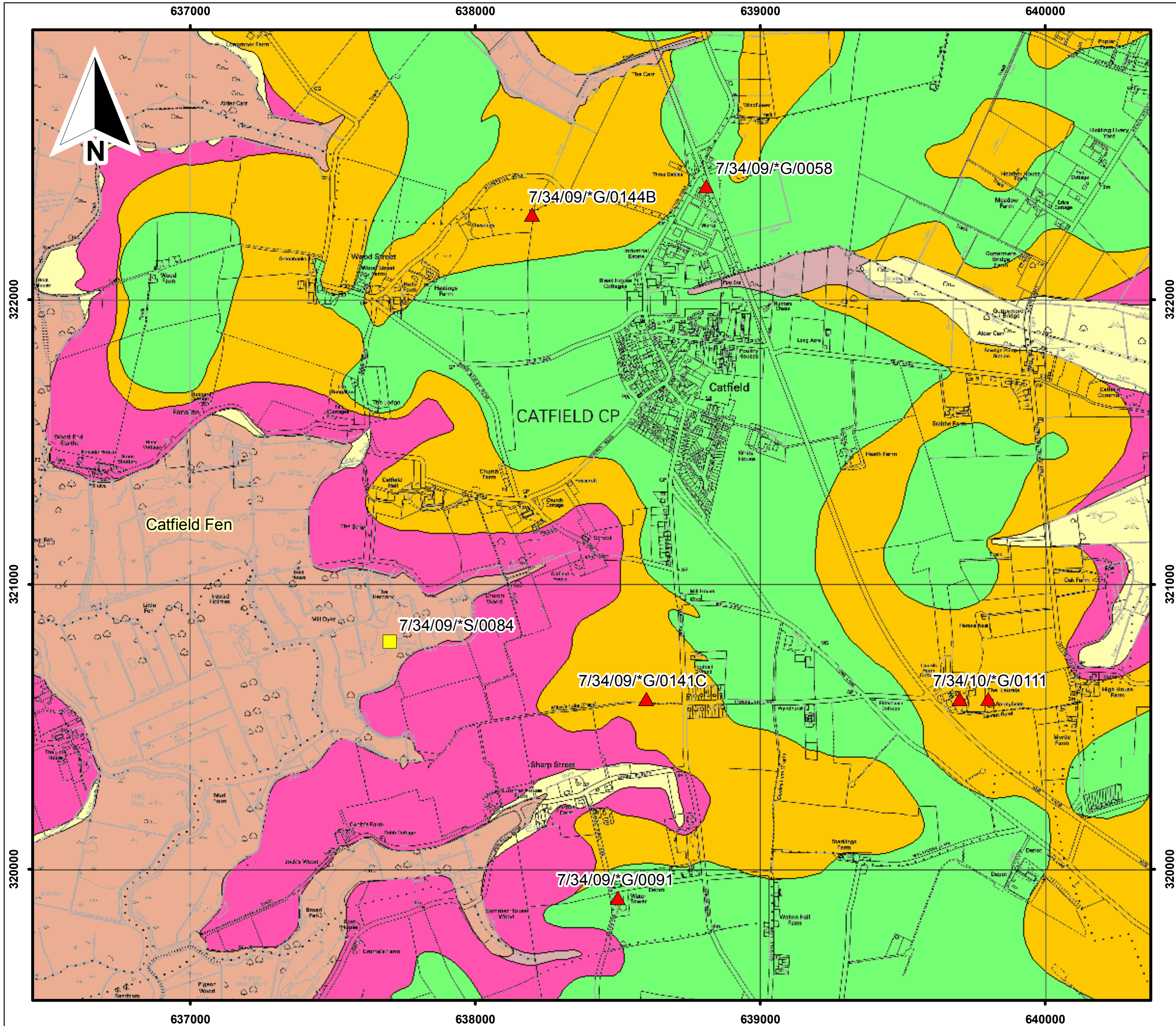
Project Path: G:/MODEL/PROJECTS/HM-250/30321/ArcGIS/Figures/30321s01a_Figure3.1.mxd

Environment Agency Anglian Region
Catfield Fen Investigation

Figure 3.1
Hydrological Monitoring and Licensed Abstractions in the Vicinity of Catfield Fen

March 2012
30321-S01a wills

amec



Key:

- Surface Water Abstraction
- Groundwater Abstraction

Drift Geology

- Alluvium
- Peat
- Head (undifferentiated)
- Till/Lowestoft Formation
- Diamicton - Corton Formation
- Sand & Gravel
- Sand/Sand & Gravel - Corton Formation

Solid Geology

- Crag Group

0 250 500 750 Metres

1:20000 @ A4

Project Path: G:/MODEL/PROJECTS/HM-250/30321/ArcGIS/Figures/30321s02_Figure3.2.mxd

Environment Agency Anglian Region
Catfield Fen Investigation

Figure 3.2
Geology and Licensed Abstractions in the Vicinity of Catfield Fen

January 2012
30321-S02 wills

amec

4. Geology

4.1 Introduction

The geology of Catfield Fen and neighbouring areas has been the subject of three main groups of studies. These were by Jennings (1952), Wheeler and Giller from the University of Sheffield mainly in the 1980s, and the University of Birmingham (Gilvear and co-workers) mainly in the late 1980s.

The peats and clays which lie beneath the fens are in turn underlain by the floor of a buried valley which comprises sands, gravels, silts and clays of the Crag. The Crag also occurs at the margins of the fens where the land gently rises to the "uplands" to the north and east, and is overlain by the mainly sandy Corton Formation (Figure 3.2).

In the following sections, the nature of the Crag will be considered in some detail since it is from this geological formation that groundwater abstraction in the area takes place, and both its lithological variation and the nature of its upper surface in contact with overlying deposits is important in gaining a hydrogeological understanding of the fens. The nature of the superficial deposits of peats and clays overlying the Crag will be considered subsequently.

4.2 Crag

Geological logs of nearby boreholes have provided information about the lithological variations of the Crag as a whole. At the AWS Ludham public water supply (PWS) source, located about 1 km to the south-east of the SE corner of the fens, the Crag is about 50 m thick and is separated from the underlying Chalk by about a 12 m thickness of London Clay. Here the Crag mainly comprises layers of sand, silty sand, silt, sandy and silty clay and clay. Such sand-rich and clay-rich layering has also been observed in other boreholes in the vicinity of the fens.

Details about the stratigraphy within the Crag at both the Ludham PWS source and at AWS Sharp Street boreholes about 400 m to the north-west (Figure 3.1) are summarised by Atkins/ HSI (2003). The Crag has been subdivided into three main hydrogeological units, the units being bounded by distinctly more clay-rich layers. A geological section crossing Catfield Fen is shown in Figure B1, extending from the Ludham Pumping Station (PS) in the south east to the north-west corner of the Fen. It illustrates the depths of these layers, as well as lateral variations in the lithology of the Crag. The line of the cross-section is shown in Figure B2.

The uppermost unit comprises fine- to coarse-grained sand with some gravel and is 13-16 m thick with its base being at -10.5 to -11.5 mAOD. It may include not only the Crag but also the Corton Formation, the two being difficult to distinguish in many places. It is underlain by a clay layer which is about 1.5 m thick, though at the Sharp Street P2 borehole it was found to include about 0.5 m of sand.

The middle unit of the Crag is about 30m thick at Ludham PS P5 but includes a 9.5 m thick silty clay layer within its sand sequence. At Sharp Street P2 this middle unit is about 40 m thick and does not include the silty clay layer seen at the Ludham PWS source, though a layer of silty sand is present at a slightly greater depth than at Ludham. A comparison of the geology encountered at these two locations therefore indicates that the middle unit has a variable thickness and may have discontinuous layering. At the base of the unit at both locations is a 1 m thick clay unit with a high natural gamma count (indicative of high clay content).

The basal Crag unit has only been penetrated at the Ludham PWS source, and is about 7 m thick, largely comprising sand, but including a clay layer about 1 m thick. The unit is underlain by London Clay which was shown in one of the Ludham PS boreholes (TG31/38b) to be about 11.6 m thick. Regionally, the London Clay is known to thin towards the west, and about 1400 m to the west of Ludham PS, adjacent to Sharp Street Fens, a borehole drilled in 2007 encountered Chalk at a depth of 60 m, directly underlying the Crag, with no London Clay present (TG31/791, Appendix I).

The nature of the Crag immediately beneath the fens of the Ant valley has been described by Jennings (1952). His paper on "The Origin of the Broads" describes the alluvial stratigraphy of the Ant valley and provides three geological cross-sections near Catfield Fen: one across Barton Broad and the west side of Great Fen (his Barton Broad – Fenside section), another from the Irstead Marshes northwards across Great Fen and into the north part of Sedge Marshes (his Irstead – Fenside section, Figure B3) and also a section further south across the River Ant (his Irstead – Sharpe Street section).

Jennings' cross sections are based on a series of auger holes which were drilled through the superficial deposits of peats and clays into the underlying floor of the buried valley. The Irstead Shoals (along which the River Ant flows out of Barton Broad) has a hard bottom of gravels. In the deepest auger bore in the Irstead-Sharpe street section the buried valley floor comprised sandy gravel, and elsewhere in this section, the floor comprised silty clay. In summarising the lithology of the Crag underlying superficial deposits within the Ant valley, Jennings (1952, p43) noted, "the hard floor of the buried valley, except on the uppermost flanks and in the very deepest bores, is a stiff clay which changes downwards, rapidly but usually progressively, into sand and gravel." Jennings considered the silty clay to be suggestive of a soil profile.

Giller (1982) undertook a detailed investigation of the Catfield and Irstead fens which included a series of closely spaced auger holes. Near the fen margin, in Sedge Marshes, peat was found to overlie sand, gravel and gritty clay (Giller & Wheeler, 1986; and ECUS, 1997). Elsewhere, the mineral ground was too deep to be encountered.

The nature of the deposits overlying the Crag will be considered in the next section.

4.3 The Superficial Deposits of the Catfield and Irstead Fens

The infill of the buried valley occurring with the Ant valley, and underlying the Fens comprises peats and clay which have a distribution which can be largely understood in terms of their paleogeography. Jennings (1952) identified the essential sequence, and this was later amplified by Giller and Wheeler (1986a) with further contributions by Sadler (1989) and the University of Birmingham team.

Jennings (1952) found that brushwood peat forms the bulk of the valley fill and this is overlain by clay or Phragmites clay (i.e. Phragmites-rich clay), this being thickest near the former watercourses and thinning away from them. In the Irstead-Fenside section, the top of this clay was 0 to -0.4 m O.D., and was thickest in the vicinity of Hundred Dyke which Jennings equated with the former course of the River Ant. The clay did not extend to the fen margin. The clay, and near the fen margins the brushwood peat, was overlain by Phragmites peat which extended to the fen surface.

The greatest thickness of superficial deposits encountered in the Irstead-Fenside section was about 9 m, whereas further south in Wrights Marsh they reach a maximum thickness of 12 m (Giller & Wheeler, 1986a).

Giller & Wheeler (1986a) present two cross sections, one running N-S from Sedge Marshes to Wright Marshes, and the other W-E from Sedge Marshes to Fenside (Figure B4). They found a wedge of "pure" clay, up to about 1 m thick, beneath Hundred Stream, and also less defined wedges further south. These clays graded laterally into Phragmites clay and this in turn graded laterally northwards into a layer of peat containing greasy organic muds. This peat/ greasy mud layer was up to 50 cm thick, with the mud content decreasing upwards to its top at a depth of about 1 m. In summary, progressing southwards from the fen margin across Sedge Marshes, the brushwood peat is overlain first by peat with greasy mud, and then after about 200 m from the fen margin by Phragmites clay, and then near the Rond and Hundred Stream by clay. A map showing the distribution of clay and Phragmites clay (and by default where they are absent) is shown in Figure B5.

The peat overlying this clay/ mud horizon was found to be about 0.8-1.5 m thick and to be either a solid, dark, humified peat in uncut areas, or a loose and sloppy fresh peat in those areas which had been subject to peat cutting (such as Fenside) and have subsequently re-vegetated. The depth of peat cutting was generally to a depth of 0.7-0.8 m over continuous peat, this being the depth that could be cut with the peat spade. Where clay deposits were present, this depth could be slightly shallower.

The paleogeography leading to the observed lithological variations within the superficial deposits has been described by Jennings (1952), Giller & Wheeler (1986a) and Wells & Wheeler (1999). The brushwood peats forming much of the valley infill resulted from carr development which was widespread in Broadland from the late Flandrian until the Romano-British marine transgression (i.e. from about 2000 to1600 B.P.) when water levels rose. Estuarine clays were then deposited, the Catfield and Irstead fens being near the head of the estuary, with organic silts and muds being deposited in marginal swamps. The clays deposited during Romano-British times represent the "Upper Clay" of the Breydon Formation. The overlying peats were deposited after the end of the marine transgression (c. 1600 B.P.), when the sea had again receded and conditions were less brackish. The development of the post-transgression fen peats has been discussed by Wells and Wheeler (1999).

Sadler (1989) has also mapped the thickness of the superficial deposits and found that a clay layer occurs at the base of the peat. The depth of top of Crag, the thickness of the clay and the consequent thickness of overlying peat are shown in Figures B6, B7 and B8. In his M.Sc. thesis, Sadler refers to these thicknesses as having been determined by augering but Gilvear (pers. comm.) has noted that much of the depth determinations were done by probing the ground by using long extendable reinforcing rods and assessing the lithology by "feel", the difference between peat, clay and Crag sands being noticeable. Unfortunately Sadler does not provide any auger hole logs both to identify their location, and to provide stratigraphic details.

Within the internal system, the basal clay appears to vary from about 0.3 to 1 m thick, where present, and to increase in thickness towards the south-west (Figure B8). It appears to be absent from some "windows" in the vicinity of North Marsh and within some dykes, where the dykes have been cut into the Crag (Figure B8). Such dyke locations appear to be the north and east of the surveyed internal system. The absence of basal clay in marginal locations has also been noted by Giller and Wheeler (1986a). In Figure B4, a cross-section shows that peat lies directly upon Crag near the northern margin of Sedge Marshes. ECUS (1997) report encountering gritty bedrock, "probably crag" within Sedge Marshes, about 25 m south of the boundary track. They also encountered firm clay at a depth of 4.3 m about 40 m further south.

The provenance of this basal clay layer is not clear. Though a "Lower Clay" (forming part of what is now called the Breydon Formation) occurs at depth nearer the coast, Jennings (1952) found no evidence of it in any of his Ant valley cross sections. It is generally regarded that this clay was not deposited as far inland as the Barton Broad part of the Ant valley. Yet it is clear that the basal clay is not confined to Catfield Fen alone. ECUS (1998) found clay above the mineral ground at Sutton Fen to the north of Catfield Fen. Also, Wheeler (pers.comm.) recalls that a basal clay layer was widespread at Catfield Fen when he undertook deep corings.

In summary, it should be noted that there are two separate clay layers at Catfield Fen. This is not always clear in the University of Birmingham work, and the two layers are equated as the same thing by Atkins/HSI (2003). The basal clay layer is widespread, but appears to be absent at the fen margins, in places near to the margins (e.g. in parts of North Marsh) and in the bottom of some dykes where they have been cut down into the Crag. At a higher level, within the peat sequence, a separate clay of Romano-British age occurs in the vicinity of the Hundred Stream but thins out to the north and east and is absent over a large part of the internal system (Figure B5).

Box 1 **Comments by Professor Gilvear**
Section 4.3 The Superficial Deposits of the Catfield and Irstead Fens *In relation to the work of Sadlar (1989) the word augering is wrong and probing would be the best term – I was present however during some of the probing and the technique worked well in identifying the base of the peat, the presence or otherwise of clay and the top of the crag.*

5. Hydrology and Hydrogeology

5.1 Introduction

The discussion about the hydrology and hydrogeology of Catfield Fen will consider the information that can be gained from the substantial body of water level and water chemistry data that are available. Initially, however, the influences on these data will be considered. These will include data relating to rainfall and evapotranspiration, these being important contributing factors affecting the water available to the fen. The available topographic data will also be considered since a topographic survey of monitoring installations was undertaken as part of this investigation in order that water levels could be compared in relation to a common datum, rather than to older surveyed datums that had been determined at different times and by different methods in the past.

5.2 Rainfall and Evapotranspiration

Rainfall data have been used for two purposes in this investigation. Firstly, daily rainfall data have been used when analysing hydrographs in order to see what effect rainfall has upon water levels, and secondly they have been used with evapotranspiration data to investigate any annual and long-term trends in the potential rainfall input to the fens.

The prime source of rainfall data has been the Barton Hall rain gauge (site id 34/09/02 at TG 354 223), located 2 km NW of Catfield Fen on the west side of Barton Broad. Meteorological Office (Met Office) processed daily data have been available since October 1980 for this rain gauge. To extend this dataset further back and to infill gaps in the record, data from two other rain gauges have been investigated. These are from Ormesby St Michael (site id 34/10/01 at TG468 152) about 11 km SE of Catfield Fen, and Buxton Dudwick Cottages (site id 34/06/06 at TG222 222) about 15 km W of Catfield Fen. Their records start in January 1961 and January 1994 respectively.

These data have been compared to the weekly rainfall data collected by Catfield Hall Estate and available since January 2009. These comparisons are shown in Figures C1, C2 and C3. Not surprisingly, the Barton Hall data show the greatest similarity to the Catfield Hall data, and are particularly similar over the period January to July 2009 and since December 2010. Differences between these dates may reflect real differences, or be the consequences of errors in the data collected from either rain gauge.

Data from the Ormesby St Michael and Buxton Dudwick Cottages rain gauges show greater scatter when compared to the Catfield Hall data. The Ormesby St Michael rain gauge shows slightly less scatter, and is more equally distributed about the Catfield Hall data, variations tending to be within 10 mm of the Catfield Hall readings. The Ormesby St Michael data have therefore been used to extend and infill the Barton Hall data. Where available, data processed by the Met Office have been used, as they depart less from the Catfield Hall data than do the raw, unprocessed data. Raw data have however been used where Met Office data have been unavailable.

A plot showing the various sources of data used during the period 1980-2011 is shown in Figure C4, and is shown in more detail for 2008-2011 in Figure C5. Data prior to 1980 is from Ormesby St Michael Met Office-processed data.

In order to assess any climatic differences between years and whether there has been any long-term trend in the effective rainfall in the vicinity of the Fen, the chosen composite rainfall dataset has been combined on a weekly basis with weekly MORECS potential evapotranspiration data for grass (PEgrass) from the Met Office for this area of Norfolk (MORECS square 121). The use of PEgrass is the most appropriate MORECS dataset to use when considering fen vegetation, and for the purpose of this simple assessment assumes evapotranspiration within the wetland environment occurs at its potential rate throughout the year.

The net rainfall after taking account of PEgrass is shown for both winter (October-March) and summer (April-September) periods from 1961 to the winter of 2010/ 11 in Figure C6. The “winter” periods are times when net rainfall exceeds evapotranspiration and water can be stored in the fens, whereas the “summer” periods are the times of greatest evapotranspiration demands when the stored water gets used up and water levels fall. Figure C6 shows those summers which had highest net evapotranspirative demand in relation to rainfall, and these appear to be those when shallow groundwater levels are low, particularly when the net rainfall in the preceding winter is relatively low (e.g. as in the summers of 1976 and 1996). This is illustrated by comparing Figure C6 with Figure C7 which shows modelled shallow groundwater levels for a model cell location at Catfield Fen for the period 1970-2005 (Entec, 2009). Figure C7 shows both the varying summer minima and those years which have been considered to be drought years by the Environment Agency. Those summers with low groundwater levels also had high net evapotranspirative demand. It is of note that several drought years (e.g. 1973-74, 1976, 1989-91, and 1996-97) were also preceded by low net rainfall. Also, several years when groundwater levels rose to relatively high levels, as in 1988, 1994, 2001 (see Figure C7) and 2007, were also those years when high winter rainfall and relatively high net summer rainfall occurred in consecutive summer/ winter or winter/ summer periods (Figure C6).

This approach of looking at variations in rainfall and evapotranspiration between “winter” and “summer” periods does not indicate any clear long-term trend showing increasing or decreasing net rainfall. However, it is a relatively simple approach which uses weekly data and divides the year into only two parts. It can be useful for comparing relative differences between individual years and summer/ winter periods, but not sufficiently detailed to identify long-term trends with any confidence.

5.3 Topographic Data

As noted in Section 3, Catfield Fen has been the subject of a comprehensive topographic survey by the University of Birmingham (1989). This is shown in Figure D1. The numerous installations on and around the Fen have also been the subject of several more recent surveys, each survey measuring the datums, and normally ground levels, at newly constructed installations. The surveys of datums have therefore taken place at different times, at different locations, by different survey teams, probably using a variety of survey methods. Surveys were undertaken by Solo Designs in 1992, HSI in 1996 and 1997, and Atkins in 2006 and 2011. These are summarised in Table D1.

In order to be able to compare water levels at different locations to a common datum, a topographic survey of currently monitored installations was undertaken by Atkins on 20 and 21 October 2011. The survey results are shown in the Atkins location diagrams included in Appendix D, and summarised in Table D1.

The details of water levels relative to a common datum (m AOD) will be discussed in the next Section, but as they are reliant on the precision of the topographic survey work over the two days of the survey, two points are worth noting.

Firstly, the datums for the boreholes NTG3270P4 and NTG3270P5 recorded on 21 October 2011 are significantly different from those recorded by the previous survey in 1997 (Table D1). The casing top monitoring datum from the 2011 survey for NTG3270P4 is 0.428 m lower than in 1997, and for NTG3270P5 it is 0.407 m higher than in 1997. Using the 2011 datums, the groundwater levels in NTG3270P4 are lower than those in NTG3270P5 (Figure E17), whereas using the 1997 datums, they are higher than in NTG3270P5 (Entec, 2010). This results in a significant change to the hydrogeological understanding of the area. The water level data using the 2011 survey levels are more consistent with those observed at nearby AWS observation boreholes at Sharp Street, and it may be that the 1997 survey data are incorrect.

Secondly, the three Catfield Hall gaugeboards on the eastern side of the Fen were surveyed on 21 October 2011 for the first time and from inspection of the survey photographs, the water levels at GB-A (TG32/710), GB-B, and GB-C were about 0.66 m AOD, 0.59 m AOD and 0.60 m AOD respectively (Appendix D). On the same day the water levels on the western edge of the internal system at NTG3261G1 were 0.33 m AOD. This difference in water levels is unexpected as previously it had been considered that there was very little if any head difference in dyke water levels across the site.

It is unfortunate that the topographic survey of the installations on the western side of the Fen were done on a separate day (20 October) from those on the eastern side as it raises the question as to whether the surveys on the two days are comparable, being related to the same datum. In order to investigate this, the Atkins survey team have subsequently on two occasions checked the survey data, and can find no reason for there being any difference between the two days. Though it therefore appears that the data as a whole are correct, there is nonetheless an uncertainty over whether water levels in the eastern drains are indeed about 0.3 m higher than those in the west. This is based on the previous understanding of dyke water level differences across the site, from LIDAR data discussed below) and from comparison of dyke water levels with groundwater levels (as will be discussed in Section 5.4.3). There is therefore a case for re-surveying the installations surveyed on 21 October together with NTG3261G1 and TG32/711 all on the same day both to confirm the head differences across the site, and to confirm the relationship between NTG3270P4 and NTG3270P5.

The use of LIDAR (Light Detection and Ranging) topographic data has also been investigated using data supplied by the Environment Agency. According to Geomatics UK Ltd (pers.comm.) the data are produced by firing a laser vertically from a plane flying at an altitude of 800 m and measuring the reflected signal off the “ground” surface. By the time the laser beam reaches the ground surface it is about the “size of a dinner plate” and unless the beam can penetrate any vegetation cover and be reflected off the ground surface, the ground surface reading will be affected by the vegetation and not be a true reading. The data can be subsequently “filtered” in order to try to correct for such vegetation influences, but as will be seen below is not necessarily fully successful. The pixel size for the topographic data 2 m^2, with a quoted error in vertical measurement of +/- 0.25 m. The precision along a particular flight line was described a "very good", being a matter of millimetres.

Filtered LIDAR topographic data are shown for the Catfield Fen region in Figures D2 and D3. These were collected from flights flown in March/ April 1999 and January 2009 respectively. The effects of leaf cover on trees is evident when comparing figures D2 and D3. The March/ April 1999 data (Figure D2) suggest that the land is slightly higher than the surrounding Fen in the south-west corner of North Marsh, in the south-east corner of Mill Marshes, and to the south and east of Catfield Broad. The aerial photograph, Figure A4, shows these areas to be covered by trees, and the LIDAR data from January 2009 (Figure D3) when there would have been no leaf cover shows the topographic differences between these areas and the adjacent fen to be much more subdued than shown in Figure D2. This point is made to show that the LIDAR data does not necessarily show ground level. Dense reed and sedge beds may also affect the penetration of the laser beam to the ground surface, and therefore affect the recorded level of the "ground" surface.

The LIDAR data shown in Figure D3 well illustrate that the catchwater drains follow the break-of-slope which separates the uplands to the east from the fen areas to the west. These fen areas appear to be fairly flat lying, though it should be noted that the coloured data intervals are 0.2 m, and therefore the change from one interval to another could be significant within a fen environment, though not necessarily so because of the potential interference effects due to vegetation and because the interval change need not indicate a 0.2 m change.

The potential impact of Fen vegetation is indicated by comparing 2009 LIDAR data with 2011 survey data at some dipwell and borehole locations. Table 5.1 shows examples from both Fen areas where the vegetation is relatively tall and "upland" areas were vegetation is shorter. Photographs of these installations showing the surrounding vegetation are to be found in Appendix D. In the fen areas, the LIDAR data appear to be giving higher values than those surveyed, whereas in the upland areas where the vegetation is shorter, the LIDAR data appear to give a closer representation of the surveyed levels, and are not significantly higher than is the case in the fen areas. These data suggest that the LIDAR data is influenced by the tall dense reed and sedge vegetation, and show levels which are higher than those surveyed.

Table 5.1 Comparison of LIDAR and Surveyed Data at the Fen and Off-Site in the "Uplands"

Installation	Location	Vegetation Type and Approx Height (m)	LIDAR Level (mAOD)	2011 Surveyed Ground Level (mAOD)
Dipwell TG32/617b	Sedge Marshes	Sedge c. 0.8 m high	0.8	0.371
Dipwell TG32/605a	Southern part of Great Fen	Reeds 1.5-2 m high	0.8	0.358
Borehole TG32/801	"Uplands" to east of Catfield Broad	Grass c. 0.1-0.2 m high	3.8 (to east of track)	3.764
Borehole TG32/805	"Uplands" to east of the Fen near to the Ludham Road abstraction, on slightly raised ground adjacent to track	Grass c. 0.1-0.2 m high	5.2-5.6 (varying on either side of the track)	5.773

In the eastern part of the Fen, taking Middle Marsh as an example, the 2009 LIDAR data show levels of 0.5 mAOD in the south-east and 0.9 mAOD in the north-west (Figure D3). This difference in level across the compartment may be wholly or partly due to differences in vegetation height/ density.

Nearby, the LIDAR data at the location of gaugeboard TG32/710 at the eastern edge of the Fen indicate a ground level of 1.0 mAOD on the “upland” side of the drain and 0.9 mAOD on the Fen side, the vegetation being fairly short on both sides of the bridge. From the photograph in the Gaugeboard Location Diagram shown in Appendix D, the top of the bridge is at about ground level, and by comparing it with the adjacent gaugeboard, the bridge top is at about the 110.3 to 100.4 mark on the gaugeboard. Using the 2011 survey data, this equates to a ground level of about 1.25-1.35 mAOD. This is about 0.35-0.45 m higher than suggested by the LIDAR data, and since LIDAR tends to overestimate, not underestimate, the ground level, this is a further indication that the 2011 surveyed gaugeboard datum level may be in error and measuring too high a level. If there is an error, and correction is made, it might remove the 0.3 m difference in dyke water levels observed between the eastern and western parts of the Fen when using the 2011 survey data (discussed above).

Due to the effect of vegetation on the LIDAR data, investigating the difference in levels between the two sets of LIDAR data (1999 and 2009) is difficult to interpret. Where trees are absent, this difference is generally within the range -0.1 to 0.1 mAOD with a scattering of pixel areas indicating changes of up to 0.2 and -0.2 mAOD. It is, however, not possible to know whether these reflect changes in ground level, vegetation height and density, or both.

Though survey data are not available to support this, field evidence suggests that the ground surface may rise towards the east across the Fen. This is based on the observed height of the compartments above the dyke water levels, since it appears that some of the western compartments such as Sedge Marshes are at a lower level compared to the dyke water level than are some other compartments to the east (e.g. Long Marsh). East-west topographic transects will be proposed in order to determine whether this is the case.

Investigation of changes in ground level at the Fen over time is limited by the fact that of the surveyed installations, there were only three that are within the body of the Fen, these all being on the western side of the Fen. These are NTG3261P3 and TG32/617b in Sedge Marshes and TG32/605a in Great Fen. The ground levels in the 2011 survey compared to previous surveys were about 2-4 cm lower at the Sedge Marshes installations and about 7.5 cm higher at the Great Fen installation. Details are given in Table D1. Furthermore, if the casing tops are considered to have stayed at the same level (m AOD), which may not have been the case, the ground level appears to have fallen by 4.7 cm at NTG3261P3 and risen by 8 cm and 3.6 cm at TG32/617b and TG32/605a respectively. Given the uncertainties involved with comparing different surveys, and the difficulty of measuring ground level in an uneven and soft setting, it is doubtful whether any significance can be attributed to these measured differences.

Comparison of differences between some of the 2011 survey levels and those given by the University of Birmingham (1988) (Figure D1) may however be significant. The levels measured in 2011 at Sedge Marshes were 0.398 and 0.371 m AOD at NTG3261P3 and TG32/617b respectively, whereas the University of Birmingham survey suggests the level is about 0.6-0.7 m AOD. In Great Fen at TG32/605a, the 2011 ground level was 0.358 m AOD, whereas the University of Birmingham level at about the same location was about 0.45 m AOD.

The University of Birmingham levels may therefore be slightly higher than those identified by current surveying methods.

On the basis of the above consideration of a limited number of data points, it appears that comparison of the available topographic survey data from different times in the past is insufficient to determine whether there has or has not been any general trend in changing ground levels over the past 20-25 years.

5.4 Water Levels

5.4.1 Introduction

The locations of monitoring currently undertaken both within and in the vicinity of Catfield Fen is shown in Figure 3.1, with details of the installations being given in Table 5.2 and borehole logs in Appendix I. Water level hydrographs are shown in Appendix E. In this section, the water level data will be discussed with a view to gaining an understanding of how the fen water levels vary and to provide information that will contribute to a view as to how the Fen functions hydrologically. Any possible impact on water levels as a result of groundwater abstraction will be considered in Section 7. Initially, however, historic variations in regional water levels will be briefly considered in order to place the discussion of Fen water levels within a regional setting.

Table 5.2 Details of Monitoring Installations In and Near Catfield Fen (including details of nearby abstraction boreholes)

Agency ID	Alternative Name	Installation Type	NGR	Location: Fen or "Uplands"	Geology Log Available?	Depth	Monitored Horizon	Screened Interval (mbgl)	Monitored By:	Logger Currently Installed?	Comments
NTG3261G1	ABM-13	GB	636654 321302	Fen	Not applicable		Dyke water level		EA (AMEC/Mouchel)	Y	Logger data show excessively large fluctuations since June 2007. Logger has been replaced.
NTG3261G2	ABM-17a	GB	636646 321302	Fen	Not applicable		Dyke water level		EA (AMEC/Mouchel)	N	Ditch goes dry at gaugeboard location in several summers.
NTG3261G3		GB	636788 321374	Fen	Not applicable		Dyke water level		EA (AMEC/Mouchel)	N	Past datum issues prior to 2003.
TG32/711	ABM-17b	GB	637170 321079	Fen	Not applicable		Dyke water level		EA (AMEC/Mouchel)	Y	Logger data appears to be more erratic in 2009 and may be indicative of poor or failing logger functioning. Logger has been replaced.
TG32/710	GB-A; Ballscroft gaugeboard	GB	637450 321058	Fen	Not applicable		Dyke water level		Catfield Hall	Y	Gaugeboard installed by Catfield Hall Estate. Monitored both by Catfield Hall Estate and the Environment Agency
	GB-B;; North Marsh gaugeboard	GB	637456 321382	Fen	Not applicable		Dyke water level		Catfield Hall	N	Shown as GB-B in Figure 3.1. Gaugeboard installed and monitored by Catfield Hall Estate.
	GB-C; The Heronry gaugeboard	GB	637705 320991	Fen	Not applicable		Dyke water level		Catfield Hall/EA	N	Shown as GB-C in Figure 1. Gaugeboard installed and monitored by Catfield Hall Estate and Environment Agency have installed a logger.
TG31/790	ABM-22	GB	637062 319947	Sharp Street Fens	Not applicable				EA (AMEC/Mouchel)	Y	Logger removed in 2009, and EC Diver re-installed on 23/5/11.
TG32/617	ABM-18a	DW	636740 321169	Fen (Butterfly Conservation land)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/617a	ABM-18b	DW	636727 321167	Fen (Butterfly Conservation land)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/617b	ABM-18c	DW	636709 321166	Fen (Butterfly Conservation land)	No	Not known, probably 1-1.5 m	Peat		EA (AMEC/Mouchel)	Y	
TG32/616a	ABM-18d	DW	636690 321164	Fen (Butterfly Conservation land)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/616b	ABM-18e	DW	636672 321164	Fen (Butterfly Conservation land)	No	Not known, probably 1-1.5m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/605	ABM-14b	DW	636586 320934	Fen (Great Fen)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/605b	ABM-14d	DW	636543 320936	Fen (Great Fen)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG32/605c	ABM-14e	DW	636524 320937	Fen (Great Fen)	No	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.

Table 5.2 (continued) Details of Monitoring Installations In and Near Catfield Fen (including details of nearby abstraction boreholes)

Agency ID	Alternative Name	Installation Type	NGR	Location: Fen or "Uplands"	Geology Log Available?	Depth (m)	Monitored Horizon	Screened Interval (mbgl)	Monitored By:	Logger Currently Installed?	Comments
TG32/606	ABM-14a	DW	636607 320933	Fen (Great Fen)	N	Not known, probably 1-1.5 m	Peat			N	Following a wetland monitoring network review, this dipwell is to be removed from the network.
TG36/605a	ABM-14c	DW	636564 320936	Fen (Great Fen)	N	Not known, probably 1-1.5 m	Peat		EA (AMEC/Mouchel)	Y	
TG32/616d	ABM-20	BH	636662 321384	Adjacent to Fen	Y	24	Crag (middle unit)	21-23	EA (AMEC/Mouchel)	Y	
NTG3261P1		BH	636657 321375	Adjacent to Fen	Y	11.35	Crag (upper unit)	5-9	EA (AMEC/Mouchel)	Y	
NTG3261P2		BH	636658 321377	Adjacent to Fen	Y	0.9	Alluvial sand	0.4-0.9	EA (AMEC/Mouchel)	N	
NTG3261P3		BH	636758 321302	Fen	Y	3	Peat	0.4-1.5	EA (AMEC/Mouchel)	N	
NTG3270P4		BH	637783 320393	Adjacent to Fen	Y	12	Crag (upper unit)	8.0-9.9	EA (AMEC/Mouchel)	Y	
NTG3270P5		BH	637734 320398	Fen	Y	0.75	Alluvial sand	0.45-0.7	EA (AMEC/Mouchel)	Y	At times in the past, the logger transducer has not been placed low enough in the hole, with the result that the hole has appeared to go dry when it may well not have done.
	Plumsgate Road 3.5 m	BH	638340 322616	"Uplands"	No	3.5	Crag (upper unit)	Not known	Mr Alston	Y	Completed depth not known, but presumed to be c.3.5 m given the borehole id. Constructed by driving a well-point. An invoice dated 30/11/98 addressed to Mr Alston from Raingear Irrigation Ltd for the installation of the "well point" refers to it being 3m deep "consisting of slotted jetting head with 1 ½" galvanised steel tube to the surface."
	Plumsgate Road 15 m	BH	638339 322616	"Uplands"	No	15	Crag (upper unit)	Not known	Mr Alston	Y	Completed depth not known, but presumed to be c.15 m given the borehole id. Constructed by driving a well-point. An invoice dated 30/11/98 addressed to Mr Alston from Raingear Irrigation Ltd for the installation of the "well point" refers to it being 15m deep "consisting of slotted jetting head with 1 ½" galvanised steel tube to the surface."
TG32/805	Catfield Pump piezo. Also called Alston OB1	BH	638529 320581	"Uplands"	N	16.5	Crag (upper unit)	c.5-15	EA (Area)	Y	Sharpin (2010) notes this is the plumbed depth. Environment Agency (1998b), prior to borehole construction, states that the piezometer should penetrate 15 m into the Crag, with perforated screen over the lower 10 m. An invoice dated 30/11/98 addressed to Mr Alston from Raingear Irrigation Ltd for the installation of the "piezometer" refers to "2" diameter galvanised steel, 15 metres long with lower 10 metres of pipe slotted."
TG32/801	Catfield Hall piezo. Also called Alston OB2	BH	638102 320790	"Uplands"	No	15	Crag (upper unit)	c. 5-15	EA (Area)	Yes	Environment Agency (1998b), prior to borehole construction, states that the piezometer should penetrate 15 m into the Crag, with perforated screen over the lower 10 m. An invoice dated 30/11/98 addressed to Mr Alston from Raingear Irrigation Ltd for the installation of the "piezometer" refers to "2" diameter galavanised steel, 15 metres long with lower 10 metres of pipe slotted."
	Alston OB3. Also sometimes known as "Clarke"	BH	638244 320283	"Uplands"	No	15	Crag (upper unit)	c. 5-15	Not monitored	N	Environment Agency (1998b), prior to borehole construction, states that the piezometer should penetrate 15 m into the Crag, with perforated screen over the lower 10 m. It is not currently monitored. An invoice dated 30/11/98 addressed to Mr Alston from Raingear Irrigation Ltd for the installation of the "piezometer" refers to "2" diameter galavanised steel, 15 metres long with lower 10 metres of pipe slotted."

Table 5.2 (continued) Details of Monitoring Installations In and Near Catfield Fen (including details of nearby abstraction boreholes)

Agency ID	Alternative Name	Installation Type	NGR	Location: Fen or "Uplands"	Geology Log Available?	Depth (m)	Monitored Horizon	Screened Interval (mbgl)	Monitored By:	Logger Currently Installed?	Comments
TG32/815	Catfield P1	BH	638540 321680	"Uplands"	Y	8.8	Crag (upper unit)	6.0-8.5	EA (Area)	N	Gravel pack extends from 0.3 m bgl to the base of the hole.
TG32/815A	Catfield P2	BH	638116 321403	"Uplands"	Y	9	Crag (upper unit)	6.3-8.8	EA (Area)	Y	Gravel pack extends from 0.3 m bgl to the base of the hole.
TG32/815B	Catfield P3	BH	637762 321450	"Uplands"	Y	7.5	Crag (upper unit)	5.0-7.5	EA (Area)	Y	No data prior to 2011 available to this study, though it is understood manual readings were obtained until about 2004/5. After this the borehole was lost. The borehole was rediscovered by the Environment Agency in May 2010, and refurbished, including the cleaning out of infilled material by Mouchel. A logger was installed in 2011. Manual data prior to 2011 on WISKI may have become corrupted as it is not possible to retrieve it from WISKI. Manual and Logger data are available since June 2011. Gravel pack extends from 0.3 m bgl to the base of the hole.
TG32/815C	Catfield P4	BH	637942 321783	"Uplands"	Y	8.5	Crag (upper unit)	6.0-8.5	EA (Area)	N	Gravel pack extends from 0.3 m bgl to the base of the hole.
TG32/815D	Catfield P5	BH	638229 322432	"Uplands"	Y	6	Crag (upper unit)	3.6-6.0	EA (Area) manual/Mr Alston logger	Y	Gravel pack extends from 0.3 m bgl to the base of the hole.
TG31/791	ABM-42a	BH	637145 319854	Adjacent to Sharp Street Fens	Y	51	Crag (basal unit and/or base of middle unit)	47-50	EA (AMEC/Mouchel)	Y	Chalk encountered at 60 m bgl with no London Clay present. Hole backfilled to 51 m bgl prior to completion. Gravel pack extends from 44 m bgl to the base of the hole.
TG31/791a	ABM-42b	BH	637144 319858	Adjacent to Sharp Street Fens	Y	10	Crag (upper unit)	7-9	EA (AMEC/Mouchel)	Y	Gravel pack extends from 5 m bgl to the base of the hole.
AWS Sharp Street P1	Catfield Sharp Street P1	BH	63813 32011	Sharp Street	Y	27	Crag (upper part of middle unit)	23-26	AWS	Y	Borehole drilled to 32m and then backfilled to 27 m bgl. Gravel pack extends from 21.5 m bgl to the base of the hole.
AWS Sharp Street P2	Catfield Sharp Street P2	BH	63813 32011	Sharp Street	Y	61	Crag (lower part of middle unit)	42-54	AWS	Y	Gravel pack extends from 38 m bgl to the base of the hole.
AWS Sharp Street P3	Catfield Sharp Street P3	BH	63813 32011	Sharp Street	Y	10	Crag (upper unit)	6-9	AWS	Y	Gravel pack extends from 4.5 m bgl to the base of the hole.
AWS Ludham P5	Catfield Ludham PS P5	BH	63853 31995	Ludham PS	Y	58	Crag (lower part of middle unit)	37-43 and 46-50	AWS? (monitored as part of AMP investigations, but not a licence condition)	N?	Gravel pack extends from 33 m bgl to the base of the hole (and therefore includes both screened intervals).
AWS Ludham 1	PWS borehole 1; BGS Nos. 148/40d	BH (abstraction)	63850 31997	Ludham PS	N (construction details only)	59.7	Crag (basal unit)	50.9-57.0	N		
AWS Ludham 2	PWS borehole 2; BGS Nos. 148/40f and TG31/38	BH (abstraction)	63853 31995	Ludham PS	Y	60	Crag (basal unit)	49.1-56.0	N		Drillers' log (Appendix I) indicates 51m of slotted screen from about 8-59m depth, with (unusually) the top 19m of annulus being cement grouted and pea gravel filling the annulus below this. Alison Selby, AWS (pers. comm.) was aware of this anomaly and noted that a CCTV survey had confirmed the shorter screened length recorded by Atkins/HSI (2003) and shown in this Table.

Table 5.2 (continued) Details of Monitoring Installations In and Near Catfield Fen (including details of nearby abstraction boreholes)

Agency ID	Alternative Name	Installation Type	NGR	Location: Fen or "Uplands"	Geology Log Available?	Depth (m)	Monitored Horizon	Screened Interval (mbgl)	Monitored By:	Logger Currently Installed?	Comments
AWS Ludham 3	PWS borehole 3	BH (abstraction)	63849 31988	Ludham PS	N	57	Crag (basal unit and lower part of middle unit)	43-50 and 53-55	N		
	Abstraction borehole for licence 7/34/09/*G/141C (Ludham Road)	BH (abstraction)	c. 638598 320600	"Uplands"	Y	Probably 33.5 m (see comment)	Abstraction from Crag (probably upper and middle units)	Probably about 4.5 – 33.5 (see comment)	N		The geological log for the original borehole drilled in 1987 shows its depth to have been 33.5 m, comprising 29 m of screen and 6m of plain casing (some of which presumably was above ground level). This borehole collapsed either in 1991 or 1993 and was replaced in the same year by a borehole located about 8m from the original. There are no clear details as to the depth or construction of the replacement borehole. A log sent from the drillers (Dereham Water Supplies) to Mr Alston in March 2012 purports to be that of the replacement, but has exactly the same lithological log and construction description as the 1987 borehole. It appears that the replacement had the same design as the original (but this is not absolutely certain).
	Abstraction borehole for licence 7/34/09/*G/144B (Plumsgate Road)	BH (abstraction)	c. 638201 322323	"Uplands"	Yes	20.5	Crag (upper unit, and possibly upper 4.6m of middle unit)	Not known.			Well log shows borehole depth to be 20.73 m. No other construction details. Drilled in January 1986.

5.4.2 Regional Setting

Borehole Water Levels

There are not many long-term observation boreholes in north-east Norfolk, but hydrographs for two are presented from the Ant catchment, one from the Bure catchment, and one in the Upper Thurne catchment near Catfield village. These illustrate the effects of high rainfall recharge periods and of drought periods on groundwater levels.

Figure E1 shows the hydrograph from a 16.5m deep observation borehole TG13/320B located to the north of Aylsham within the Bure catchment. It is constructed within Sands and Gravels/ Crag and its water level response clearly shows the influence of major recharge periods. For example, groundwater levels rose sharply in 2001 as a result of both high rainfall during the winter and rainfall which exceeded PEgrass in the following summer (see Figure C6). This lead to very high groundwater levels throughout the region and to localised groundwater flooding.[2] In subsequent years groundwater levels gradually declined due to there being less overall recharge to the aquifer system, and with the storage within the system gradually being reduced by, for example, baseflow to rivers.

Groundwater levels then rose again sharply in 2007 largely due to there being high net rainfall during the summer. This would have limited any development of soil moisture deficit during this period and allowed recharge to occur. Water levels continued to rise into the subsequent 2007/8 winter since the winter rainfall did not have to make up any significant summer soil moisture deficit. The hydrograph shown in Figure E1 also shows the high recharge that occurred in 1988, as well indicating low water levels during the drought years of 1989-1992 and 1995-1997 when the borehole went dry.

This form of variations can also be seen in the shorter record from the Crag observation borehole TG32/914 to the east of Catfield village (Figure E2). The recharge events of 2001 and 2007 can be discerned as well as the low groundwater levels during the drought period 1995-1997.

The two observations boreholes within the Ant catchment both monitor Chalk groundwater levels (Figures E3 and E4). They show the various recharge events and drought periods identified in the Crag hydrographs and in Figure C6. They also have a longer record than for the Crag boreholes, and it is interesting that both Chalk hydrographs show that groundwater levels during the 1989-92 drought period reached lower levels than during the summer of 1976. Even comparing the two Chalk hydrographs indicates there is some regional variability in the relative groundwater level minima achieved in different years (for example, when comparing 1976 and 1982 in the two hydrographs).

Dipwells

Dipwell hydrographs are shown for two wetland sites in the Upper Thurne Broads and Marshes SSSI (Figure E5) and for four sites in the Ant Broads and Marshes SSSI (Figure E6). The details within these individual

[2] The contribution of Gavin Sharpin of the Environment Agency in drawing attention to these recharge events is acknowledged.

hydrographs will vary in a manner that is site specific, but they are shown in order to give a sense of how fen water table levels are fluctuating at locations other than Catfield Fen. Unfortunately, none of the dipwells has a long record, all starting to be monitored in either in 2006 or 2007. Winter water levels tend to be above or very close to ground level and the lowest water levels during the monitored period were in the summer of 2009, closely followed by 2010. Both these summers had relatively high net evapotranspiration (Figure C6).

The Upper Thurne hydrographs show evidence of low water levels in the summer of 2006, when monitoring began. In the Ant catchment only the first reading from Hall Fen occurred at this time, but for some reason does not show the low level. The next readings in late August 2008 are all at a time when the water tables have risen from their summer minima.

Broad Water Levels

Recorded water level variations at both Barton Broad and Hickling Broad also show the effects of the groundwater recharge events that took place in 2001 and 2007 (Figures E7 and E8). The water levels are affected by tidal events and rainfall, but these fluctuations are superimposed on trends where water levels are at their highest at the times of the high recharge periods of 2001 and 2007 and then subsequently decline. These are very similar to the groundwater trends shown in Figures E1 to E4, the declining trends being based on the fall in groundwater storage in the aquifer systems. The River Ant flowing into Barton Broad receives flow from both Chalk and Crag covered areas.

The influence of the groundwater contribution to river flow within the River Ant is also indicated by the baseflow (BFIHOST) index at Honing Lock, which is between Stalham and North Walsham, to the north of Barton Broad. In the absence of significant river augmentation (e.g. by sewage effluent), as is the case for the River Ant, this is index is a measure of the proportion of river runoff that is derived from stored sources of water, for example groundwater. The higher the baseflow, the more the river flow can be sustained during dry periods. Some Chalk streams, for example, have baseflow indices greater than 0.9. At Honing Lock, the index is 0.81 (Marsh & Hannaford, 2008). This is relatively high and is an indication that the Broad and its levels will be noticeably affected by variations in Chalk and Crag groundwater storage in the upstream catchment.

5.4.3 Water Levels in Boreholes

Boreholes at the fen occur in two groups, one being at the NW corner of the Fen and the other at the SE corner.

There are four boreholes installed to different depths within the north-western group, one shallow borehole only 1.5 m deep being constructed within peat in Sedge Marshes (NTG3261P3, Figure 3.1). The other three boreholes TG32/616d, NTG3261P1 and NTG3261P2 are located just to the north of the Fen and have screened depths of 21-23 mbgl, 5-9 mbgl and 0.4-0.9 mbgl respectively. Their monitored water levels are shown in Figure E9, and with the exception of TG32/616d, extend back to 1996. The deepest borehole, TG32/616d, was constructed in May 2006.

During the 1996-2011 period the borehole data indicate groundwater levels were at their lowest in 1996. They rose to their highest levels in 2001, and the hydrographs show a similar form to those observed in the regional observation boreholes (Section 5.4.2). High groundwater levels occurred as a result of the recharge events of 2001 and 2007 with subsequent declining trend in water level in the years following each recharge event.

Since the boreholes are screened at different depths they offer the opportunity to determine if there is the potential (not necessarily the actuality) for upward or downward groundwater flow. Figure E10, and the more detailed Figure E11, show that Crag groundwater levels at the 21-23 m depth (middle Crag unit, TG32/616d)) are very similar to those at 5-9 m depth (shallow Crag unit, NTG3261P1) in winter/ spring, but tend to be higher than at the 5-9 m depth in summer/ autumn. They are both higher than in the shallowest boreholes, water levels in NTG3261P1 tending to be 1-7 cm higher than in the adjacent NTG3261P2.

There is therefore the potential for flow to contribute to the fen, but whether it does or not is dependent on the hydraulic conductivities of the intervening material. Upward flow to the fen surface could be limited by clays within the Crag, the clay at the base of the peat, and the peat itself which has been shown by ECUS (1997) to have some low hydraulic conductivities. Near the Fen margins, in those places where the clay is absent (Section 4.3), there is greater potential for Crag groundwater flow to the peat deposits and to the dykes. It is of note that in winter and spring there is little difference between the groundwater levels in the middle Crag and shallow Crag boreholes, suggesting there is little potential for groundwater movement between them, and that in summer and autumn there is the potential for upward groundwater flow within the Crag (Figures E10 to E12).

Comparison of the borehole hydrographs with dyke water levels at NTG3261G1 shows similarities in their water level variations (Figure E12 & E13). The Crag water levels in the shallowest borehole at only about 0.9 m depth are up to 10-20 cm higher than the dyke water levels in winter and then decline at the same rate and about to the same level as those in the dyke system in the summer (Figure E13). The groundwater levels tend to be slightly higher than those in the dykes both when dyke water levels are falling and when they are rising. This suggests that the dyke water levels may be influenced by the Crag water levels in the non-winter periods.

Given there is little difference between the groundwater heads in the middle Crag unit and in the lower part of the upper Crag unit, any groundwater input to the dyke is likely to be largely or solely from the upper Crag unit, and may have a large component of lateral flow to the dykes at the fen margin where the clay at the base of the peat is absent and therefore the peat rests directly on Crag. The marginal dykes may also be cut into the Crag in places. As will be discussed in Section 5.5, there are some water chemistry data which indicate that the dyke water levels in this area are a mix of both rain water and groundwater. The Crag groundwater levels appear to be very responsive to rainfall events (Figure E46) and with the dyke surface waters also being responsive to rainfall events (Figure E59) it is not straightforward to distinguish which, groundwater or rainfall, is more significant in controlling the dyke water levels. However, the observation that the dyke water level minima are very similar to those in the adjacent shallow Crag (Figure E13) suggests that the dyke water levels are maintained by Crag groundwater levels at least in summer.

Water levels in the south-east corner of the Fen are monitored by two boreholes NTG3270P4 and NTG3270P5 and their hydrographs are shown in Figures E14 and E15. NTG3270P4 monitors Crag groundwater levels at depths of 8-9.9 m bgl, and shows lower water levels than those observed in the shallow NTG3270P5 which is only 0.70 m deep. The monitoring of water levels in this shallow borehole has been problematic at times in the past due both to logger malfunctioning and also to the transducer sometimes not being placed low enough in the hole to monitor the water levels. The data are however sufficient to draw conclusions about the relationship between the shallow and deeper groundwater levels and to assess the impact of nearby groundwater abstraction (Section 7).

The significance of the 2011 topographic survey has been discussed in Section 5.3, and it has been noted that the re-survey of past datums has resulted in the groundwater head relationship being reversed (for example, compared to that presented in Entec, 2010). The resulting head relationship using the 2011 survey levels, as presented in Figures E14 and E15, is more consistent with that observed at nearby AWS observation boreholes at Sharp Street which also monitor water levels at different depths within the aquifer (Figure E40). It is also interesting to note that though the groundwater heads observed at both the AWS Sharp Street boreholes and at NTG3270P4 and P5 indicate the potential for downward groundwater movement, this pattern is not observed at the north-west corner of Catfield Fen where the middle and shallow Crag heads either show little difference between them or the potential for upward flow depending on the time of year (see above).

The form of the groundwater head variation in the deeper of the two boreholes (NTG3270P4) is similar to that seen in the other boreholes, with evidence of the recharge events in 2001 and 2007 (Figure E14). As in other boreholes, high water levels also occurred in 2003 and 2004. This form of variation is not so clear in the shallow borehole (NTG3270P5) because groundwater levels are at or close to ground level for a large of the year. The annual water level minima are, however, generally similar in form to those observed in the nearby NTG3270P4.

Since there is the potential for downward groundwater movement in this area of the Fen, and upward movement in the NW corner, the head variations over time at two Crag boreholes of similar depths have been compared in order to see there has been any increase in the head difference between them. Any such increase might be indicative of increased drawdown as a cone of depression has developed around groundwater abstraction in the vicinity of the SE corner. It should however be recognised that such comparison is subject to much uncertainty because the lithologies within which the water table is rising or falling may be different and variable at the two locations and therefore the head variations may not be directly comparable. The comparison is shown in Figure E16. The difference in the summer minima between the two boreholes, year-on-year, does vary slightly but not in any apparent systematic way. At first sight, the difference in the winter water levels appears to have increased slightly over time, but it is more likely that the separation is greater when winter groundwater levels are relatively low, and less when they are relatively high. No conclusion can be gained regarding abstraction impact using this approach.

The relationship between the groundwater heads at the south-east corner of Catfield Fen are compared with dyke water levels at the eastern side of the Fen (TG32/710) in Figure E17. These heads are not directly comparable because the gaugeboard is about 750m NNW of NTG3270P4 and P5, but the hydrogeological map of the area (Figure B2) suggests that the Crag groundwater level would be similar at both locations. The dyke water levels appear to have a similar form to the groundwater hydrographs with little or no difference in the timing of their minima. However, it should be noted the dyke water levels appear to be higher than the groundwater levels, and if these levels were correct, there would not groundwater discharge to the eastern dykes. The groundwater chemistry of these dykes indicates that groundwater does contribute to the dykes near the eastern margin. Therefore, because there is uncertainty over whether the correct datum has been applied to the data from gaugeboard TG32/710, and the suggestion that the dyke water levels should be similar to those at some of the western locations (Section 5.3), the groundwater heads in NTG3270P5 have been compared with dyke water levels at TG32/711 (Figure E18). The relationship between the groundwater heads and these water levels, if the TG32/710 datum were amended, would be similar to the relationship between dyke and Crag water levels observed in the north-west corner, described above. The data in the south-east corner are of poorer quality and more difficult to compare because of the greater distance between the borehole and gaugeboard, but as in the north-west, the groundwater minima appear to be at a similar level to dyke water level minima. In this case in the south-east, any groundwater flow to the dykes, in the absence of any upward head gradient, would be laterally from the upland area to the east.

Finally, a pair of observation boreholes installed to different depths in the Crag have been monitored since 2008 (TG31/791 & 791a), and add to the picture of groundwater head relationships to the south of Catfield Fen. They are adjacent to Sharp Street Fens, and as at NTG3270P4 and P5 and AWS Sharp Street, these boreholes show that there is the potential for downward flow within the Crag at this location. Their hydrographs are shown in Figure E19.

5.4.4 Water Levels in Dipwells

Currently, there are just two lines of dipwells at Catfield Fen, both being at its western end, one being in Sedge Marshes in the internal system, and the other nearby at the southern end of Great Fen in the external system. One dipwell in each line has a logger installed and their water levels are shown in Figure E20. Data are available only since mid- to late-2006. At both locations water levels are above ground level in winter, and as with the dyke water levels discussed below in Section 5.4.5, the shallow groundwater levels in the internal system tend to be maintained at higher levels for longer in the internal system than in the external system during the spring. A difference between the internal and external systems is that since 2008 the maximum winter water levels in the internal system have tended to show a rising trend. This is the opposite of that observed in the external system dipwell and in the internal dykes (Figures E20 & E22). The summer groundwater levels tend to be lower in Sedge Marshes than in Great Fen in most years, the dipwell location in Great Fen tending to be waterlogged for much of the year.

During a site visit on 27 February 2012 the Sedge Marshes, with its sedge cover cut to a low level, could be seen to be waterlogged with the water in the internal dyke by the Rond apparently being at the same level, with no embankment to prevent continuity between their water levels. This similarity in water level is corroborated by the data in Figure E21.

Comparison with dyke water levels during the period since 2006 indicates that fen groundwater levels tend to be similar or slightly lower than the dyke water levels in both the internal and external systems (Figures E21 to E23). The difference between the dyke and dipwell water levels tends to increase as water levels fall. This relationship whereby dyke water levels tend to be at similar or higher levels to those within the fen compartments (at least that within Sedge Marshes) is present both using the 2011 surveyed datums and those previously used when considering the monitoring since 1996 (Entec, 2010).

This is opposite to the relationship noted by the University of Birmingham study (Gilvear et al., 1997). Their understanding was that that “normally the peat water levels are above the drainage ditch water levels” (p124). The locations of the University of Birmingham piezometers and water level monitoring sites are shown in Figure E24, Piezometers monitoring water levels at different depths were installed and since these were grouped in some places, vertical differences in head could be measured. The hydrographs from the installations within the internal system are shown in Figures E25 to E28. The location for the “ring dyke” water level measurements is not recorded, though Figure E23 indicates that water levels within the internal system were both near the location of the current NTG3261G1 and also in the dyke on the western side of Middle Marsh.

A comparison of the different sets of monitoring is not straightforward as they are separated both in time and space. The current monitoring in Sedge Marshes is on the western side of the internal system, whereas the University of Birmingham data are from central and more easterly and northerly locations. There are however several reasons for questioning the University of Birmingham data and therefore some, not all, of its conclusions. The relative levels between piezometers at any one location are likely to be correct given their proximity to each other. However, the differences between ring dyke water levels and those observed at various piezometer groups may include surveying errors due to the long distances between the ring dyke water level monitoring site and piezometer locations. The possible errors in the comparison of peat and dyke water levels are suggested by the following points:

- It appears from the piezometry that the peat water levels were at or close to ground level in the winter months. Though this is not stated by Gilvear at al. (1997), it is implied by data presented by Gilvear et al, (1994, Figure 10). Based on the water levels presented in Figures E25 to E27, it appears that ground level at ground levels at P8 and P9 (central Fenside Marsh) and P12, P13 and P14 (west side of Middle Marsh) were at about 0.6 mAOD, whereas at P10 and P11 (NE Fenside Marsh) levels were about 0.4-0.5 mAOD. These differences may be correct but are not suggested by the University of Birmingham topographic and water level data shown in Figure D1;

- P15 is located near the catchwater drain in the north-eastern part of Sedge Marshes and not far from the current NTG3261P1. Both installations were installed to a similar depth into the Crag. Figure E28 (and Figure E27) shows that the dyke water level fell to 0.2-0.3 m below the minimum Crag water level in the summer of 1990. This is different from the observations since 2006 which have shown the minimum dyke water level to be very similar to the shallow Crag water levels. It is recognised that the summer of 1990 was a very dry period when groundwater levels were probably very low, but if the Crag has a role in maintaining dyke water levels, as was suggested in Section 5.4.3, the Crag summer level would be similar to that in the dyke;

- Given that winter peat water levels were at about ground level in 1989 and 1990, if the dyke water levels were relatively lower, then this might indicate either that the dyke water levels were at a lower level than they are currently at Sedge Marshes, or that the ground surface is higher to the east of Sedge Marshes.

Consequently, the relationship between peat water levels and dyke water levels in 1989 and 1990 as determined by use of the topographic survey data applied to installations is questioned. However, though the University of Birmingham topographic survey (Figure D1) does not indicate a rise in ground level towards the east across the Fen, this may account for the understanding that peat water levels were higher than dyke water levels, if this was in part based on field observation (for which there is no mention). The possibility that the ground level does rise towards the east was indicated during a site visit in February 2012 when, viewed from the Rond, it appeared that the internal dyke water level was at about the same level as Sedge Marshes and causing surface flooding, but Long Marsh to the south and east appeared to be higher than the dyke water level and not inundated. Therefore, though time has elapsed since the University of Birmingham study, it would be useful to clarify the current relationship between dyke and peat water levels by installing a dipwell on the eastern side of the Fen, probably in Middle Marsh, and by carrying out two east-west topographic transects, one from Great Fen to the Ballscroft in the north and another further south from Irstead Poors Fen to the Glebe, to the east of Church Wood (location names are shown in Figures A2 and A3).

In the past vertical hydraulic gradients within the peat (and clay) has been investigated through the use of nests piezometers installed at different depths (University of Birmingham, 1989 and 1991; Gilvear et al., 1994 and 1997) and through temperature profiling (ECUS, 1997). At two sets of nested piezometers at depths of 1.5 and 5.6 m (P8 and P9; Figure E25) and 1.0 and 3.0 m (P12 and P13; Figure E27) a downward gradient was observed throughout the year. At another pair monitoring depths of 0.9 (peat) and 1.3 m (clay) (P11 and P10; Figure E26) differences in level were very similar for much of the year, but water levels in the clay were higher than the shallower peat during the summer 1990, indicating the potential for upward flow, though whether this actually occurred from the clay is not known.

A separate 9 m deep piezometer into the Crag (P14, next to P12 and 13; Figure E27) showed higher heads than at shallower levels, the difference being similar to the head differences observed at the north-west corner of the site (e.g. Figure E9), though with the data from the two locations covering different times periods it is not possible to draw any conclusions as to whether any significant differences exist between the two locations. In 1990, data from University of Birmingham (1991) show that Crag groundwater heads in the 9m deep P14 were about 3-10 cm higher than in the 1 m deep P12, and about 10-20 cm higher than in the 3m deep P13. This indicates that there is the potential for downward water movement within the peat, and that given the presence of a clay at the base of the peat, overlying the Crag, there is the potential for upward flow from the Crag, but no indication from the peat heads that this is actually taking place. Gilvear et al (1997) used these data to conclude “The upper peat appears to discharge downwards and laterally towards the drainage ditches for most of the year and the lower peat receives water from the Crag” (p124), but the basis for asserting this on the basis of data which describe the potential rather than the actuality for such movement is not clear.

The study by ECUS (1997), building on earlier work by Giller, used a temperature profiling technique to investigate water movement vertically within the peat and found that movement was downward at the test locations.

Therefore, though there is some evidence for upward flow within the peat, most evidence suggests downward flow.

Finally, the relationship of the dipwell water levels with those in Barton Broad are shown in Figure E29. Within the external system, it appears that the dipwell in Great Fen exhibits winter and summer water levels that are similar to those in the Broad, without the large water level fluctuations occurring in the Broad. The Barton Broad minima tend to occur slightly in advance of the dipwell water level minima, but such is the overall similarity in form that the Broad probably influences the external system dipwell water levels, with the dipwell water levels showing a slight lag in response.

5.4.5 Water Levels in Dykes

Surface water monitoring at the current installations first started in October 1996 (Figure E30) with dataloggers being installed in two gaugeboards in the internal system in June 2006 (Figure E31). A third logger was installed at the Ballscroft gaugeboard (TG32/710), near Catfield Hall, in August 2010. The monitoring is mainly located towards the western side of Catfield Fen, the only exception being the TG32/710 (also known as GB-A, and as the Ballscroft gaugeboard) which is near the eastern margin within a catchwater drain. It was installed by Catfield Hall Estate, manual records since January 2004 having been provided by the Estate (Figure E30).

Within the internal system, the water levels in the dykes on the western side of the Fen (NTG3261G1, TG32/711 and NTG3261G3) are virtually identical, which is not unexpected as the dykes are wide, connected, and not impeded by weed (Figures E30 & E31). However, when comparing the eastern and western sides of the internal system, both manual and logger water levels from TG32/710 have a near identical form to those obtained from other gaugeboards in the internal system to the west, but they appear to be 30-40 cm higher. Since it is believed that there are good connections between both the western and eastern dykes and that the internal system is generally a closed system, both a similarity in form and level would be expected, so this difference is unexpected. The possibility that there may have been an error in the datum level measured by the 2011 topographic survey has been discussed in Section 5.3. Though the survey data have been checked and no error found, there is uncertainty as to whether water levels in the eastern drains are indeed about 0.3 m higher than those in the west. This is based on the previous understanding of dyke water level differences across the site, from LIDAR data which suggests little difference in levels (Section 5.3), and from comparison of dyke water levels with groundwater levels (Section 5.4.3).

Manual data from the current gaugeboards extends back to 1996, with logger data available since 2006 (Figures E30 & E31). The logger data show short-term water level rises and falls which appear to be related to rainfall events (e.g. Figure E59). These can be very marked. For example at the end of March 2008, water levels rose by about 10 cm within 5 days, reaching a level of 0.71 mAOD, and then fell back again within a week to the pre-rainfall event levels. The reason for the sudden falls in level indicates water is rapidly lost from the dyke system. This could be by infiltration into or inundation of fen compartments, or by leakage out of the internal system (Section 5.5.2), or both.

Longer-term trends are not very clear, and are subtle and subdued, but comparison with the groundwater hydrographs and related Broad hydrographs discussed in Section 5.4.2 (Figures E1 to E4 and E7 & E8) show some similarities. In both the internal and external systems (Figures E30 & E32), water levels during the winter of 2000/1 were high, but instead of showing the subsequent declining trend observed in three of the four regional boreholes (Figures E1, E3 and E4) and in the Broads (Figures E7 and E8), the mean water level “trend” from 2002 to 2006/7 appears to have been approximately horizontal, the use of “trend” being used advisedly given the large water level fluctuations particularly in 2002 to 2004.

The water levels in the winter of 2006/7 rose to higher levels than in the immediately preceding years, and since then there appears to have been a general annual declining trend similar to that seen in the regional observation boreholes, including the one near Catfield village (TG32/914) , and in the Broads. The declining trend is particularly noticeable when considering the winter water levels (Figure E31).

The form of the surface water hydrographs are similar to that for the Crag borehole located to the east of Catfield village (cf. TG32/914, Figure E2), though it should be noted that the surface water levels tend to rise several months earlier than at TG32/914. In the autumn of 2003, surface water levels started to rise between 11 September and 15 October whereas at the Crag borehole TG32/914 groundwater levels were still at their minimum for the year on 11 November and only subsequently started to rise. Likewise, dyke water levels started to rise in September 2006, about 3 months in advance of the rise in groundwater levels at all the four regional observation boreholes.

However, adjacent to Catfield Fen, the rise and fall of Crag groundwater levels occurs at about the same time as the dyke water levels, and the dyke water level minima each summer appear to be very similar to the lowest levels recorded within the shallow Crag. This has been shown in monitoring data from the north-west corner of the Fen (Figure E13) and there are indications this may also be the case in the south-eastern and eastern parts of the Fen (Figure E18). This has been discussed above in Section 5.4.4.

During the period since October 1996, the lowest dyke water levels occurred in the summer of 2009 when levels fell to about 45-50 cm below their winter levels. Other low summer minima occurred in 1997, 2006, 2010 and 2011 (Figure E30). For comparison with other past years, data provided by Natural England for the period 1967-1978 showed that the minima in August 1976 was about 70 cm below the winter water levels at that time. Other water levels monitored at the same location (P in Figure B4) during 1980-84, a relatively wet period, show that summer water levels fell to about 25-30 cm below their winter levels (Figure E32). However, though it is recognised that these data show ranges in water level fluctuation, it is not known whether the winter levels were the same when past monitoring posts were used as they are now when using the current gaugeboards. The datasets are therefore not directly comparable.

Comparison of internal and external water levels (Figure E33) near to Commissioners' Rond shows that winter water levels in the internal system tend to be slightly higher than in the external system at NTG3261G2 , though this is not always the case, and that following the decline in external system water levels in the spring, the water levels in the internal system tend to be maintained in some years at slightly higher levels for longer, before declining to summer minima. This delay in water level fall within the internal system, compared to the dyke at NTG3261G2, can be seen in the spring periods of 2006, 2007, and 2009, but does not appear to have occurred in 2008, 2010 or 2011. (Figure E34).

Two previous studies have also measured the water levels in both internal and external systems (Giller and Wheeler, 1986a, and University of Birmingham reported by Gilvear et al., 1997). Giller and Wheeler (1986a) measured water levels in 1980 and 1981 during which June 1980 and March to May 1981 were reported as being exceptionally wet. This lead to "extensive, deep inundation from October 1980 to July 1981". The effects of this can be seen in the water level record (Figure E35) which shows spring 1981 high water levels were maintained at a high level much longer in both internal and external systems than in 1980. Internal water levels were slightly higher than in the external system by about 2-4 cm in the winter and were maintained for longer than in the external system in spring 1980, but not in 1981.

Water level data from the internal and external systems presented by Gilvear et al. (1997) (Figure E36) showed little difference between the two systems during the winter of 1988/89, the internal system being about 0-5 cm higher than the external system. In early 1990, water levels in the internal system were about 10 cm higher than in the external system, and water levels subsequently fell to about 45 cm below the winter level. It is not clear from the data to what extent internal water levels were maintained at higher levels than the external system during the spring periods.

Whether the summer minimum in the internal system dyke waters is lower, higher or the same as in the external system is often not clear because G2 is sometimes recorded as being “dry”. Water levels at NTG3261G2 appear not be recorded below about 0.41 mAOD since 2002 (Figures E33 and E34). Before 2003 water levels at NTG3261G2 have been recorded at levels down to 0.30 m AOD and it appears that broadly the summer minima in the internal system are similar to those in the external system (Figure E4). The location of NTG3261G2 is currently within an overgrown dyke, quite different from the broad clear dyke in which NTG3261G1 (G1) is located. It appears that silting up of the dyke at NTG3261G2 has made it shallower than when it was first installed.

Following the summer minima, the rise in water levels in both internal and external systems occurs with a similar timing and at a similar rate (Figures E33 and E34). In some years, the water level rise in the external system slightly precedes that in the internal system, as in 1980 and 2010, but this does not appear to be the norm.

A comparison of these water levels with those at Barton Broad is shown in Figure E37. The winter water levels in Barton Broad are similar to those at Catfield Fen, though possibly slightly lower than in the internal system. The decline in Barton Broad water levels in spring is steeper than in either the internal or external system (at NTG3261G2), suggesting that water levels within the internal and external systems are buffered in some way. A consequence is that the summer minima in Barton Broad occur slightly earlier than at the gaugeboards. The rise in water levels in Barton Broad during the autumn has a similar timing and rate of rise as seen in the internal and external system gaugeboards.

The reason of the buffering of the decline of dyke water levels in spring, and the reason for the external system being apparently more buffered in some years than others is not clear. It appears that the internal dyke water levels are influenced by Crag groundwater levels, at least in determining the lowest levels in summer. The possibility that this is also occurring in Great Fen should be considered, but it is perhaps more likely that the buffering noted is a result of flow out of the system towards the Broad being delayed by the overgrown dyke system in the Great Fen area.

The differences between the levels observed at NTG3261G1 in the internal system and those observed at other gaugeboards is shown in Figure E38, and clearly shows that the internal system levels are similar to each other, but that there are differences in the relationship between NTG3261G1 and NTG3261G2. This is shown in more detail in Figure E39. This Figure omits those NTG3261G2 water levels which may be anomalous due to the dyke at the gaugeboard location being effectively dry, and can be understood by comparison with Figure E33 which shows the actual manual water level data at the two gaugeboards. Figure E39 shows that, at the times of manual readings, for most of the monitored period water levels in the internal system have been higher than in the external system, but there have been some occasions, shown by negative values, when the reverse has been the case. It is difficult to identify any trend. There is some indication that the amount by which the internal system can be higher than the external system has been less in recent years, since 2008, but this is not always the case as in early 2009. The reduction in the difference may be due in part to the water levels at NTG3261G2 being relatively higher than in some previous years (Figure E33) and this may be a consequence of the ditch becoming more overgrown and silted up. However this is not certain.

5.5 Water Chemistry

5.5.1 Introduction

Information about the water chemistry at the Fen has been gained using two datasets. One is through the use of dataloggers which record water conductivity (EC) and the other is through the chemical analysis of water samples. These are considered in the following sections.

5.5.2 Conductivity

EC logger data are available from two gaugeboard locations within the internal system, TG32/711 and NTG3261G1 (Figure F1), but none are available from the adjacent external system. The EC traces from the internal system show some very prominent spikes, which are related to tidal surges which progressed up many Broadland rivers at particular times. Similar EC spikes can be recognised at other Broadland sites, their timing and duration of elevated EC being related to the degree of connection to the river, and the ability of the drainage system to purge itself of the saline water that penetrated the site.

There are limited EC logger data from the River Ant, though a site (TG31/697c) adjacent to Reedham Marshes which is connected to the River Ant to the south of Catfield Fen shows a similar EC spike occurring in November 2007 at about the same time as the spike shown at TG32/711 (see Figures F2 and F3 for comparison). A longer record of EC spikes is shown in Figure F4 for a gaugeboard on the River Yare near Brundall Marina. This also shows the main EC spikes occurring in October/ November 2006 and November 2007.

EC responses to the tidal surges of October/ November 2006 and November 2007 are also recorded at the internal system gaugeboard data from Catfield Fen (Figure F5). Though the data are not complete in 2006, Figure 4 shows that EC started to rise at NTG3261G1 on about 30 November 2006, on about the same day as that observed in the River Yare near Brundall (Figure F4). Unfortunately data are not available for TG32/711 at this time, though the start of the EC record shows a rapidly declining EC following what appears to have been a "spike".

The data are more complete for the 2007 tidal surge and show several differences from the response shown to the 2006 tidal surge. At TG32/711, the EC started to increase rapidly on 10/11 November 2007, 2-3 days later than in the River Yare near Brundall (Figure F4), and reached a peak value of 3857 µS/cm on 16 November (Figure F5). This compares to a background EC value of about 600 µS/cm. The EC recorded at NTG3261G1 shows a delayed and much reduced response to the tidal surge. The EC started to increase on 3 December 2007 and rose to only 980 µS/cm. At both TG32/711 and NTG3261G1 EC levels returned to normal at the same time, probably as a result of the opening of the northern sluice near NTG3261G1. Catfield Hall Estate records indicate that the northern sluice was opened for a few days in December 2007.

These details of the timings and magnitudes of the EC spikes are of note. In both 2006 and 2007, saline water appears have penetrated into the internal system fairly rapidly following the progress of the tidal surge up the River. In 2006, for dyke water at NTG3261G1 there appears to have been little delay in EC levels becoming elevated. In 2007, however, it is at TG32/711 where there is little delay in response to increasing EC, whereas at

NTG3261G1 there was a substantial delay in the EC rise, and the rise when it occurred, was of a reduced magnitude when compared TG32/711. It appears that in 2007, the incursion of saline water into the internal system occurred to the south of TG32/711, with the consequent delayed response at NTG3261G1. In 2006, however, it appears from the rapid response to the tidal surge that saline water may have entered the internal system near to NTG3261G1.

It is of note that the recorded water levels at the times of the tidal surges did not rise to unusually high levels. The 15-minute logger data recorded at NTG3261G1 in 2006 show that water levels showed no marked spike in water levels which might be attributed to an overtopping of the Commissioners' Rond (Figure F6). There was a gradual rise in water levels from 0.54 mAOD on 30 October 2006, when EC levels started to rise, to 0.64 mAOD on 21 November 2006, but this may be due at least in part to rainfall (Figure F6). The rise in water levels at TG32/711 at the time of the tidal surge appears to be slightly more marked, rising from 0.49 m AOD on 11 November 2007 to 0.56 mAOD on 16 November (Figure F7). This rise may be due in part to rainfall events, but comparison of the magnitude of water level rises with the magnitude of rainfall events suggest the water level rise may also be due in part to the impact of the tidal surge. Limited data from NTG3261G2 suggests that water levels in the external system were slightly higher than in the internal system at TG32/711, though it is not clear whether the water levels recorded at NTG3261G2 are the same as in the external system near TG32/711.

The water level change within the external system at the time of the tidal surges is indicated from data collected from two nearby gaugeboards to the south. One is connected to the River Ant by Reedham Marshes (TG31/697c) and the other (TG32/790) is in the Sharp Street Fens to the south of Mud Point, and to the south of the low-lying bund at the southern end of Catfield Fen. At the time of the 2006 tidal surge, water level data are only available from TG31/790, and these show a water level rise of about 10 cm over a period of about 7 days. At the time of the 2007 tidal surge, water levels rose at both gaugeboards by 20 cm also over a period of about 7 days. At both locations, the levels to which the water rose were not unusual. Water levels at TG32/790 covering the period of the 2007 tidal surge are shown in Figure F8. EC data of uncertain quality from TG32/790 are shown in Figure F9. Furthermore, a comparison of water level data from TG32/790 in Sharp Street Fens with those from TG32/711 in the internal system is given in Figure F10 and suggests that flow from the south into the Catfield Fen's internal system is possible at times (even given possible inaccuracies in the relative datum measurements for the two gaugeboards).

Movement of water across the low bund separating the two Fens has been observed on several occasions by Andy Hewitt (a reed and sedge cutter who has worked in the area for the past 25 years). He has seen it moving both into and out of the internal system at different times (pers. comm.). Water has been seen flowing swiftly over the bund out of the internal system, after heavy rainfall in early March 2012, on a day when water levels at NTG3261G1 and TG32/711 were read on the gaugeboard markings as 5.6 and 6.4 respectively (0.550 and 0.557 mAOD which given reading errors are essentially the same) (Mr Alston, pers.comm.). Such levels are not unusual in winter periods. A photograph of this overflow is shown in Figure J10.

In conclusion, it appears that at the time of the 2006 and 2007 tidal surges, saline water was able to enter the internal system. It did this at times when water levels appear not to have been unusually high and therefore cannot be attributed with any certainty to the overtopping of the Commissioners' Rond. ECUS (1997, p50) note that in "very exceptional circumstances the Commissioners Rond, which separates the two systems, can be overtopped by floodwater locally", but it does not appear that this was the case at the times of the tidal surge events. It is not known for certain how the saline water entered the internal system but it may be that in October/ November 2006 it entered by leakage either through or around the northern sluice near NTG3261G1, and in November 2007 it entered from a location to the south of TG32/711, either through or around the southern sluice or over the low-lying bund at the southern corner of internal system (Figure 3.1; Figure A4).

Andy Hewitt (pers. comm.) has noticed that at the time of sedge cutting, sedge floating on the dyke water tends to collect around the northern sluice, therefore indicating some leakage through the sluice. Since he does not cut reed or sedge within the internal system near to the southern sluice, it is not known whether anything similar occurs near to it at such times. Dense weed growth occurring locally within the internal dyke adjacent to the southern sluice has been observed but its significance is not known. Flow in both directions over the low-lying bund has also been observed at different times. It is therefore important to note that the EC data give an indication that the internal system is not a completely sealed system, even without the Rond being overtopped, and this is something that is corroborated by other observations. Such movement appears to be an element of the hydrology of the internal system, and not just at the times of tidal surges.

5.5.3 Water Chemistry Analysis

Water chemistry sampling has been undertaken at various times during the past 30 years. The chemistry of surface waters from the Fen and from within the peat have been discussed by Wheeler and Giller (1981) and Giller and Wheeler (1986a and 1986b). Groundwater and surface waters were sampled in May to August 1988 by Collins (1988), and in each August and September during 2001, 2002, 2003 and 2004 as part of AMP studies (Atkins/HSI, 2005). Surface waters from dykes were also sampled in September 2005 (Ewan, 2005).

The analyses presented by Collins (1988), Atkins/HSI (2005) and Ewan (2005) are shown in Tables F1, F2 and F3 respectively, and the locations of their surface water sampling shown in Figures F11, F12 and F13 respectively. Collins (1988) also included groundwater analyses from peat piezometers and the Ludham PWS source, and the AMP studies included groundwater samples from boreholes at Catfield Fen, from several observation boreholes at Sharp Street to the south of Catfield Fen (Figure 3.1), and from the Ludham PWS source. Rainwater and Barton Broad water chemistries have also been considered.

As part of this investigation AMEC has re-examined these analyses, and the results are shown in Appendix F. They are summarised in Table F4 and divided into groups based on their chemistry. These comprise four groupings of dyke waters, and groundwaters from different depths. The samples assigned to the different chemical groupings are identified in Table F5. There are a significant number of analyses which have a poor ion balance (particularly from Collins, 1988) (Table F5), and these have not been included in the various plots and analysis of results.

The range of chemistries is shown not only for individual determinands in the "box and whisker plots" (Figures F14 to F23) but also in the Piper, Durov, Ternary and Definition plots (Figures F24 to F27). The Definition plot shown in Figure F27 is of a similar form to one used by Gilvear et al. (1997) and has been used to identify the chemical groupings. Other plots (e.g. Figure F28) have been used to further discriminate between different chemical groupings and help to distinguish some waters (e.g. deep Crag groundwater in Figure 28) from other groupings which may appear similar in some other plots (e.g. Figure F27). In some plots a red triangle has been used to assist in the investigation of potential mixing between three end-members, taken for the purpose of investigation to be rainwater, shallow Crag and deep Crag.

The locations of the four surface water types are shown with the sample numbers in Figures F11, F12 and F13.

Type 1 waters have a significant rainwater component and could also be influenced by Crag and/ or Broad water. The sample locations are mainly from within the internal system and are largely from ponded and peat surface water, rather than from dykes (Figure F11).

Type 3 waters tend to occur in the dykes bordering or close to the eastern margins of Catfield Fen (Figures F11, F12 and F13), and have a chemistry that is indicative of a significant component of input from shallow and middle Crag groundwaters. It is worth noting that such waters within Collins' sampling occur at locations where the dykes are believed to have been cut down into the Crag (Figure B8).

Type 2 waters could be a mixture of Type 1 and Type 3 waters, or could be a distinct type not reliant on such mixing. Samples of this type are from both the internal and external systems and from both dyke waters and peat surface waters (Figures F11, F12 and F13).

Type 4 waters show evidence of pollution and have been found at two locations (Figure F11). The location (No.30) near Fenside has been identified in the past as being subject to septic tank pollution (Collins, 1988). Another location (No.43) has also been identified in the current investigation as being subject to pollution. Though it was given a location name of "Spring" by Collins (1988), its polluted chemistry may be due to it being largely or wholly sourced from runoff flowing down School Road and draining into the field ditch via a road drain opposite the school.

Given the location of North Marsh and Middle Marsh where the underlying clay is in places absent, there is the potential for groundwater discharge to occur to the fen surface in these areas, but the precise location of such discharges is not known and they may not to be currently active. The chemistry data from within these fen compartments is very limited and comprises only one analysis which comes from Middle Marsh and has a Type 1 chemistry. This is not sufficient to make any judgment about any potential groundwater discharge to these areas.

The chemistry of Crag groundwaters appears to differ throughout the aquifer. Deep Crag groundwaters have a distinct Ca-HCO_3 chemistry with low SO_4 concentrations and high Ca/Mg ratio, whereas shallow Crag groundwaters have high SO_4, Mg and nitrate concentrations and lower Ca and HCO_3 concentrations. Middle Crag groundwaters tend to have intermediate compositions but in some cases, at some times, Ca and HCO_3 concentrations are higher than in the deep Crag groundwaters. The high SO_4, Mg and nitrate concentrations in the shallow Crag and some middle Crag groundwaters may well indicate an agricultural source and be indicative of the groundwater being derived from relatively recent recharge water. The high Ca content of middle Crag groundwater may reflect its recharge source which could possibly be from till-covered areas to the east.

The chemistry of peat groundwater recorded at NTG3261P3 in Sedge Marshes has very high sodium and chloride concentrations. Giller and Wheeler (1986b) have noted high sodium (together with high calcium, magnesium and potassium) concentrations in estuarine clays underlying the area to the south (Figure B5), much higher than in the overlying surface peats. Given that NTG3261P3 appears to be further north than the estuarine clays and is screened at a relative depth of 0.4-1.5 mbgl, the origin of the high sodium and chloride may be due to seawater incursion at the time of a tidal surge, the water finding a route into the interior of the Sedge Marshes via the mapped dyke (which may be overgrown) near to NTG3261P3 (Figure 3.1). There may be difficulty in flushing such salt water from this location.

Though the chemical typing presented above is very similar to that of Collins (1988) and presented by Gilvear et al. (1997), based as it is on a cross-plot type that they also used (Figure F27), the interpretation of the types is slightly different because much more groundwater data has become available through the AMP studies (e.g. Atkins/HSI, 2005). The interpretation of Type 1, 2, and 4 waters are very similar to those presented by Collins (1988) and Gilvear et al. (1997).

A difference is in the emphasis and origin given to the Type 3 waters, with this investigation giving slightly greater emphasis to the source of Type 3 waters being from the Crag than do Collins (1988) and Gilvear et al. (1997). The availability of sample analyses of middle Crag groundwater since their work has led to the suggestion here (Appendix F) that Type 3 waters include a component from the middle Crag. The question then arises as to how the middle Crag groundwater gets to the dyke system, since its estimated depth at the marginal catchwater dyke near TG32/710 is about 18 m. Gilvear et al. (1997) interpreted the Type 3 waters as resulting from “influx from the surrounding fertilised and limed fields, with possibly some influx from the Crag aquifer”. This may be a source of the Type 3 waters, and it is worth noting that a field drain draining arable fields to the east discharges at the north-east corner of the Fen, not far from the location of Collins’ sample site 13 (Figure F11). However, a greater variability in the water chemistry of the Type 3 waters identified by this current investigation might be expected if runoff/ interflow from the arable land to the east is a major source of water for the eastern catchwater dyke. The details of the source or sources of the water in the catchwater drain may need to await further studies, and potentially the acquisition of new data from future boreholes. However, it would appear that the Type 3 waters have a significant groundwater component.

Crag groundwater tends to have moderate to high iron concentrations and in some parts of Broadland ochre is deposited in dykes where there is some Crag groundwater discharge. A lack of ochre deposition within the dykes at Catfield Fen is not necessarily an indication that the Type 3 waters do not have a groundwater component. Depending on complex chemical conditions, emerging iron-rich groundwater may precipitate its iron within the dyke sediment, rather coming out of solution in the form of ochre. Though the details are not fully known, Giller and Wheeler (1986a) in a discussion about nutrient sources and peat chemistry at Catfield Fen make the following comment in relation to total and extractable iron noting that “consistently high values were recorded from sites close to the upland margins, indicating some input from the adjoining mineral ground” (p112).

Finally, it should also be noted that the study by Atkins/ HSI (2003b) concludes that “the hydrochemistry of the dyke waters appears to be distinct from the shallow Crag which suggests little or no contribution to the dykes from groundwater.” (p34). From the results of the present investigation, this would appear not to be the case, particularly for Type 3 waters. Atkins have noted that unlike shallow Crag groundwater, the dyke waters have low nitrate concentrations. This is the case for several, but not all, of the identified Type 3 waters, and nitrate is often quickly taken up by plant vegetation within wetland dykes.

5.6 Summary and Assessment of How the Fen Functions Hydrologically

Catfield Fen lies within the Ant valley to the east of Barton Broad and comprises an 'internal drainage system', which is bounded to the west and south by the Commissioners' Rond and to the north and east by "uplands", and Great Fen which lies to the west of the Commissioners' Rond, outside the north-western part of the internal system. Great Fen is part of the 'external drainage system' which occurs between the Commissioners' Rond and Barton Broad and is regarded as having free, though impeded access for River Ant, and less so to Barton Broad, via a system of dykes. The internal system is crossed by a dyke system which is believed to be unimpeded without any retaining structures within it.

Along the length of the Rond, there are two structures, one in the north and one towards the south of the Fen, which are potential routes by which water can move between the external and internal systems. Another potential water transfer route, one which has not previously been formally recognised, is via a low-lying bund at the southern end of Catfield Fen, just to the east of the Commissioners' Rond (Figures 3.1 and A4).

Water input to the internal system from the upland areas to the east occurs from a field drain which discharges to a drain at the eastern edge of North Marsh, and from surface watercourses in the Glebe area near Catfield School and in the south-east corner of the Fen. A spring which shows a small flow throughout the year is understood to occur in the Glebe area, and a former owner of Catfield Hall, Mr McDougall, thought there were springs not only in the Glebe but also in the North Marsh and Middle Marsh areas. It is not known whether these springs within the fen compartments are currently ever active.

The Fen is underlain by peat to depths of almost 7 m in the south-east parts, and the peat is in turn underlain in most places by a clay layer which overlies the Crag. The Crag underlies the whole of the Fen at depth and forms the lower slopes of the uplands which surround the Fen on its northern and eastern sides. Above the Crag there are two separate clay layers in many, but not all, places. The basal clay layer is widespread, but appears to be absent at the fen margins, in places near to the margins (e.g. in parts of North Marsh) and in the bottom of some dykes where they have been cut down into the Crag. At a higher level, within the peat sequence, separate clay of Romano-British age occurs in the vicinity of the Hundred Stream but thins out to the north and east and is absent over a large part of the internal system (Figure B5).

Trends in water levels over time have been investigated in regional boreholes, at Barton Broad and in the boreholes, dipwells and gaugeboards at the Fen. The long-term hydrographs from regional observation boreholes indicate that in north-east Norfolk the lowest groundwater levels in the period since 1952 occurred during the drought period 1989-1992. This is based on observations of Chalk groundwater levels, since Crag observations do not go back this far, but the two formations do seem to have similar forms of hydrograph. The borehole hydrographs also illustrate the effects of high rainfall recharge periods on groundwater levels. Groundwater levels tend to rise significantly during major recharge events, as in 2001 and 2007, and then gradually decline in subsequent years due to there being less overall recharge to the aquifer system, and with the storage within the system gradually being reduced by, for example, baseflow to rivers. The hydrograph for Barton Broad shows a similar form of long-term trend, a consequence of the River Ant having a large component of baseflow contributing to its flow.

The Crag boreholes close to the Fen show similar trends in level, and overall have been declining since the last major recharge event in 2007. Likewise, the gaugeboard levels in both the internal and external systems show similar trend. For the dipwells, the currently observed record is relatively short, having only started in late 2006, and though the trend observed in boreholes and gaugeboards can be seen in the dipwell hydrograph from the external system, which is influenced by Barton Broad levels, it is not particularly apparent in the dipwell hydrograph from the internal system at Sedge Marshes.

The hydrological functioning of the Fen has been described by previous workers, the two main schools being the University of Sheffield (Giller, Wheeler and co-workers) and University of Birmingham (Gilvear and co-workers). Their views have been summarised by the Environment Consultancy University of Sheffield (ECUS) (1997) and Gilvear et al. (1997). The University of Sheffield has based its understanding on botanical, ecological, geological and hydrological studies, and the University of Birmingham has based its understanding on geological, hydrogeological and hydrological investigations. Though differing in detail, both consider the rainfall to be the main water input to the Fen. They both believe that groundwater constitutes a minor input to the water balance of the internal system, and that, although there is little evidence of upwelling groundwater feeding the Fen, groundwater could provide a base level within the system. Consequently if Crag heads were lowered, then water levels in dykes which are in places cut down into the Crag could also be lowered, leading to reduced storage within the system. The water levels within most fen compartments would therefore be indirectly affected, not directly since the clay at the base of the peat occurs underneath the majority of the Fen, and there is no good evidence for upward groundwater flow through it.

Water chemistry data analysis for the current investigation indicates that the fen compartments have a significant rainwater component but could also be influenced by Crag and/ or Broad water. The chemistry of such fen water has been grouped as belonging to Type 1 waters. Some dykes near the eastern margin of the Fen have been cut down into the Crag and exhibit a water chemistry which suggests a Crag groundwater input (Type 3 waters). Further from the margin, the dyke waters appear to be a mixture of the Type 1 and Type 3 waters.

It appears that the dykes on the eastern side of the Fen have a significant groundwater input, and from dyke water level data on the western side of the internal system it appears that dyke water levels are maintained by the Crag. However, the dyke water chemistry in the west does not show the predominance of groundwater input seen in the east, but a mixture of groundwater and surface waters. The groundwater influence on dyke water levels in the west may not therefore be due to direct groundwater input, but to a maintenance of levels that is linked by the unimpeded dyke network to the dykes on the eastern side of the Fen which are more directly influenced by groundwater heads due to the clay separating the Crag from peat being absent.

Within the fen compartments of the internal system, the water chemistry indicates that the peat water is largely or wholly derived from rainfall. This is supported by the ecological findings of ECUS and Giller, Wheeler and co-workers who find the communities are rainfall not groundwater influenced. Water flow within the peat has been largely found to be downward. The dipwell data for Sedge Marshes collected since 2006 shows that water levels tend to fall to lower levels in the summer than the dyke waters, and have a slightly different form to the recent year-on-year reduction in winter dyke water levels in that the winter dipwell water levels have tended to rise since 2008. The form of levels achieved in winter may be in large part a result of rainfall influences, though it has also been observed that dyke water levels appear to have an influence on water levels in Sedge Marshes at least for part of the winter. Within Great Fen in the external system, the dipwell water levels appear to be significantly influenced by the level in Barton Broad.

In the internal system, further to the east than Sedge Marshes, it may be that the ground surface rises slightly, though this has still to be confirmed by a topographic survey. Visual observation suggests this may be the case, and if so it would allow the differences between the current dipwell observations and those of Gilvear et al. (1997) to be reconciled. Whereas the current observations indicate the dyke water levels tend to be slightly higher than the dipwell water levels at Sedge Marshes, the University of Birmingham monitoring further to the east suggested that water levels in the compartments were higher than those in the dykes. If the ground levels are higher towards the east, the rainfall-fed peat water within the compartments may well be higher than the dykes and therefore flow towards the dykes. As a result, this would explain why the dyke waters away from the eastern marginal areas do not retain the Type 3 chemistry but are Type 2 waters which are considered to result from a mixing of groundwater and rainwater.

A consequence of water levels in the compartments being higher than in the dykes would be that if the head difference between the two increased, whether by reduction in dyke water level or increase in ground level or both, the flow out of the fen compartment would increase and therefore the water table within the fen compartment would be lowered relative to the ground surface. A reduction in dyke water level might occur in response to a lowering of Crag groundwater level, leakage from the internal dyke system, an increase in ground level through vegetation litter accumulation or the process of terrestrialisation, or any combination of these factors.

The general lowering of Crag groundwater levels has been observed since the major recharge event in 2007 and reflects a regional groundwater trend. Groundwater levels could also be lowered by groundwater abstraction located locally in the region of the Fen.

Dyke water levels could also be lowered by leakage not only through the sluices but also probably more significantly over the low-lying bund at the southern margin of the internal system. The potential for leakage has been indicated by EC data which has shown that saline water from tidal surges can enter the internal system at times when water levels are not abnormally high. Flow entering and leaving the internal system over the low-lying bund has also been observed at different times. It is therefore important to note that the EC data give an indication that the internal system is not a completely sealed system, even without the Rond being overtopped, and this is something that is corroborated by field observations. Such movement appears to be an element of the hydrology of the internal system, and not just at the times of tidal surges. The short-term rapid rises in water level within the internal dykes are related to rainfall events and the equally rapid falls indicate water is rapidly lost from the dyke system. This could be by infiltration into or inundation of fen compartments, or by leakage out of the internal system, or both.

The possibility that the ground level has risen should also be considered. All these potential factors that might affect the wetness of the fen compartments will be discussed further in Sections 7 and 8.

The hydrological system described above is complex. There is some groundwater input to dykes near the eastern margin, rainfall input to the fen compartments as well as dyke water entering the fen compartments in places and probably water from the compartments entering the dykes in other places. The dyke water levels are also subject to the ability of the internal system to retain water. At times water flows over the low bund at the southern end of the internal system, and probably to a lesser extent leaks through the sluices. The potential for such leakage will be another factor that will influence the levels that can be maintained in the internal dyke system.

Box 2 Comments by Professor Gilvear

Section 5.2 Rainfall and Evapotranspiration

I would like to reiterate that the rainfall and potential evapotranspiration data analysed shows that in the vicinity of Catfield Fen there is no overall long-term trend towards drier summers and as such this argument cannot be used to explain the drying out of the fen. In relation to the last paragraph above I do not agree with this. It can be used to identify trends in summer wetness or dryness but the lumped approach may not pick out a trend at higher temporal resolution (e.g. just solely examining what is happening in July and August).

Section 5.4.3 Water Levels in Boreholes

The significance of the windows in the clay, the lack of clay beneath some of the dykes and at the margins of the fen in terms of a potential flow pathways for inflow of groundwater or leakage of water from the fen under a downward head gradient is not given enough emphasis. It is this fact that makes the fen potentially sensitive to groundwater abstraction.

Section 5.4.4 Water Levels in Dipwells

I would disagree with the statement that a reversal in flow direction (between the late 1980s and the present day) between the fen peat and the dykes is unlikely. In the late 1980s the peat water levels were higher relative to the dyke water levels (Gilvear et al, 1997). The dykes acting to drain water away from fen compartments at that time then is entirely plausible. Similarly if today the fen water tables are lower and drying out of the fen peat appears widely accepted, a reversal of flow direction and the dykes acting as a source of water to the fen also could be real.

Section 5.4.5 Water Levels in Dykes

The use of a changing climate to explain the water levels on Hickling and Barton Broad appears contradictory to the finding that there was no trend in effective precipitation in the vicinity of Catfield fen (as shown in Figure C6).

Section 5.5.2 Conductivity

There is little or no actual evidence for leakage/seepage out of the internal system and is likely to be restricted to periods when there is a large head difference and this would not be apparent during dry periods. As such the hydrological process is only hypothesised as a means of potential loss of water from the internal system at Catfield fen and thus the causing of its drying out.

Section 5.6 Summary and Assessment of how the Fen Functions Hydrologically

The hydrology section of this report is a valiant attempt to describe the hydrology of the site, given its complexity, but the repeated use of words and phrases such as “appear” and “may be” indicates that there is difficulty in definitively determining sources and movement of water and quantifying water fluxes. As such making definitive conclusions as to the site not being impacted by groundwater abstraction is unwise.

Although there is clear evidence that saline water has penetrated the bunds this only seems to have happened on two occasions and when there was a high head. To jump to the conclusions that leakage or flow over the bund can be the cause of the drying out of the fen in my mind is a leap to far. Flow over the bund form east to west has not been observed.

6. Licensed Abstractions

The locations of licensed abstractions in the vicinity of Catfield Fen are shown in Figure 3.2 (and in Figure 3.1 for those closer to the Fen). Details of the licences, including the licensed quantities, are summarised in Table 6.1. They include five licences for groundwater abstraction and one for surface water abstraction.

Of these licences, two are considered to be insignificant in terms of actual impact on the Fen. The licence held by Simply Strawberries Ltd (7/34/09/*G/0058) is located is about 1.4 km NE of the closest part of the Fen and is only used for general farming and domestic use with an annual licensed abstraction of 9.1 TCMA. It is considered that because of its distance and size it will have no detrimental impact on the Fen.

Likewise, the surface water abstraction at Catfield Fen (7/34/09/*S/0084) is not considered to cause an adverse impact on the Fen as it has never been used. It is licensed for the purpose of spray irrigation with a licensed quantity of only 0.7 TCMA (700 Ml/a), though the daily licensed quantity also allows up to 700 Ml/d to be abstracted. If this full licensed quantity were to be abstracted in one day, it is estimated that this could cause a 1-2 cm fall in dyke water levels within the internal system. However, it is understood both from the absence of abstraction returns and comments made by Mr Harris (the current licence holder) that abstraction has not taken place since the licence was issued to the Harris' in April 1994. Prior to this, the licence was held by MacDougall and Partners of Catfield Hall Farm, and in a letter to the National Rivers Authority of 7 June 1991, Mr K A McDougall notes the licence had never been used.

Since use of these two licences is not considered to have an impact on Catfield Fen, and therefore not a possible cause for the perceived drying out of the Fen, they will not be considered further in this investigation of abstraction impacts on the Fen.

The remaining abstractions comprise one used for the purpose of public water supply (PWS) and three for spray irrigation. For ease of identifying abstractions, the licence holder's name and where appropriate abstraction location are noted in the following sections and in the Appendices, rather than using the licence numbers which in several cases have changed over the history of the licensed abstraction. The commonly used licence numbers and identifying names used in this report are as follows:

- 7/34/09/*G/0091 AWS Ludham;
- 7/34/09/*G/0141C Alston Ludham Road;
- 7/34/09/*G/0144B Alston Plumsgate Road;
- 7/34/10/*G/0111 Overton.

Time series plots showing the history of annual abstraction licence quantities for each licensed abstraction are given in Figure G1, with plots showing the actual annual quantities abstracted shown in Figures G2. The actual annual quantities abstracted for those licences are shown in Figure G3, with the total abstractions added in Figure G4. Since the spray irrigation abstractions take place for just part of the year, not the whole year, Figure G5 is a diagrammatic representation of the form of these abstractions over six-monthly periods and can be used for making a comparison between them and the quantity abstracted by the AWS Ludham PWS source. A similar plot for the years for which daily data area available for spray irrigation abstractions is shown in Figure G6.

These licences will be considered in turn below.

Table 6.1 Abstraction Licences in the Vicinity of Catfield Fen

Licence Name	Licence Number	Use	Abstraction Point	Time Limits	Abstraction Season	Abstraction Days	Licence Quantities: Abstraction point Quantity (not including restrictions imposed by licence aggregates)			Licence Quantities: Maximum Licensed Quantity (including restrictions imposed by licence aggregates)			Licence Conditions and Comments
							Daily	Annual		Daily	Annual		
							Peak Licensed		Av. Over Abstraction Period	Peak Licensed		Av. Over Abstraction Period	
							Ml/d	TCMA (Ml/a)	Ml/d	Ml/d	TCMA (Ml/a)	Ml/d	
SIMPLY STRAWBERRIES LTD	7/34/09/*G/0058	General Farming & Domestic	WELL AT CATFIELD		Annual	365	0.091	**9.10**	0.02		**9.1**	0.02	
ANGLIAN WATER SERVICES LTD	7/34/09/*G/0091	Potable Water Supply - Direct	2 BORES NR THE GROVE,CATFIELD		Annual	365	2.273	**512.00**	1.40		**1507.0**	4.13	* Point 1 (Ludham) is part of licence which also includes points 2 and 3 (East Ruston and Witton) * Point 1 (Ludham) is not aggregated with the other points on the licence * Points 2 and 3 (East Ruston and Hole House Witton are aggregated together) * The licence was originally issued on 17/10/1973 * The licence was most recently re-issued on 25/10/2011 with the annual abstraction quantity from Point 1 (Ludham) being reduced from 680Ml/a to 512 Ml/a * At Point1 (Ludham) up to and including 31/3/2018 abstraction is allowed from 3 boreholes, two not exceeding 76 m in depth and one not exceeding 57 m in depth. From 1 April 2018, abstraction is allowed from two boreholes not exceeding 76 m in depth * For abstraction from Point1 (Ludham), there is a Monitoring Condition that up to and including 31/3/2018 water levels should be recorded hourly at Sharp Street P1, P2, & P3 and at P6 at the Ludham PWS site.
ALSTON	7/34/09/*G/0141C (also known by its current licence no. AN/034/0009/009)	Spray Irrigation - Direct	BOREHOLE AT CATFIELD GT YARMOUTH	31/03/2012	1 Apr-31 Oct	214	0.800	**22.70**	0.11		**22.7**	0.11	* Groundwater levels at 3 locations to be monitored prior to abstraction (TG32/805, TG32/801, &"Alston Obs 3 (Clarke)". Daily between Apr-Oct and weekly between Nov-Mar * Licence assessed under Regulation 48 * Abstraction originally licensed on 1/2/1988 under lic. no. 7/34/09/*G/0111, and then subsequently as 7/34/09/*G/0130, 7/34/09/*G/0141, 7/34/09/*G/0141A, 7/34/09/*G/0141B, and 7/34/09/*G/0141C.

Table 6.1 (continued) **Abstraction Licences in the Vicinity of Catfield Fen**

Licence Name	Licence Number	Use	Abstraction Point	Time Limits	Abstraction Season	Abstraction Days	Licence Quantities						Licence Conditions and Comments
							Abstraction point Quantity (not including restrictions imposed by licence aggregates)			Maximum Licensed Quantity (including restrictions imposed by licence aggregates)			
							Daily	Annual		Daily	Annual		
							Peak Licensed		Av. Over Abstraction Period	Peak Licensed		Av. Over Abstraction Period	
							Ml/d	TCMA (Ml/a)	Ml/d	Ml/d	TCMA (Ml/a)	Ml/d	
ALSTON	7/34/09/*G/0144B (also known by its current licence no. AN/034/0009/008)	Spray Irrigation - Direct	BORE AT PLUMSGATE ROAD CATFIELD	31/03/2012	1 Apr-31 Oct	214	1.090	**68.00**	0.32		**68.0**	0.32	* Groundwater levels at 3 locations to be monitored (TG32/815D hourly. Also the "Plumsgate Road 3.5 m and 15 m" boreholes). * Licence assessed under Regulation 48 and is time limited * Abstraction originally licensed in March 1986 under lic. no. 7/34/09/*G/0108, and then subsequently as 7/34/09/*G/0126, 7/34/09/*G/0144, 7/34/09/*G/0144A and 7/34/09/*G/0144B.
H A OVERTON & SONS	7/34/10/*G/0111	Spray Irrigation - Direct	WELLPOINTS AT CATFIELD, NORFOLK		1 Apr-30 Sep	183	1.200	**72.70**	0.40		**72.7**	0.40	* Aggregate between points on licence (Point 1 wellpoints; Point 2 borehole) * Abstraction from 20 wellpoints (base licence) is assessed under Regulation 50 * Abstraction from borehole (variation) is assessed under Regulation 48 * Licence originally issued on 22/3/1967.
H A OVERTON & SONS	7/34/10/*G/0111	Spray Irrigation - Direct	BOREHOLE AT CATFIELD	31/03/2013	1 Apr-30 Sep	183	1.200	**72.70**	0.40		**72.7**	0.40	* The Agency may request monitoring of local groundwater levels to support any future application to abstract from the borehole.
T C & A M HARRIS	7/34/09/*S/0084	Spray Irrigation - Direct	CATFIELD BROAD AND ASSOCIATED DITCHES		1 Apr-30 Sep	183	0.7	**0.7**	0.004		**0.7**	0.004	Licence issued to Harris 6/4/1994, and prior to this it was held by McDougall of Catfield Hall Farm.

The major groundwater abstraction in the area is from the AWS Ludham PWS source (7/34/09/*G/0091) located about 0.9 km SE of the nearest part of the Fen. This source is included in a licence which includes aggregate limits for the abstraction that can be taken from three separate PWS sources, that is those at Ludham, East Ruston and Witton. However, the Ludham source now has its own separate licensed abstraction limits and these will be considered here.

The PWS source was originally licensed in 1973 and initially was licensed to abstract 2.273 Ml/d. This was equivalent to 829 TCMA, this being a figure that appeared in later endorsements when the licence was aggregated with abstraction from the East Ruston PWS source, the total from both being 1068 TCMA. Later in 1981, there was the intention to separate the Ludham source within the aggregated licence so that separate abstraction limits were defined for the source. It was initially proposed that the annual quantity should be 829 TCMA, but following an objection from Nature Conservancy Council expressing concerns about the impact on the Ant valley and Cromes Broad, and since the water company did not require the proposed total, the annual licensed total was reduced to 680 TCMA in 1982. It remained at this value until 25 October 2011 when the licensed annual quantity was reduced by 25%, becoming 512 TCMA (Figure G1). This reduction was in response to the Habitats Directive Review of Consents Options Appraisal undertaken for Upper Thurne Broads and Marshes SSSI in which recommendations were made to reduce the potential impact of abstractions on Mrs Myhill's Marsh to the west of Hickling Broad.

The licence permits abstraction from three boreholes at the Ludham source. Two of the boreholes abstract from basal Crag unit (Section 4.2) and the groundwater is therefore representative of the "deep Crag" (Section 5.5.3). The third borehole was drilled in 2002 and licensed in September 2004. It differs from the other two boreholes in that it is screened over two intervals, allowing abstraction from both the basal and middle Crag units (Figure E40).

The actual abstraction has been fairly constant for the past 19 years, but has varied over its history. Figure G2 illustrates these variations. From 1973 to 1984, abstraction averaged 434 TCMA (c. 55% uptake of the licensed total at that time). There was then a period of reduced abstraction from 1985 to 1991 when the annual average was 216 TCMA (32% uptake). Subsequently the abstraction increased significantly in 1992 and remained at a high level averaging 556 TCMA (82% uptake) from 1992 to 2010.

The spray irrigation abstraction closest to Catfield Fen is from Mr Alston's Ludham Road borehole which is about 0.65 km SE of the nearest part of the Fen (Figure 3.1). This licence (7/34/09/*G/141C) was originally issued in February 1988 and allows 22.7 TCMA (0.8 Ml/d peak) to be abstracted during April to October.

The original borehole which was drilled in 1987, and subsequently collapsed in 1991 or 1993, was 33.5 m deep with the lower 29 m screened. It was subsequently replaced, the Environment Agency (1998a) indicating it should be to the same design, though there are no good records of its actual construction (Table 5.2). The geological log for the original borehole shows the penetrated sequence as comprising mainly sand, some beds being described as "blowing sand". Two clay beds occur in the interval 18.3-22.3 m bgl, with a thin 0.9 m thickness of sand and clay between them. Both the sequence and depths (m OD) are very similar to those observed at the AWS Sharp Street P2 observation borehole situated about 650 m to the SW, with the clays beds separating the upper and middle sand aquifers (Atkins/ HSI, 2003). If the current replacement Ludham Road abstraction borehole is screened from about 4.5-35 mbgl, it is likely that it draws water both from the shallow Crag unit (which may include Corton Formation), and from the middle Crag unit. However, an historic lack of water level responsiveness within a nearby observation borehole has caused Environment Agency (2001) to suggest that the current screened depth may be more limited than in the original borehole, and be below the 16.5 m depth of the observation borehole. If this is the case, abstraction may be largely from the middle Crag unit. This will be discussed further in Section 7.2.

Over the licensed period uptake has averaged 63% of the licensed total although abstraction has varied considerably each year, varying according to seasonal irrigation requirements, and was close to the licensed total in 1995, 2002, 2003, 2006, and 2008-2010.

Mr Alston's other abstraction borehole is located about 1.35 km N and NW of Catfield Fen near to Plumsgate Road (Figure 3.1). The licence (7/34/09/*G/144B) was originally issued in March 1986 and allows 68.0 TCMA (1.09 Ml/d peak) to be abstracted during April to October.

The borehole log provided to the Environment Agency by Mr Alston in a letter of 15 March 2002 shows the borehole to be 20.7 m deep and comprise sands with interbeds of sandy clay and clay. The screened interval is not identified, but if it is similar to the Ludham Road borehole, which may be the case, abstraction would appear to be from both the shallow and middle Crag units.

Abstraction has varied considerably each year, varying according to seasonal irrigation requirements, and was highest in 2009 (Figure G3). Over the licensed period uptake has averaged 30% of the licensed total.

Mr Overton's abstraction (7/34/10/*G/0111) comprises 20 wellpoints and one borehole. It is located on the eastern side of the groundwater and topographic divide which separates the Ant and Upper Thurne catchments and is about 1.7 km E of the nearest part of Catfield Fen. Though the licence was originally issued in 1967, early abstraction data are not available, the most recent year being 1996. The licence allows 72.7 TCMA (1.2Ml/d peak) to be abstracted during April to September. The licence states the wellpoints should not be more than 10 m deep and the borehole not more than 30 m deep.

Abstraction has varied considerably each year, varying according to seasonal irrigation requirements, and was highest in 2009 (Figure G3). The uptake over the period for which abstraction data are available (1996-2010) has averaged 19% of the licensed total.

The provisions of this licence are to be changed with the authorised quantity in drought years to be reduced to 55 TCMA. This measure results from the conclusions of the Habitats Directive Review of Consents Options Appraisal undertaken for Upper Thurne Broads and Marshes SSSI component of the Broads SAC in which recommendations were made to reduce the potential impact of abstractions on Mrs Myhill's Marsh to the west of Hickling Broad.

7. Impact of Licensed Abstractions

7.1 Introduction

The main licensed abstractions in the vicinity of Catfield Fen have been described in Section 6 and their impact on the Fen will be discussed in turn in this section. The discussion will be largely based on what impacts have been observed from the various monitoring installations on the Fen and in its surroundings. Previous studies will also be considered.

In considering the impact of abstraction, the depths of the intervals from which the boreholes draw water should be considered and the groundwater head variations at different depths within the Crag. These have been described in part in Section 5.4, and are further illustrated in Figure E40 which shows screened depths and water levels in boreholes along a hydrogeological section from the north-west corner of the Fen to the AWS Ludham PWS source.

Since groundwater abstraction for spray irrigation occurs when there is no rainfall, and at times when groundwater and surface water levels would be declining naturally or are at low levels, the method by which the abstraction impact can be discerned is by deviations from the "natural" groundwater level trend at the start of pumping, and assessing whether there is a recovery of water levels back to this trend when abstraction ceases. For example a declining water level trend might steepen after the start of pumping as a result of the abstraction. In addition the effects of rainfall may need to be considered as well as the geology in the vicinity of the abstraction borehole and at location of the water level observations. This approach which is commonly used in hydrogeology is considered in the following sections.

7.2 Alston Abstractions

7.2.1 Plumsgate Road

The abstractions licensed to Mr Alston comprise the Plumsgate Road abstraction (7/34/09/*G/0144B) and the Ludham Road abstraction (7/34/09/*G/0141C). The Plumsgate Road abstraction has three observation boreholes located close to it and the impact of the abstraction at these locations will be considered initially, mainly in order to see the sort of impact that can occur at such distances. The impact of the Plumsgate Road abstraction will then be considered further afield, before investigating the impact of the Ludham Road abstraction, firstly on water levels at the nearest boreholes, and then at dipwells and gaugeboards within the Fen. The impact of the Plumsgate Road abstraction at installations at the Fen will also be considered.

The observation boreholes located near the Plumsgate Road abstraction comprise the 6m deep TG32/815d, 100 m to the north, and two wellpoint observation boreholes (Plumsgate Road 3.5 m and Plumsgate Road 15 m) located about 300 m to the north. The two wellpoints are close to Sutton Fen to the north. Boreholes TG32/815d and Plumsgate Road 3.5 m are monitoring water levels in the upper Crag unit, whereas the Plumsgate Road 15 m borehole are monitoring the middle Crag unit.

The abstraction borehole was drilled to a depth of 20.7 m, and if constructed to a similar design to Mr Alston's Ludham Road borehole, drilled by the same contractor, it is likely to be abstracting from both the upper and middle Crag units. However, drawdown data shown in Table 7.1 show that drawdowns are greater in the 15 m deep borehole than in the adjacent 3.5 m borehole, which suggests either that the main inflow horizons providing water for the borehole are from the middle Crag unit, or that the middle Crag unit is acting is semi-confined by the clay or silty clay layer which separates it from the shallow Crag unit, or both. Groundwater hydrographs from the three observation boreholes are shown in Figure E41. The highest groundwater heads are recorded from the deepest observation borehole (Plumsgate Road 15m), and these sometimes become artesian in winter when heads are over 1 mAOD, ground level being at 0.85 mAOD. These artesian heads may be due to the influence of the clay/ silty clay separating the middle and upper Crag units acting as a semi-confining layer. Borehole logs for the abstraction borehole (BGS TG32/101) and TG32/815d are included in Appendix I, and illustrate the variability of the lithologies within the geological sequence.

The form of the groundwater hydrographs are similar for the Plumsgate Road 3.5 m and 15 m boreholes, but though the form of fluctuation shown in the hydrograph for TG32/815d has many similarities, including observable declines due to abstraction, the amplitude of the fluctuations is markedly larger than for the other two observation boreholes. The reason for this is not fully understood but it seems likely that it is due to a logger issue related to temperature compensation. Such compensation is required in loggers because the transducer membrane is affected by temperature, and in unvented loggers the calculation of barometric pressure effects also requires temperature compensation. Such hydrographs which appear in many respects to be correct but which have large amplitude fluctuations are sometimes known to be caused by this logger issue. An indication that there is a logger issue is that inspection of the hourly logger data show an approximate 24 hour cycle, which many be related to temperature fluctuations. The hourly data from the other boreholes do not show such a regular pattern.

Comparison of daily average logger data (Figure E41) with hourly logger data (Figure E42) from the three observation boreholes shows that although the hourly data show greater water level fluctuations that do daily data for the nearby borehole (TG32/815d), there is little difference in the amplitude of the hydrograph traces for the more distant boreholes 300 m away. The use of daily data when looking at most hydrograph traces is therefore appropriate for the purpose of identifying abstraction impacts.

The impact of the Plumsgate Road abstraction on groundwater levels in the nearby boreholes can be seen in Figure E41 and E42 which show the entire record of logger data, and the form of abstraction on a daily basis in four different years. Then impact is however clearer when looking at shorter timescales, as in Figures E43 to E46. Both the impact of rainfall and abstraction are illustrated when the paired hydrographs with their data are compared with water level peaks and troughs. The drawdowns related to some of the abstraction periods are shown in Table 7.1.

The drawdowns at TG32/815d, about 110 m from the abstraction borehole, varied from about 0.23 to 0.34m for abstractions of about 680-850 m^3/d in 2009, and yet were significantly less in 2011 when drawdowns of 0.15-0.17m were observed when abstraction was 600-650 m^3/d. Such differences between years were not observed at the Plumsgate Road 3.5 m borehole, and it may that the variation in observed drawdowns at TG32/815d reflect the differing amplitudes of hydrograph fluctuations observed in the two years (Figure E41) and are therefore partly related to the logger issue.

At the Plumsgate Road 3.5 m borehole, 320 m to the north of the abstraction drawdowns were consistently about 0.03-0.04 m for abstractions of 600-800 m^3/d. The deeper Plumsgate Road 15 m borehole showed drawdowns of 0.07-0.11 m for abstractions of 680-850 m^3/d.

Table 7.1 Examples of Water Level Fall at Observation Boreholes near the Plumsgate Road borehole During Abstraction Periods

Period of Abstraction	Approx. Average Abstraction (m^3/d)	Borehole	Distance from Abstraction (m)	Observed Water Level Fall (m)	Estimated Water Level Fall Due to Groundwater Recession (m)	Estimated Water Level Fall Due to Abstraction (m)
27/4/09 – 13/5/09	800	TG32/815d	110	0.347	0.009	0.34
27/4/09 – 13/5/09	800	Plumsgate Rd 3.5m	320	0.062	0.035	0.03
27/4/09 – 13/5/09	800	Plumsgate Rd 15m	320	0.185	0.096	0.09
20/5/09 – 7/6/09	680	TG32/815d	110	0.248	0.015	0.23
20/5/09 – 7/6/09	680	Plumsgate Rd 15m	320	0.158	0.085	0.07
9/9/09 – 8/10/09	850	TG32/815d	110	0.411	0.071	0.34
9/9/09 – 8/10/09	850	Plumsgate Rd 15m	320	0.138	0.031	0.11
29/5/11 – 17/6/11	650	TG32/815d	110	0.186	0.041	0.15
29/5/11 – 17/6/11	650	Plumsgate Rd 3.5m	320	0.039	0.005	0.035
9/7/11 – 13/7/11	600	TG32/815d	110	0.165	-0.003	0.17
9/7/11 – 13/7/11	600	Plumsgate Rd 3.5m	320	0.022	-0.026	c.0.03

Further south at the north-west corner of Catfield Fen, at a distance of 1800 m from the abstraction, the hydrographs for boreholes for TG32/616d and NTG3261P1 are shown with abstraction and rainfall data in Figures E47 to E50. TG32/616d monitors groundwater heads in the middle Crag unit, and NTG3261P1 monitors the shallow Crag unit, as shown in the cross-section Figure E40. Entec (2010) noted that during the abstraction period of September-October 2009 "abstraction appears to have lowered groundwater levels, for example, by about 7 cm in P1" (p13). However, this is not now considered to be the case for several reasons including further inspection of the hydrographs, consideration of the drawdowns noted in Table 7.1, calculated drawdowns and past studies.

Abstraction from the Plumsgate Road borehole appears to have occurred on many occasions when there was a lack of rainfall and evapotranspiration was high. Though it appears that groundwater levels could have been lowered by 7 cm due to abstraction of about 800 m^3/d in September-October 2009, a very similar decline in water levels was observed in September 2008 (5 cm) when abstraction was only about 300 m^3/d, and at the end of October 2009 a decline in water levels was observed in the absence of abstraction (Figure E47). A lowering of water levels from 8 April to 3 May 2010 also occurred in the absence of abstraction (Figure E49). It therefore seems that both the abstraction and groundwater level fall are in response to the same common factor, namely conditions of elevated evapotranspiration.

In order to assess how far the cone of depression might extend, aquifer characteristics (parameters) are chosen and for a worst-case prediction of drawdown, a Theis analytical method can be used. This is worst-case because the Theis method relies on a number of assumptions which are rarely met, and in not meeting these assumptions actual drawdowns are less than those predicted by the method. The aquifer parameters can be estimated from the results of test pumping boreholes.

Test pumping of the Plumsgate Road abstraction borehole in 1985 provided data that were difficult to analyse due to the unusual behaviour of water level variations in the observed drawdowns, which was considered to be due to the complex geology in the area which did not fulfil the assumptions of the conventional analytical techniques adopted to determine aquifer parameters. This analysis indicated a range of transmissivity values from 800 to 3000 m^2/d and a storativity of 0.25 (Anglian Water Authority, 1986; Environment Agency, 2008). It was concluded that the cone of depression extends mainly to the north, where transmissivity appears to be higher.

Test pumping of the Catfield Fish Refuge borehole, 1.5 km to the east, provided aquifer parameters values with a transmissivity of 950 m^2/d and a storativity of 0.05 (LWRC, 1992). Test pumping of the Ludham Road borehole provided a transmissivity value of 406 m^2/d (Anglian Water Authority, 1987). The variability of aquifer parameters across the area was highlighted by the Environment Agency (1998a), and concluded that for abstractions from the Crag at depths equivalent to those of the Alston and Overton abstractions, values for transmissivity of 450 m^2/d and storativity of 0.05 were appropriate.

Using the Theis method, the drawdown curve can be generated for different times since the start of pumping, and for different distances from the pumping borehole. By matching the observed data to a particular curve for chosen aquifer parameters, the "worst-case" drawdown for different distances can be predicted. In doing this, the Theis predictions are partly linked to observation and are not reliant on its assumptions alone. By matching the observed drawdowns shown in Table 7.1 for boreholes TG32/815d and Plumsgate Road 15 m, with the Theis curve produced for a transmissivity (T) of 450 m^2/d and storativity (S) of 0.05 the predicted drawdown at 600 m from the abstraction borehole would be 1 cm, and not observable at 1000 m. It should be noted these are the predicted drawdowns within the middle Crag aquifer, and those in the shallow Crag may be less. Using the original test pumping results from the Plumsgate Road abstraction, if a T value of 3000 m^2/d is used (the higher end of the analysis range) and S is 0.25, the Theis curve does not reproduce the observed drawdowns. Using a T of 800 m^2/d (the lower end of the analysis range) and a S of 0.25, the predicted drawdown at 600 m would be 2 cm and negligible (2 mm) at 1000 m. Reducing the storage to 0.05 for the same T increases the estimated drawdown proportionately. In providing these predicted drawdowns it should be noted that the purpose is not to provide solid predictions of drawdowns, but to give an indication of what is likely to be a worst-case scenario in relation to drawdowns resulting from the quantities that have been abstracted.

Though there may be no change in groundwater level at the Fen boundary, the effects of drawdown could cause a reduction in the groundwater head gradient leading towards the Fen with a consequent reduction in flow towards the Fen. This potential change in flow has been investigated through the use of Darcy's Law which relates head gradient, hydraulic conductivity and flow. Using a value for hydraulic conductivity of 3.2 x 10^{-2} m/d obtained from a falling head test carried out at NTG3270P4 (HSI, 1998), and assuming a 0.2 cm fall in water level at TG32/815c (600 m from the abstraction borehole) with no change at the Fen boundary, the flow through a thickness of Crag 1 km wide and 10 m deep at the Fen boundary would be reduced in the summer from 0.56 m^3/d without abstraction, and 0.544 m^3/d with abstraction. Not only is this a very small reduction in flow, it is also a very small flow, and only some of this would potentially emerge at the Fen, the rest flowing in the Crag beneath the Fen. Also it is the change in groundwater head, rather than groundwater flow, that will be the main influence on potential groundwater input to the Fen. For these various reasons, the potential reduction in flow towards the Fen is not considered to have any impact on the Fen.

In summary, as outlined above, the lowering of groundwater levels in September-October 2009 is not considered to be a result of abstraction from the Plumsgate Road borehole as suggested by Entec (2010), and it is not considered that the abstraction has any impact on groundwater levels at the north-west corner of the Fen nor of flow to it.

The logger data from the observation boreholes near the Plumsgate Road abstraction only extends back to 2008, but there are manual data which extend back to 1992 (Figure E51). The hydrograph for TG32/815d does not appear to be showing any sign of declining water levels and the form is similar to the hydrographs for two boreholes which are further from the Plumsgate Road abstraction (Figure 3.1), and therefore would presumably exhibit less impact from abstraction. All the hydrographs show similar features to those in the regional observation boreholes (Section 5.4.2), namely high groundwater levels during the high recharge periods in 2001 and 2007, both of which were followed by a gradual decline in groundwater levels, and low groundwater levels during the drought periods of 1992 and 1996. The only difference in the hydrographs is that the water levels at TG32/815d tend to reach their annual minima and maxima very slightly earlier than at TG32/815a and TG32/815c. This could reflect the differing depths to the water table in the three boreholes. The depth to water table in TG32/815d is about 1 m or less, whereas in TG32/815a it is about 6 m, in TG32/815c it is about 5.5 m, and in another nearby borehole TG32/815b it is 3.5 m. The greater depth to water table in TG32/815a and TG32/815c may well lead to the effects of recharge being delayed when compared with TG32/815d.

The daily logger water level traces obtained from these boreholes in 2011 and early 2012 are shown in Figure E52). These traces, from three boreholes all in the area to the north-north-east of Catfield Fen, all show a similar water level decline, but little or no response to rainfall events even though their geological logs show the geology to be predominant sand and gravel (LWRC, 1992; Entec, 2010). They are not, however, completely unresponsive, as their long-term records of manual water level show. This is also shown following the heavy rainfall that fell on 4-5 March 2012. Figure E52 shows that the water levels in TG32/815b rose rapidly by 3cm between 5 and 7 March. The water levels in TG32/815c also rose, but the start of the rise was delayed until 10 March and continued until 17 March. The greater depth to water table at TG32/815c may have been a factor for this delay relative to TG32/815b.

A barely perceptible rise in water level also occurred in TG32/815a on about 8 March (corrected for logger time error, Figure E52). This is probably a further delayed response to the rainfall of 4-5 March. However, a feature of these three boreholes (TG32/815a, b & c), which they share with TG32/805 to the south (see next section), is the general lack of responsiveness of the water table to rainfall events. Though there have been past issues with them becoming infilled with sand this does not seem to have been an issue at least with TG32/815b which after initially having a depth of 4.89 m was cleaned out to a depth of 6.275 m on 3 June 2011. Its depth on 20 March 2012 was 6.34 m. Likewise, the depth of TG32/815a was 8.37 m on 3 June 2011 and 8.27 m on 20 March 2012. The poor responsiveness to recharge is not fully understood, especially when there is clearly some responsiveness. It may be related to the depth to water table, and the presence of gravel which would have both high storage and high permeability.

These three boreholes, located between the Plumsgate Road abstraction and Catfield Fen, do not show any evidence of long-term decline. The hydrograph records are consistent with those observed regionally elsewhere and have shown lower groundwater levels in the past, for example during the drought years of 1992 and 1996, than they have in recent summers (Figure E51). Inspection of the logger data for 2011 shows a 2-3 cm fall in water levels during the period 22 July to 15 September 2011 but there was no significant abstraction during this period, the main period of abstraction being from 19 April to 18 June. A delay between the start of abstraction and the start of a drawdown may occur, but a delay of 3 months at a distance of 600 m is not expected. The use of the Theis approach described above has indicated that a drawdown of 1-2 cm could occur at a distance of 600 m, but no impact would be expected at a distance of 1000 m, the distance between the abstraction and TG32/815b.

In conclusion, there is no observational evidence that the Plumsgate Road abstraction is having an impact on the north-west corner of Catfield Fen, and on the basis of observed drawdowns near to the abstraction borehole, pumping test analysis and theoretical worst-case predictions of drawdowns, it is not considered that there will any drawdown at the Fen. Three boreholes located between the abstraction and the closest part of the Fen at about a 1 km distance from the abstraction are responsive to water level change but less so than would be ideal in seeking to determine short-term drawdown. However, the prediction of worst-case drawdown is such as to indicate no drawdown at the borehole nearest the Fen, and only a small drawdown of 1-2 cm at the mid-way borehole TG32/815c which is 600 m from the abstraction. Since these drawdown calculations tend to be overestimates of what would actually occur, a drawdown might not be expected to be detected at borehole TG32/815c. These various strands of evidence support the conclusions of past Environment Agency reports that the abstraction is not having an impact on the Fen.

7.2.2 Ludham Road

The Ludham Road abstraction borehole was originally 33.5 m deep with the lower 29 m screened when it was drilled in 1987. It subsequently collapsed and was re-drilled in either 1991 or 1993. Its construction is not recorded, but it is believed to be to the same design as the original borehole (Section 6), though there is some uncertainty as will be described below. Given it is constructed as originally designed, the borehole will be abstracting water from both the shallow and middle Crag units. Two nearby observation boreholes, TG32/805 and TG32/801 are at distances of 60 m and 530 m respectively from the abstraction borehole, and both monitor the shallow Crag unit. In addition, two boreholes monitoring the shallow Crag unit are located at the south-east edge of the Fen at a distance of 850 m. These are NTG3261P4 and NTG3270P5 (Figure E40).

Groundwater levels in boreholes near to Mr Alston’s Ludham Road abstraction are shown in Figure E53 together with daily abstraction data since 2008. Though abstraction has occurred since 1988 (Figure G3), daily data are only available from 2008 to present.

The hydrograph shown for observation borehole TG32/805 in Figures E53 and E54 is of note. There is an apparent lack of any water level response to abstraction from the borehole which is only 60 m from it. This is surprising not only because the borehole is so close to the abstraction but also because whereas the groundwater level in observation borehole is about 3.5 mbgl, the drawdown in the abstraction borehole during pumping could be up to 12 m or more. During test pumping of the borehole in 1987 a maximum drawdown of 12.56 m was observed after pumping for 67.5 hours at an average rate of 860 m^3/d (the current peak licensed rate being 800 m^3/d) (Environment Agency, 2001).

The hydrograph for TG32/805 has a similar form to those from TG32/815a, TG32/815b and TG32/815c shown in Figure E52, and discussed above. The Environment Agency (2001) also noted that TG32/805 responded less to abstraction than was expected and ruled out possible infilling by plumbing the depth to 16.2 m and noting that the water level dropped quickly following a slug test carried out by Mr Alston. The borehole therefore appeared to be responsive to water level changes and Environment Agency (2001) concluded that the production borehole construction (which was, and is, not known) was such that the screened interval was below the base of the observation borehole. If this is the case, the screened interval would be within the middle Crag unit alone, below the clay interval which is at 18.3-22.3 m depth. This could further reduce any water level response within the observation borehole resulting from abstraction. This conjecture is, however, uncertain as water levels from the shallow Crag unit in a nearby borehole (TG32/801) do show some response due to abstraction, and if constructed as directed by the Environment Agency (1998b), its depth would be above the clay interval. As there is no geological log available for TG32/801, what lateral variation in lithology there might be between it and TG32/805 is not known, and this could account for differences in their water level response.

Observation borehole TG32/801 is located between the Ludham Road abstraction borehole, and the Church Wood area of Catfield Fen (Figure 3.1). It is about 530 m from the abstraction borehole and about 100 m from the closest part of the Fen. It was drilled in about 1998 for Mr Alston, at the same time as two other observation boreholes were drilled for him (TG32/805 and Aston Obs3). Its actual construction and depth are not known, but prior to construction, the Environment Agency (1998b) stated that each observation borehole should penetrate 15 m into the Crag and have perforated screening over their lower 10 m. If constructed to a 15 m depth, its base would be about 1 m above the clay interval separating the shallow and middle Crag units.

Water level hydrographs for TG32/801 showing daily Ludham Road abstraction and daily rainfall are shown for 2009 in Figures E54 and E55, and for 2010 and 2011 in Figures E56 and E57. These Figures show that there are several water levels falls which are not related to absence of rainfall but are related to abstraction, and such falls do not occur in the absence of abstraction indicating that they are not solely due to the effects of evapotranspiration. Some examples are given in Table 7.2.

Though the groundwater levels appear to be lowered by abstraction, they also tend to recover quickly back to the level associated with the natural groundwater recession following the end of abstraction and respond quickly to rainfall events (e.g. in September 2010, and February and March 2011). The groundwater level declines at TG32/801 tend to be about 4-6 cm for abstractions of up to 770 m^3/d. These are close to the peak daily licensed quantity of 800 m^3/d.

Table 7.2 Examples of Water Level Fall at TG32/801 during Abstraction Periods from the Ludham Road Borehole

Date of Abstraction	Approx. Average Abstraction (m^3/d)	Distance from abstraction (m)	Observed Water Level Fall (m)	Estimated Water Level Fall Due to Groundwater Recession (m)	Estimated Water Level Fall Due to Abstraction (m)
18-26 August 2009	600	530	0.05	0.02	0.03
14-19 September 2009	310	530	0.05	0.03	0.02
30 Sept-3 October 2009	370	530	0.03	0	0.03
15-20 May 2010	750	530	0.11	0.06	0.05
18-28 May 2011	770	530	0.13	0.09	0.04
17-23 August 2011	720	530	0.06	0	0.06

Further from the Ludham Road abstraction, at a distance of 850m from it and at the south-east corner of Catfield Fen, NTG3270P4 is screened at a depth 8.0-9.9 m bgl and yet shows no observable impact due to the abstraction. A fall of about 4 cm appears to occur on about 15-20 May 2010, coinciding with an abstraction period (Figure E56) but other abstraction periods show no such response, and similar falls can occur in the absence of any abstraction from Ludham Road (as in mid-February 2010, and March and July 2011). During 2009, the apparent lack of response to abstraction is further illustrated in Figure E54.

The shallow piezometer at this location, NTG3270P5, shows larger water level variations, with more rapid falls and rises in water level than those observed in the nearby NTG3270P4 (Figures E56 and E57) and these do not seem to be related to abstraction. The rises appear to be in response to rainfall events and the falls are likely to be largely due to evapotranspiration. There is no observable impact due to abstraction from the Ludham Road borehole.

Daily abstraction and rainfall data are compared with dyke water levels in Figures E58 and E59 for the period for which logger data are available, and for the shorter period 2008-2009 in Figures E60 and E61, and for 2010-2011 in Figures E62 and E63. There are no discernible effects due to the Ludham Road abstraction, though the effect of rainfall events in causing water level rises is clear in many cases. Falls in water levels often occur in the absence of abstraction, and during abstraction in many cases there is no deviation in the recessionary trend. This is the case even at gaugeboard TG32/710 within the catchwater drain on the eastern side of the Fen which is considered to have a high groundwater component, and which is close to a drain that has been reported by Sadler (1989) (Figure B8) as having no intervening clay between the base of the dyke and the Crag. This suggests that though the dyke water and its level may be affected by changes in groundwater conditions in its vicinity, it is not very responsive to such changes.

Likewise, daily abstraction data are compared with dipwell water levels from the western side of Catfield Fen, both within the internal and external systems, in Figure E64 for the period for which logger data are available. These dipwells are situated about 2 km from the Ludham Road abstraction. If there was a discernible impact on dyke water levels due to abstraction, then an impact on dipwell might have been possible to observe, but this is not the case and no impact on dipwell water levels can be discerned.

Entec (2010) had proposed that a dipwell be installed in Middle Marsh, about 1.3 km from the Ludham Road abstraction but such is the distance from it that any direct impact on the dipwell water levels would be unlikely to be discernible, and any effect resulting from any impact on dyke water levels also appears not to be discernible. The use of such a dipwell within Middle Marsh would be in order to identify any long-term trends in peat groundwater levels on the eastern side of the Fen, to investigate their relationship with vegetation communities of interest, and to monitor any relationship with dyke water levels. Currently this is possible at only the one dipwell location within the internal system.

The effects of abstraction on Crag groundwater levels at the north-west corner of Catfield Fen are investigated for the period 2008-2009 in Figure E65, and for the period 2010-2011 in Figure E66. The observation boreholes are about 2 km for the Ludham Road abstraction borehole, and their hydrographs show no discernible impact on groundwater levels due to the Ludham Road abstraction.

The available data indicates that abstraction at close to its peak licensed rate from the Ludham Road borehole causes a drawdown within the Crag of about 12 m at the point of abstraction, a drawdown of about 0.04-0.06 m at a distance of 530 m from the abstraction (at TG32/801), and no observable drawdown at a distance of 850 m at NTG3261P4 (Figure 3.1). The dyke at the margin of the Fen at Church Wood, near to TG32/801, is about 630 m from the Ludham Road borehole, and has input from Crag groundwater (Figure F12). It appears likely that groundwater levels in the vicinity of this dyke would be reduced by a few centimetres (probably less than 5 cm). The summer minimum groundwater levels in TG32/805 are about 0.5 m higher than at NTG3270P4 so it appears that the groundwater gradient is towards the Fen in this area (Figure B2), and if the dyke water levels are similar to those on the west side of the Fen, a consequence of the Ludham Road abstraction will be both to cause a small drawdown in groundwater level near the margin of the Fen and to reduce the groundwater gradient, and therefore any lateral groundwater flow towards it. Therefore groundwater input to the dyke would be reduced during periods of abstraction.

It could be argued that in the summer months, dyke water levels may be determined by the groundwater level in the adjacent Crag (Figure E18, Section 5.4.3), and if these groundwater levels were lowered further by abstraction, there is a possibility that the dyke water level could also be drawn down. If the ground level in some of the eastern compartments is at higher level than to the west, and if as a consequence the water table beneath them is at a higher than in the surrounding dykes, increased drainage of the compartment could occur during the period when dyke water levels are reduced due to abstraction. Any such increased drainage would probably cease when abstraction ceased because rapid recovery of the Crag water levels back to the levels associated with the natural recession is observed. The water levels within the compartments would however have been lowered and would not recovery since they rely largely on rainfall for their water supply. This is, though, based on little evidence and relies heavily on conjecture. There are several factors that are not known. These include:

- Whether the lowering of groundwater levels locally near parts of the eastern margin can have a widespread influence on dyke water levels throughout the Fen;
- Whether the dyke water levels are responsive to small changes in groundwater level which may be short-term. The dyke water level data do not indicate that this is the case;

- Whether the compartments on the eastern side of the Fen are at a higher level than to the west. This was suggested in Section 5.4.4 but will not known until some topographic transect surveys are undertaken;

- Whether the water table in the eastern compartments is higher than in the dykes during the spring and summer months. It may be higher in the winter, but whether it is in spring and summer will only be known by installing at least one dipwell within an eastern compartment and comparing its levels with the water levels in a nearby dyke.

There is therefore much uncertainty about what impact the Ludham Road abstraction may or may not have on the Fen. It is considered that the Ludham Road abstraction has only a small localised effect on groundwater levels near to Church Wood, and that when abstraction ceases groundwater levels return rapidly to the level that would have occurred without the abstraction. Observed data do not show any effect on water levels within the Fen. It would seem unlikely that this localised effect on groundwater levels could have a widespread effect on Fen water levels, particularly as dykes with groundwater input also occur further north near Middle Marsh where groundwater levels would not be lowered by the Ludham Road abstraction. However, whether there is an impact or not on the Fen cannot be determined with any certainty until the form of water level variation within the catchwater drain at Church Wood is known, the connectivity of the dyke system and of changes in levels within it is better established, and there is better knowledge of the relationship throughout the year between water table levels within eastern compartments and adjacent water levels in dykes.

7.3 AWS Ludham

The AWS Ludham PWS source (7/34/09/*G/0091) has been the subject of many studies promoted under the AMP programme which have investigated the potential impact it might have on the surrounding area (e.g. @one Alliance, 2006a & b, 2007, 2008) and on Catfield Fen in particular (e.g. Atkins/HSI, 2003 a & b, 2005).

Atkins/HSI (2003b) with its supplementary report (Atkins/HSI, 2005) are the main reports which summarise the investigations and make an assessment of the impact on Catfield Fen. The investigation included the drilling of boreholes, the identification of the aquifer as being multi-layered with unconfined and semi-confined units separated by clay horizons (Section 4.2), water chemistry sampling (Section 5.5.3), the carrying out of pumping tests, and radial flow modelling.

Within the AMP programme of investigations, test pumping of the Ludham PWS source has occurred on three occasions. These took place in August-November 2002, September 2003 and November/ December 2007. As part of this testing, boreholes NTG3270P4 and NTG3270P5 were monitored together with the AWS Sharp Street observation boreholes which are located midway between the PWS abstraction and Catfield Fen, about 450 m from both the PWS source and NTG3270P4 (Figure 3.1). These Sharp Street boreholes comprise a deep Crag borehole (P2) which is screened within the bottom of the middle Crag unit (and possibly including part of the basal Crag unit), P1 is screened in the upper part of the middle Crag unit, and P3 is screened within the upper Crag unit. NTG3270P4 at the south-east corner of Catfield Fen monitors a similar horizon to that monitored by Sharp Street P3. The screened intervals are shown in the cross-section in Figure E40, and borehole logs included in Appendix I.

Observed water levels, rainfall and abstraction covering the period of the 2002 and 2003 pumping tests are shown in Figure E67, with more detail being shown in subsequent Figures. In 2002, the test pumping involved increasing the output from the two licensed boreholes from an average rate of 1.57 Ml/d to an average of 2.36 Ml/d over a period of 91 days. Figure E68 shows the form of this abstraction, and the observed water levels can be compared both to the abstraction rate and rainfall. The hydrographs show that heads decrease with depth both prior during and after the test period. The groundwater heads at depth (P2 and P5) were drawn down more (0.6-0.7 m) during the test pumping than those in the upper middle Crag unit (P1)(0.4-0.5 m) and the effects of test pumping on the shallow Crag unit (P3) was not discernible. The reduction in head was greatest at depth because the abstraction was from the basal Crag unit.

The impact of the test pumping on NTG3270P4 is also not discernible (Figure E69) particularly when a longer period of record is considered (Figure E70). The impact of rainfall on the shallow borehole NTG3270P5 is clear (Figure E68) and the deeper NTG3270P4 also shows a marked response to large rainfall events and to steady rises due to wet periods (e.g. mid October to mid-November 2002, see Figure E69).

In September 2003, following some clearance pumping and a “failed” constant rate test which was aborted after 5 days, the new Ludham borehole No.3 was tested for a period of 7 days from 23-30 September 2003. It was pumped at a rate of 2.5 Ml/d while borehole No.1 maintained a pumping of 1.55 Ml/d to supply. The total output from the source during the test was therefore about 4 Ml/d, which is about 1.75 times the licensed peak daily rate of 2.273 Ml/d. Figure E71 shows a similar, though greater impact, on heads at the various levels monitored at Sharp Street when compared with the heads resulting from the smaller abstraction during the 2002 test. Heads in the deep Crag fell by about 1.4 m, and in middle Crag by about 0.7 m. Heads in the shallow Crag unit (P3) appear to have been lowered by about 0.07 m as a result of the test pumping (Figure E72). Water levels monitored using a shaft encoder in a dyke on Snipe Marsh near the Sharp Street boreholes, showed no influence due to pumping during either the 2002 or 2003 tests.

Water level data from NTG3270P4, at a similar level to Sharp Street P3, are difficult to interpret during the 2003 test because of the erratic logger behaviour both before during and after the test (Figure E73). It does however show a seasonal response to water level change, and there is an indication of a rise in water level following the end of the test pumping (Figure E74), but given the quality of the data no comment about the impact can be given.

The most recent pumping test took place from 20 November to 5 December 2007, with an objective to give an indication of the actual drawdown below Ant Broads & Marshes SSSI due to the PWS abstraction. However, its scope was constrained by PWS operational issues, including the need to maintain supply and problems with maintaining pumping continuously. The test was aborted after 16 days with problems controlling pumping rates, attributable to a burst main. The results in relation to Catfield Fen are shown in Figure E75. The increase in pumping rate (the “signal”) during the test was not large, and some rainfall events and periods also occurred during the test. There was no observable impact on water levels at the Fen. The logger data from NTG3270P5 should be regarded as suspect given the large sudden rises in the water levels which are unrelated to rainfall events.

The results of the test pumping show that pumping from the Ludham PWS source causes a cone of depression to occur which affects the deep and middle Crag units. Though there was no clearly discernible effect on shallow Crag groundwater levels during the 2002 test, the 2003 test did show that a small drawdown was observable in the shallow Crag. This occurred not only when pumping rates were significantly above the licensed rate, but also with the additional abstraction being from the lower part of the middle Crag unit, through the use of the new borehole No.3. Either or both may have contributed to the impact in the shallow Crag being observed.

The test pumping caused no observable impact on water levels at the Fen. The potential impact of abstractions on groundwater levels at the Fen has, however, been investigated by groundwater model used by the Environment Agency in its assessment of groundwater abstractions as part of the Review of Consents process (Entec, 2009b). As part of the consideration of Site Options, an assessment cell (cell G) was chosen in the southern part of Catfield Fen in the vicinity of Rose Fen and Long Marsh. The output from the model include data from a number of layers with the model and predictions of groundwater levels in the highest peat layer (Layer 1) under a number of modelled abstraction scenarios. These include a Naturalised scenario for which there were no abstractions operating, an Historic scenario using actual historic abstraction data from all licensed abstractions, a Fully Licensed scenario using the full licensed quantity each year, and a Real Fully Licensed scenario which incorporates licence group aggregates, licence conditions and changes to specific licences where required in order to represent a more realistic maximum abstraction scenario for the modelled area.

The modelled groundwater heads under different abstraction scenarios for Layer 1 of assessment cell G are shown in Figure E76. The modelled groundwater levels are shown for the period 1970 to 2005, and there appears to be no obvious decline in groundwater levels over that period. Drought summers (e.g. 1976, 1990, 1996) are clearly seen, but the changes in impact due to abstraction are difficult to see because of their small scale. Figure E77 presents these changes by comparing the water levels for different abstraction scenarios with those that the model predicts would occur in the absence of abstraction (i.e. the Naturalised scenario). It should be emphasised that Figure E77 shows changes in water level differences, not changes in water level, and it does not show “actual” water level differences but “modelled” differences. The reasons why the modelled differences may be different from actual differences will be considered below, but nonetheless Figure E77 does show the form of differences that might occur and provides an indication of which abstractions might have an impact on the Fen, though it does not enable the significance of the impact to be determined.

Figure E77 shows that compared to Naturalised conditions, heads appear to have been reduced by up to about 0.03 m due to Historic abstraction, and if abstraction were to be a Fully Licensed rate, heads could be reduced by up to about 0.06-0.07 m in some drought periods. The form of the Historic difference trace is interesting. If it is compared to the graph of annual abstraction (Figure G2), it very clearly reflects the variations in abstraction from the Ludham PWS source. The PWS source started abstraction in 1973, and there was a period of much reduced abstraction between 1985 and 1991. Subsequently, from 1992 and 1993, abstraction increased to its current levels which are a fairly constant year-on-year rate and at a higher level than before 1992/1993. These changes are mirrored in the modelled head output. This output does not distinguish the impact of different abstractors, but it indicates that the Ludham PWS is a major contributor to these small changes in water level.

There are several factors that may affect these modelled water level changes. The model currently does not include any layering within the Crag. This may have an effect on vertical flow, and this omission may affect the model’s prediction of shallow water levels and their variation. Also, the model does not currently take account of the Commissioners’ Rond and of any effect this may have on water levels within the internal system. It is also not known if it can reproduce results similar to those observed at the Sharp Street boreholes during the pumping tests.

At the time of the pumping tests the background abstraction from the PWS source was about 1.5 Ml/d, and when this was raised in the 2003 test to 4 Ml/d, about a 2.7 times increase, the shallow Crag water levels appeared to be lowered by about 0.07m after 7 days pumping. It is not known what the actual decline in shallow Crag water levels has been as a result of the PWS abstraction of 1.5 Ml/d, but it seems likely that there has been a decline when compared to naturalised conditions.

Water level data collected since 1996 as part of the current monitoring have not shown any evidence of having been affected by the Ludham PWS abstraction, but this is probably because during this period, with the exception of the relatively short pumping test, abstraction rates have been fairly constant and it has not been possible to observe the effects of any long-term changes in abstraction rates. The 2003 constant rate test has however shown that groundwater heads in the shallow Crag can be reduced by abstraction from deeper levels. Therefore over the period of PWS abstraction since 1973 it seems likely that there will have been a decline in shallow groundwater heads in the vicinity of the Fen. The magnitude and significance of this decline is not known, but in the absence of any major change in the actual abstraction from the PWS source, an indication of this may be obtained from a well-calibrated groundwater model.

7.4 Overton Abstraction

Mr Overton's abstraction licence (7/34/10/*G/0111) allows 72.7 TCMA (1.2Ml/d peak) to be abstracted during March to September from 20 wellpoints up to 10 m deep and a borehole up to 30m deep. It is located about 1.7 km from the nearest point of Catfield Fen, with Mr Alston's Ludham Road abstraction located between it and the Fen at a distance of 1 km. The level from which groundwater is abstracted is similar to that at Ludham Road, and the actual daily quantities abstracted also appear to be similar in magnitude. The abstraction is licensed for similar quantity to Mr Alston's Plumsgate Road.

The actual annual abstraction for which data are available since 1996 is shown in Figure G3. Daily abstraction rates are similar to those from the Ludham Road borehole. Its peak annual abstraction appears to have been in 2009 when the total abstracted was about the same as from the Plumsgate Road borehole. In other years, the total abstracted is often less than from the Ludham Road borehole. Given its similarities to the Ludham Road abstraction, both in depth and quantities abstracted, and its greater distance from the Fen, it is considered that the impact of its abstraction on the Fen will not be discernible.

Box 3	Comments by Professor Gilvear

Section 7.2 Alston Abstractions

Due to the lack of responsiveness of the boreholes between the Plumsgate Road abstraction and the fen there no evidence of the impact of groundwater abstraction on Crag water levels near the fen or on the fen at the location where if there was an impact it would most likely exist.

These locations where no discernible effect of fen peat water levels are observed are at the furthest extremity of the fen from the abstraction and thus cannot be used to infer what is happening in the middle of the fen. As such it is unwise to make definitive conclusions as to the impact of groundwater abstraction.

It should be noted that although the effects of individual pumping periods on groundwater levels appear short-lived they are undertaken at times when the fen vegetation is already stressed. Pumping only occurs at times of a large soil moisture deficit at crop rooting depths. It should also be noted that studies by Mike Harding (Natural England et al., 2011) have shown falls of 2-3 centimetres in East Anglian fens can cause changes in vegetation community composition.

Section 7.3 AWS Ludham

It could equally be argued and concluded there is no good evidence that the Ludham PWS source is not having a significant impact on Crag water levels beneath the fen. The fact of the matter there is no good evidence either way. In addition the text says "whether or not this impact is significant is not known". This should be given greater emphasis in regard to uncertainty as to the impact of groundwater abstraction.

8. Possible Reasons for the Fen Drying Out

8.1 Expressions of Concern

Concerns regarding the drying out of the Fen have been expressed at various times over the past 20 years. In his letter of 7 June 1991 to the National Rivers Authority, a former owner of Catfield Hall, Mr K McDougall, expressed "extreme concern" about the dryness of the fens after "3 dry seasons". He again wrote to English Nature in August 1993 expressing "grave fears for the future of Catfield Fen SSSI in relation to the insidious lowering of the ambient water levels over the last 25 years." This view was shared by Clive Doarks (English Nature) who relayed these concerns to the National Rivers Authority in a letter of 11 August 1993, and asked for a thorough hydrological investigation. Copies of these letters and of other correspondence referred to in this Section are shown in Appendix H.

More recently Mr and Mrs Harris of Catfield Hall contacted the Environment Agency in September 2008 to express their concern about the dryness of the Fen, and in a letter to the land agent for Catfield Hall Estate, dated 7 November 2010, Alec Bull noted "My observations over a ten year period suggest that the site is drying and the process has been gathering pace over the last two years."

Following these concerns being expressed, a Compendium of ecological and eco-hydrological evidence has been produced (Natural England et al., 2011). Natural England subsequently stated in their letter of 7 April 2011 to the Environment Agency that "The evidence presented demonstrates a long-term trend of drying on this site which appears to be accelerating. There is evidence of vegetation change consistent with drying of the wetland habitat."

As part of the Compendium Clive Doarks (Natural England), in a Note dated 21 December 2010, compared NVC quadrat data collected from the Butterfly Conservation land (i.e. Sedge Marshes and Fenside Marsh, Figure A2) in 2007 with the NVC map produced in the early 1990s for the Fen Resource Survey. The percentages of woody species occurring within quadrats on land to the east owned by Mr and Mrs Harris were also compared for surveys undertaken in the early 1990s and in 2009.

Doarks concluded:

- "Natural England sees no evidence of major shifts in NVC community within Catfield Fen, hence at this time serious, probably irreversible damage has not occurred on site;
- We cannot however conclude that damaging shifts in the vegetation quality are not occurring on account of the time lag between adverse environmental conditions and its manifestation in NVC community present on site;
- There is evidence to show an increase in woody species within the open herbaceous fen communities that have remained in continuous cutting and clearing management;
- The increase in woody species could be due to a number of individual or several factors in combination; these include drying conditions increasing opportunities for germination or changes in the management of the open fen".

Within the Compendium there are also the following conclusions from historic aerial and historic photographic evidence:

- There has been a significant reduction in the stature of the reed within the reedbed areas in Catfield Hall Fen. Such a reduction is consistent with a reduction in water supply during the growing season;
- The aerial photography shows the scrubbing up of large parts of the fen, a process that appears to have accelerated since the early 1980s. There also appears to be evidence of a reduction in the area of shallow open water".

Also within the Compendium, Alec Bull begins his ecological assessment with the following comment which gives an indication of his view as to when the increased drying out has been taking place: "Following relatively sudden drying out of the fens at Catfield Hall between 2007 and 2010…". This does however appear to be in addition to a longer period of drying out.

8.2 Past Studies

One particular past study, not referred to in the Compendium, is of note as it investigated vegetation changes at the Fen over the period from the early 1970s to the 1990s. ECUS (1997), in a study prepared for the Broads Authority and English Nature, compared vegetation survey data by Wheeler in the 1970s and by Wheeler and Shaw in the 1980s with those of the Fen Resource Survey in the 1990s. Both the Sedge Marshes in the internal system and the main Liparis area of Great Fen in the external system were investigated.

At Sedge Marshes samples from 1972 were compared with the Fen Resource Survey and found to show no major differences. ECUS (1997) note "This consistency confirms casual observations that there has been little substantial change in Sedge Marshes over the last 20 years (Wheeler has visited this area almost every year since 1972)". Also as a footnote to this quote, "There has been some localised change, some suggestive of increased wetness, presumably due to regulation imposed by the level of the sluice that connects to Great Fen." (p70).

At Great Fen, comparison of survey data from the 1970s and 1980s with those of the Fen Resource Survey (1990s) indicated a substantial change in species composition such "that the vegetation recorded in the 1990s is a rather impoverished reflection of its condition in the 1970s. The cause of this is not known: drying (perhaps caused by terrestrialisation), inadequate vegetation management, nutrient enrichment and base cation depletion could all provide contributory explanations" (p71).

In considering the revegetation of turf ponds at Catfield Fen, Giller and Wheeler (1996a) noted some historic observations about the rate of peat accumulation. "Contemporary observations in Broadland turf ponds by Gunn (1864), possibly referring to those at Catfield, suggest a rate of peat 'growth' of 'a foot [30 cm] in twenty years' - a high rate but compatible with an estimate (by turf cutters) of 'about twenty inches [50 cm] in sixteen years' in peat workings at Isleham, Cambridgeshire (Babington, 1860)." (p236). These rates of peat growth may be 'high', but they do give an indication of the rates of terrestrialisation are possible within turf ponds.

8.3 Possible Reasons for the Fen Drying Out

The possible reasons for the Fen drying out are varied and may involve several factors which are acting in combination to produce the effects described by the Compendium (Natural England et al., 2011). These might include the effects of groundwater abstraction, overflow of dyke water over the low-lying bund at the southern end of the internal system, leakage through sluices, changes in water management, and the process of terrestrialisation which could lead both to the infilling of former pond areas and to the general rise in the ground surface. These will be addressed below.

Water level data from the Fen show evidence of winter dyke water levels becoming progressively lower in recent years since 2007. However this trend appears to be related to regional trends in Crag groundwater levels. These show an overall rise in response to major recharge events, as in 2001 and 2007, and then gradually decline in subsequent years. This is a trend that is also seen in the Barton Broad water levels. The dyke water levels seem to be affected by Crag groundwater levels and therefore reflect this trend. It is of note that the lowest Crag groundwater levels at least since the 1970s, and possibly since the 1950s, probably occurred during the drought periods of 1989-1992. It was at this time that Mr MacDougall raised concerns about the Fen drying out, though he also noted concerns about the lowering of water levels over the previous 25 years.

The water levels within the fen compartments of Great Fen in the external system seem to be largely affected by water levels in the Broad. In the internal system, investigations of peat water flow and water chemistry indicate that rainwater is the major water source, and in Sedge Marshes water level data also suggest the significance of rainfall influences, though dyke waters also have an influence at least for part of the winter. Further to the east, there are indications that the ground level may be slightly higher than to the west, though this has still to be confirmed by a topographic survey. If this is so, rainfall-fed peat water within the compartments may well be higher than water levels in adjacent dykes, and therefore there could be flow towards the dykes. This would be greatest in winter when the head differential would be greatest. In such circumstances any lowering of dyke water level, or raising of the ground surface, could lead to increased drainage of water from the compartments to the adjacent dykes and this could lower the water table relative to ground level.

The lowering of dyke water levels, other than by the normal influences of increasing temperature and evapotranspiration, could be a result of several factors including groundwater abstraction, overflow via the low-lying bund at the southern end of the internal system, and by leakage through the sluices. Any lowering of winter water levels would mean there would be less water stored within the internal system, and less available to sustain the fen in the spring and summer periods.

The groundwater abstractions that could affect shallow Crag groundwater levels at the Fen are those from the Ludham PWS source and from the Ludham Road borehole which is used for spray irrigation purposes. The impact from the PWS source may be relatively widespread since it has been abstracting continuously since 1973, and the amount of drawdown could be several centimetres. However, any such changes have not been clear from the water level data observed since 1996, and might not be expected to be seen since the PWS abstraction has been fairly constant over this period. The Ludham Road abstraction is considered to have only a small localised effect on groundwater levels near to Church Wood, the estimated drawdown being less than 5 cm, and when abstraction ceases groundwater levels return rapidly to the level that would have occurred without the abstraction. Observed data do not show any effect on water levels within the Fen. It would seem unlikely that this localised effect on groundwater levels could have a widespread effect on Fen water levels, particularly as dykes with groundwater input also occur further north near Middle Marsh where groundwater levels would not be lowered by the Ludham Road abstraction. However, whether there is an impact or not cannot be determined with any certainty until the form of water level variation within the catchwater drain at Church Wood is known, the connectivity of the dyke system and of changes in levels within it is better established, and there is better knowledge of the relationship throughout the year between water table levels within eastern compartments and adjacent water levels in dykes.

A known factor in reducing water levels in the dyke system is overflow over the low-lying bund at the southern end of the Fen. Overflow through a breach in the bund was seen at this location in early March 2012 when dyke water levels were at 0.55 mAOD (Section 5.5.2). These levels are not unusual in winter periods. Since any breach in a soft embankment will tend to get larger over time, it may be that the amount of water lost from the internal system has also increased over time. It may be a contributing factor to the fen drying out.

Leakage through the northern sluice is also known to occur, and may also occur at the southern sluice. Such size of these losses is not known, but the sluices are believed to be in reasonably good condition, so the losses may not be significant.

The changed management in terms of sluice opening regime warrants consideration. Giller and Wheeler (1986a) note that the “internal system dykes are largely isolated from the external system, except at times of complete surface flooding and occasionally during summer low water when water was allowed to enter from the external system” (p236). This statement is of interest for several reasons. It indicates that at times when summer water levels were low, it was sometimes found useful for the management of the internal system for water to be allowed to enter it from the external system. Also, this is a practice that no longer takes place, possibly since the late 1980s (Peter Riches, pers. comm.).

Sluice management is now much more controlled with the sluice only being opened for a few days in some, not all, winters in order to let water out of the internal system. The reason for keeping the sluices largely closed is to maintain water levels in the internal system. The opening of the sluices is controlled by Consents issued by Natural England. The period of consented opening is restricted to the end of December to mid-January and is for the purpose of lowering the water levels in the internal system to facilitate reed cutting (Peter Riches, pers. comm.). The opening of the sluices in summer is therefore no longer permitted but it was clearly an adopted practice prior to 1984 (when the paper was written) and possibly up until the 1990s. An email from Sandy Holburn describing the former practice on the marshes is shown in Appendix H. In this email Mr Neave is described as allowing “inflow through the rond when external conditions permitted.” The change in current water management practice will mean that less water is introduced into the internal system, and there is therefore less available within storage to maintain water levels at higher levels than would otherwise be the case. Andy Hewitt and Colin Firmin (pers.comm.), both of whom have cut reed and sedge on the Fen, have both mentioned the importance of maintaining water movement through the Fen in order to maintain healthy plant growth, and to prevent stagnation. This water movement was created in part through the use of the sluice.

It should also be recognised that the reduction in area of shallow open water referred to in the Compendium (Section 8.1), may be due not only to increased drainage, as described above, but also to the process of terrestrialisation. The terrestrialisation of turf ponds can occur at a faster rate than might be supposed. The rate of 30 cm peat growth in 20 years referred to in Section 8.2 may be a rate under conditions that are more optimal for growth than currently exist at Catfield Fen, but it does indicate that turf ponds can be infilled within a timescale that might be considered relatively short.

The process of terrestrialisation does not only occur in turf ponds and it is clear from Sandy Holman's email that past fen management practices recognised this and took steps through "turfing out" to reduce its effects. The turfed-out peat was dried and sold for fuel. The current management practice at Catfield Hall Estate seeks to prevent or limit the process of terrestrialisation by removing all cut material when reed (and a little sedge) is cut, this taking place on a rotational basis. It is understood that the Catfield Hall Estate stripped some peat off part of North Marsh in the 1990s, as can be seen in the aerial photograph, Figure A4, where the black peat area is clearly visible. It would interesting to know what difference this may have made to the vegetation communities, water levels and ground surface level when compared to nearby areas that were not turfed-out.

9. Third Party Comments

9.1 Background

As part of this work consultation has happened with various interested parties, inviting their comments. Those interested parties who have provided written comments are:

- Mr A Alston;
- Anglian Water Services;
- Broads Authority;
- Environment Agency;
- Mr and Mrs T Harris;
- Natural England;
- Mr R Overton.

Comments have been received at two points in time, firstly after the draft report was issues in February 2012 and again following the issue of Draft Final Report in April. The first set of comments is reproduced in Appendix K and the second set of comments is given in Appendix L. To avoid any misrepresentation no attempt has been made to summarise the comments and therefore the reader is directed to the two appendices. Inclusion of these comments does not indicate endorsement or otherwise by AMEC.

In addition more detailed discussions have been held with Professor David Gilvear of Stirling University with the aim of identifying areas of agreement about the hydrogeological functioning of the site and the possible causes for drying out of the Fen. Discussions took place both prior to the issue of the Draft Final report in April (those comments have been reproduced at the end of the relevant sections above) and subsequently, with the latter discussions captured in the following sequence of documents:

- 1 May 2012 – Comments by Gilvear (Box 4);
- 22 May 2012 – Response and comments by AMEC (Box 5);
- 1 June 2012 – Further comments by Gilvear (Box 6);
- 11 June 2102 – Final Comments by AMEC with final comments by Gilvear (Box 7).

Box 4	**Comments by Prof. Gilvear**

Comments on Dr Mason's Second Report on Catfield Fen

Highlighting Areas of Agreement and Disagreement

1. Possible Causes of Drying

These are given on page 73 of the Report as:

- effects of groundwater abstraction;
- overflow of dyke water over the low-lying southern bund;
- leakage through sluices;
- changes in water management;
- process of terrestrialisation leading to general rise in the ground surface.

These are accepted as the possible causes.

2. Effects of Groundwater Abstraction

Geology and Hydrogeology

Agreed:

- that the crag is divided into three units which have some connectivity between them;
- there is no basal clay layer at the margins and no upper clay on North Marsh, the majority of Middle Marsh, the eastern half of South Marsh and everything to the east of the Broad;
- there are windows in the clay layers and some of the dykes and (the Broad) are cut down into the crag. There is connectivity between the surface peat and the crag;
- the water chemistry shows groundwater (Type 1 and Type 3) within the dykes;
- there is the potential for groundwater discharge to occur on the Fen;
- there is spring water discharging on to the Fen from the Glebe and possibly from other sources;
- that dyke water levels may be influenced by crag water levels in the non winter periods;
- the site is a very complex geological and hydrogeological site making interpretation of data difficult and unreliable;
- that Broad water levels are affected by variations in the crag and chalk groundwater storage.

The areas of disagreement can be summarised as follows:

2.1 There is insufficient analysis in the report of the effect of cones of depression on the lateral flow of water to Catfield Fen.

2.2 Too little emphasis is given to the potential role of irrigation in the critical summer months.

2.3 There is too much reliance on modelling which is based on inadequate data and is very challenged in a complex site such as Catfield Fen – it is also relevant that the assumptions made, which have a most significant effect on modelled outcomes, are judgemental and have changed materially over time.

2.4 There is insufficient recognition of the deficiencies in the data.

2.5 In view of the above, the clear statement that the Plumsgate Road abstraction "does not have an impact", does not recognise either the very inadequate data on which it is based or the considerable indirect evidence for abstraction having an impact and is not merited.

2.1 **Cones of depression and catchment water fluxes in the vicinity of Catfield fen – the impact of groundwater abstraction (the stockade theory).**

In terms of the drying out of Catfield fen the critical time is when water levels are low in summer and there is a high soil moisture deficit due to lack of rainfall and high evapotranspiration. Such periods will normally correspond with periods of abstraction for spray irrigation. The study by AMEC (2012) in relation to the impacts of groundwater abstractions has focussed on the extent of water level drawdown below the fen and around its margins with the assumption being made that zero drawdown at the fen margins represents no impact. Here consideration is given to water fluxes from the wider groundwater catchment to the fen and possible impacts of the cones of depression caused by the groundwater abstraction. It is not a detailed analysis but is seen as highlighting a missed component of the assessment by AMEC (2012) and one that warrants attention. The real issue under scrutiny at the present time is the drying out of the fen in the summer months and from a hydrological perspective this has to be a result of either a reduction of water inputs or increased water losses over the summer.

Box 4 (continued)	Comments by Prof. Gilvear

During dry weather conditions the fall in the water table will be a function of the balance between water inputs and losses. It is accepted that lateral inputs of groundwater, presumably from the shallow layers of the aquifer occur and this together with any movement of water through unsaturated layers will be the only input in times of no rainfall. The total contribution of groundwater input to the budget may be relatively small but in dry weather it will be 100% of the input. In effect these groundwater inputs will trickle charge the fen with water helping to offset water storage decline. The dominant loss from the internal system at Catfield fen during times of low water will be evapotranspiration (likely to be in the order of 3 mm per day). This is in the absence of downward head gradients in the groundwater systems caused by groundwater abstraction. In this discussion we will assume no vertical leakage of fen waters to the groundwater system. If this does occur it will heighten falls in fen water levels during periods of drought stress.

The precise catchment area feeding groundwater to the fen is unknown but based on interpolated groundwater contours (AMEC, 2012, Figure B2) for the Upper Crag it is small and approximately 2 km^2 in extent. The internal system at Catfield fen is about 0.5 km^2 in area. Within this catchment the effects of 4 groundwater abstractions (Plumsgate Road (Alston) Ludham Road (Alston), Overton and AWS Ludham) will be fully or partially present and because of the connectivity in the system impact on the Upper Crag. Assuming the cones of depression for spray irrigation (Plumsgate Rd, Ludham Rd, and Overton) have a radii of 750 metres none will extend to the fen margins but they would during pumping prevent the natural movement of water to the fen over approximately half of the catchment area. Cones of depression with a radii of 1000 metres would impact the majority of the Upper Crag groundwater catchment feeding Catfield fen. It should also be noted that the majority of these assumed cones of depression in the case of Overton and Plumsgate Road do however lie outside of the catchment area. If the AWS Ludham source has an assumed cone of depression with a radius of 1200m, which is realistic it would be impacting on groundwater levels in the same areas as Ludham Road (Alston) and Overton and thus there will be a cumulative effect on the groundwater system.

At this moment in time the 3D nature of the cones of depression that form in the groundwater system is not known but during test pumping in 1987 at an average rate of 860 m^3 d (licensed rate is currently 800 m^3 d) a water drawdown of 12.56 m was observed at Ludham Road (Alston) (AMEC 2012) and thus their effect can be large. Such cones of depression during pumping will intercept water moving from upgradient hydraulic head areas within the groundwater catchment and also reverse flow away from the fen and to the borehole down gradient. Thus lateral flow of groundwater to the fen will be stopped and restricted to any unaffected areas of the catchment.

The volumes of water abstracted during spray irrigation abstraction represent a theoretical loss of groundwater that would otherwise drain towards the fen. It is worth assessing how these volumes may impact on fen groundwater levels. This can be done by dividing the volumes abstracted by the fen area and expressing it as mm drawdown of water levels per day or over a period of dry weather when daily pumping may occur. Here it is assumed that 10%, 25% and 45% of the cone of depressions for Overton, Plumsgate Rd, and Ludham Rd (Alston) lie within the groundwater catchment draining to Catfield fen. The values are 0.2 mm for Overton (based on licensed daily rate of 1.2MLD), 0.5 mm for Plumsgate Road (based on a licensed daily rate of 1.090 MLD), and 0.7 mm Ludham Road (Alston) (based on a licensed daily rate of 0.8 MLD). Thus the abstraction is withdrawing a combined total of 1.4 mm per day of water in terms of fen water levels. If we assume a dry weather period of 30 days this represents 42 mm or 4.2 centimetres. This is not a statement of the drawdown that will occur due to spray irrigation abstraction but gives an indication of the potential impact. Modelled abstraction effects and evapotranspiration combined could lead to a potential drawdown of over 4 mm a day if not offset by groundwater inputs from beneath the fen. In comparison to the spray irrigation abstraction the AWS Ludham Road abstraction (based on a licensed daily rate of 2.27 MLD) with an assumption of 33% of cone of depression within the Catfield fen groundwater catchment area has a similar value - 1.5 mm per day or over 30 days 45 mm or 4.5 centimetres.

This narrative and analysis, although a theoretical modelling exercise based on a number of assumptions, illustrates clearly the potential impact of groundwater abstraction on Catfield fen. The analysis and values used in estimating the extent of the groundwater cones of depression and their location in relation to the groundwater catchment draining to the fen are based on information in the AMEC (2012) report.

2.2 Too little emphasis given to the potential role of irrigation in the critical summer months

The Report fails to address the potential effect of irrigation in the critical summer months when rainfall is low and evapo-transpiration high. At these times groundwater accounts for a very significant proportion of Catfield Fen's water supply.

Appendix G5 highlights this lack of analysis. The combined effects of irrigation as compared to the public water supply needs to be shown on at least a weekly not a six monthly basis. Both draft and final Report have downplayed the potential effect of irrigation as compared to the public water supply. In this respect the Report is unbalanced.

Box 4 (continued) Comments by Gilvear

2.3 Too much reliance on modelling which is based on inadequate information and is very challenged in a complex site such as Catfield Fen

2.3.1 Catfield Fen is a complex site

Sharpin's 2010 report states "Given the complex hydrology of the area, it is not possible to use standard analytical solutions to accurately estimate the drawdown in the Crag beneath Catfield Fen that results from abstraction under licences 0141C and 0144B".

We agree.

2.3.2 There are problems with the base data

The Plumsgate Road analysis in the Report is now largely based on Theis analysis. However, the Report states:

"Test pumping of the Plumsgate Road abstraction borehole in 1985 provided data that was difficult to analyse due to the unusual behaviour of water level variations in the observed drawdowns which was considered to be due to the complex geology in the area which did not fulfil the assumptions of conventional analytical techniques adopted to determine aquifer parameters."

We agree - it is unwise to make firm statements based on such fragile foundations.

2.3.3 The modelling assumptions have changed significantly over time

Comparison of the assumptions made in the 1996 Licence Application Determination Report compared to the Report merely confirms one instance of this. In 1996 English Nature reported

"Of particular concern is Catfield Fen which they consider is already significantly affected by water abstractions in the vicinity".

The 1996 Report commented "there is a predicted drawdown of 6 – 11 cm at this site". The Report now gives the figure as "negligible", the difference being entirely due to assumption changes.

The FOI act information supplied to Dr Mason by us included clear suggestions that Environment Agency Staff were seeking to reduce the calculated effect of abstraction to below certain levels. There is no evidence in the Report that Dr Mason has pursued or considered this issue.

2.4 Insufficient emphasis is given to the malfunction of the monitoring equipment and consequent inadequacies of the data in the Report

It is fair to conclude from the draft Report that as far as Plumsgate Road is concerned the monitoring equipment is either in the wrong place or "has not been good enough quality to assess the impact of groundwater abstractions".

The Ludham Road monitoring devices have also exhibited a history of unaddressed malfunction.

See T Harris' original submission to Dr Mason for details – Appendix K in the Report

The following comments seem appropriate:

- The deficiencies in the data are not properly recognised in the Report;
- There are few firm "facts" only interpretations - the recognition that Dr Mason has changed his analysis in each of the three reports he has produced confirms this;
- In a complex site such as Catfield it will always be difficult to prove or disprove "correlations" particularly when the effects of abstraction are likely to be diffuse and take place over time, so that one wouldn't expect to see a direct effect from abstraction;
- No attempt has been made mathematically to assess correlations – the Harrises would like to assess whether this might not be possible and seek access to the core data.

2.5 Comments on main abstraction sites

i. Plumsgate Road

The definite conclusion in the Report's conclusion is not merited being based on modelled and unreliable data and assumptions. The Report clearly highlights the importance of Type 3 water in summer and the direct connectivity with the Crag on the eastern part of the site. In these circumstances it would be surprising if abstraction had no effect and Mike Harding's paper confirms that a very few centimetres can be damaging, particularly if it happens year after year. In a complex site such as Catfield Fen, the effects of abstraction are likely to be diffuse and take place over time.

Box 4 (continued) Comments by Gilvear

ii. Ludham Road

It agreed that the Ludham Road abstraction is having an effect on the SSSI, the only question is "How much?".

It is not accepted that it necessarily only has a "small localised effect". The recovery noted emphasises the good conductivity under Catfield Fen which is relevant when considering the overall potential effect of abstraction on the Fen. Mike Harding's paper confirming that only a very few centimetres effect can be damaging is also relevant.

iii. PWS

We agree with the Report's comment that:

"The impact from the PWS source may be relatively widespread since it has been abstracting continuously since 1973 and the amount of the drawdown could be several centimetres".

iv. Overton

We agree that the considerations are similar as for the Alston licences.

3. Overflow of dyke water over the southern bund

We accept the evidence presented in the Report for this but do not consider that this is either a new or potentially major issue because:

- there is no evidence that the condition of the bund has changed materially over the last twenty years – in fact there are mature trees growing on it
- inspection of the data suggests that the overflow only occurs at high levels of water in the internal system when it is effectively "full"
- the Report states that "for most of the monitored period water levels in the internal system have been higher than the external system" – confirming that the bund is effective in restraining water overflow from the internal system
- the critical period is the summer when the southern bund is of little relevance.

NB reed cutters, including Andy Hewitt who is quoted in the Report, have consistently over the last twenty years pushed for opening the sluices in spring to allow water to flow from the internal system. They have been criticising present water management practices for holding too much water in the internal system for too long. If they had their way there would have been less water buffering in the winter months

For these reasons we consider that the southern bund overflow is unlikely to be either a new or material issue causing the summer drying.

4. Leakage through the sluices

We accept that there may be some minor leakage particularly through the northern sluice but understand that there is a general consensus that this is unlikely to be a material cause of the drying.

5. Changes in water management

The Report is incorrect in stating that "the reason for keeping the sluices closed is to prevent Broad water from entering the internal system". The key aim of the management strategy which is approved by Natural England is to keep water in the internal system.

This has sometimes proved unpopular with reed cutters who have sought to reduce the level of water in the internal system. They would prefer less water buffering in the winter months.

It is agreed that the sluices are kept closed in summer to protect both the quality and quantity of the water in the internal system but this is most unlikely to be a significant issue. As Wheeler commented in 1986:

"Internal system dykes are largely isolated from the external system, except at times of complete surface flooding and occasionally during summer low water when water was allowed to enter from the external system." There are few opportunities owing to the prevailing summer water levels.

Overall there has been little material change in the water management system over at least the last thirty years and it is most unlikely to be a cause of the drying.

Box 4 (continued) Comments by Gilvear

6. Process of terrestrialisation leading to general rise in the ground surface

It is agreed that neither the LIDAR nor recent Atkins studies provide any evidence of a general rise in ground surface and accept the Report's conclusion that "it appears that comparison of the available topographic survey data from different times is insufficient to determine whether there has or has not been any general trend in changing ground levels over the past twenty to twenty-five years".

As regards the Catfield Hall Estate, it is unlikely that there has been any such rise because:

- fen management practices remain unchanged, eg Middle Marsh is cut rotationally and the spoil carted away – there is an agreed, with Natural England, programme for cutting and clearance of scrub;
- the level of the dykes, which are particularly relevant because of their connectivity with the crag, remain unchanged;
- North Marsh and Rose Fen have, with the approval of Natural England, been cleared back to the rhizome layer but still feature the symptoms of drying.

In practice all the Marshes are cut rotationally except the Mill Marshes in accordance with the consultation and agreement of Natural England.

7. Overall conclusions

The Report is useful because it gathers together a great deal of relevant information. Particularly important are the acceptance for the first time of the following:

- that the site is drying
- the recognition of the connectivity of the crag with the surface and the absence of the celebrated clay layer over large parts of the eastern side of Catfield Fen
- the importance of ground water, particularly in summer, to the Fen

The Report is also helpful in that it identifies the potential causes of drying which we accept. The problem is that, as the Report recognises, the site is complex which makes it difficult to come to conclusions which can be definitely proven. However, we suggest that any objective analysis of the agreed possible causes confirms that abstraction potentially plays a significant role, probably the most significant role. This is the "elephant in the room" and one which, under the precautionary principle, requires action NOW before the internationally significant site which is Catfield Fen is beyond repair – like East Ruston!

Box 5 Responses and Comments by AMEC

Background to this discussion document

AMEC has prepared a report on Catfield Fen ("The Mason Report") with the objectives of

- To assess how the Fen functions hydrologically and hydrogeologically;
- To assess the Fen's sensitivity to water abstraction;
- To comment on possible causes for the site drying out.

One of the aims was also to identify with interested parties those areas of agreement and disagreement on the hydrogeological functioning of the site. The following paper (reproduced in black text) was prepared by Professor Gilvear of Stirling University (independent technical advisor to Mr & Mrs Harris) to set out their comments on the report and to identify areas of agreement and disagreement.

Their document has been annotated by AMEC (in blue) in order to seek resolution or to identify those points where agreement cannot be reached.

A final "agreed" version of this document will be included in the AMEC report as a record of the discussions that have taken place.

Tuesday 1 May 2012

Comments on Dr Mason's Second Report on Catfield Fen Highlighting Areas of Agreement and Disagreement

1. Possible causes of drying

These are given on page 73 of the Report as:

- effects of groundwater abstraction;
- overflow of dyke water over the low-lying southern bund;
- leakage through sluices;
- changes in water management;
- process of terrestrialisation leading to general rise in the ground surface.

These are accepted as the possible causes.

2. Effects of groundwater abstraction

Geology and Hydrogeology

Agreed:

- that the crag is divided into three units which have some connectivity between them;
- there is no basal clay layer at the margins and no upper clay on North Marsh, the majority of Middle Marsh, the eastern half of South Marsh and everything to the east of the Broad;
- there are windows in the clay layers and some of the dykes and (the Broad) are cut down into the crag. There is connectivity between the surface peat and the crag;
- the water chemistry shows groundwater (Type 1 and Type 3) within the dykes;
- there is the potential for groundwater discharge to occur on the Fen;

Box 5 (continued) Responses and Comments by AMEC

- there is spring water discharging on to the Fen from the Glebe and possibly from other sources;
- that dyke water levels may be influenced by crag water levels in the non winter periods;
- The site is a very complex geological and hydrogeological site making interpretation of data difficult and unreliable;
- that Broad water levels are affected by variations in the crag and chalk groundwater storage.

The available evidence provided by University of Birmingham work (and included in publications by Gilvear) shows the clay to be absent over small areas in the eastern part of the Fen and in places in the base of dykes where these have cut through the clay layer. Our report recognises that there is connectivity between the Crag and surface waters in these locations where the clay layer is absent, but not throughout the Fen.

AMEC would agree that the site is complex geologically and hydrogeologically and that the relationship between groundwater within the Crag and water levels in dykes across the site is difficult to ascertain with a high level of confidence. We do believe that the conceptual model of the site is one where agreement can be reached and the data can be sensibly interpreted.

We would point out that we do not however consider there to be a direct link between the Crag and the Fen water levels whereby there is a one to one relationship i.e. a 1m decrease in Crag water level would result in a 1m fall in ditch water level, or 10 cm rise in ditch water levels would results in a 10cm rise in Crag groundwater levels.

We would also note that storage in the Crag does not affect the water levels in the Broad but storage may affect the timing of any changes The Chalk storage is not important at this location.

The areas of disagreement can be summarised as follows:

2.1 There is insufficient analysis in the report of the effect of cones of depression on the lateral flow of water to Catfield Fen.

2.2 Too little emphasis is given to the potential role of irrigation in the critical summer months.

2.3 There is too much reliance on modelling which is based on inadequate data and is very challenged in a complex site such as Catfield Fen – it is also relevant that the assumptions made, which have a most significant effect on modelled outcomes, are judgemental and have changed materially over time.

2.4 There is insufficient recognition of the deficiencies in the data.

2.5 In view of the above, the clear statement that the Plumsgate Road abstraction "does not have an impact", does not recognise either the very inadequate data on which it is based or the considerable indirect evidence for abstraction having an impact and is not merited.

The issue of the need to assess cones of depression preventing lateral flow on the Fen is discussed as the end of the following section.

We note that the comment that the summer months are critical and that later "*The real issue under scrutiny at the present time is the drying out of the fen in the summer months*". This is the first time that the issue of the fen drying out has had a season attached to it. We would therefore like to understand what this is related to and what change is considered to be "critical". The following clarification therefore needed:

a) Are there concerns about only lowered water levels in summer, not all year round? Could the increase in woody vegetation (scrub), which is one of the indicators of the fen drying out, occur solely as a result of lower water levels in summer periods, or would it require a more general reduction in the wetness of the fen surface?

b) If the Fen is suffering an overall reduction in the wetness of the Fen surface throughout the year, then does this indicate that the major contributor to this reduction in wetness is something other than the spray irrigation abstraction? (Note: "reduction in wetness" rather than "lowering of water levels" is used in order to include the possibility of terrestrialisation, and because there is no good evidence of a long-term lowering of water levels)

Our assessment has been based on reviewing the monitoring data in and around Catfield Fen, reference to previous studies and use of supporting calculations as appropriate. No new numerical groundwater modelling has been undertaken.

Box 5 (continued) Comments and Responses by AMEC

We have based some of our conclusions on hydrogeological judgement and as such these will change as new information arises that causes us to re-consider.

The data have not been statistically assessed but we do not think this detracts from the conclusions drawn.

We consider our conclusions with respect to the Plumsgate Road abstraction to be appropriate in light of the information available.

2.1 **Cones of depression and catchment water fluxes in the vicinity of Catfield fen – the impact of groundwater abstraction (the stockade theory).**

In terms of the drying out of Catfield fen the critical time is when water levels are low in summer and there is a high soil moisture deficit due to lack of rainfall and high evapotranspiration. Such periods will normally correspond with periods of abstraction for spray irrigation. The study by AMEC (2012) in relation to the impacts of groundwater abstractions has focussed on the extent of water level drawdown below the fen and around its margins with the assumption being made that zero drawdown at the fen margins represents no impact. Here consideration is given to water fluxes from the wider groundwater catchment to the fen and possible impacts of the cones of depression caused by the groundwater abstraction. It is not a detailed analysis but is seen as highlighting a missed component of the assessment by AMEC (2012) and one that warrants attention. The real issue under scrutiny at the present time is the drying out of the fen in the summer months and from a hydrological perspective this has to be a result of either a reduction of water inputs or increased water losses over the summer.

During dry weather conditions the fall in the water table will be a function of the balance between water inputs and losses. It is accepted that lateral inputs of groundwater, presumably from the shallow layers of the aquifer occur and this together with any movement of water through unsaturated layers will be the only input in times of no rainfall. The total contribution of groundwater input to the budget may be relatively small but in dry weather it will be 100% of the input. In effect these groundwater inputs will trickle charge the fen with water helping to offset water storage decline. The dominant loss from the internal system at Catfield fen during times of low water will be evapotranspiration (likely to be in the order of 3mm per day). This is in the absence of downward head gradients in the groundwater systems caused by groundwater abstraction. In this discussion we will assume no vertical leakage of fen waters to the groundwater system. If this does occur it will heighten falls in fen water levels during periods of drought stress.

The precise catchment area feeding groundwater to the fen is unknown but based on interpolated groundwater contours (AMEC, 2012, Figure B2) for the Upper Crag it is small and approximately 2km^2 in extent. The internal system at Catfield fen is about 0.5 km^2 in area. Within this catchment the effects of 4 groundwater abstractions (Plumsgate Road (Alston) Ludham Road (Alston), Overton and AWS Ludham) will be fully or partially present and because of the connectivity in the system impact on the Upper Crag. Assuming the cones of depression for spray irrigation (Plumsgate Rd, Ludham Rd, and Overton) have a radii of 750 metres none will extend to the fen margins but they would during pumping prevent the natural movement of water to the fen over approximately half of the catchment area. Cones of depression with a radii of 1000 metres would impact the majority of the Upper Crag groundwater catchment feeding Catfield fen. It should also be noted that the majority of these assumed cones of depression in the case of Overton and Plumsgate Road do however lie outside of the catchment area. If the AWS Ludham source has an assumed cone of depression with a radius of 1200m, which is realistic it would be impacting on groundwater levels in the same areas as Ludham Road (Alston) and Overton and thus there will be a cumulative effect on the groundwater system.

At this moment in time the 3D nature of the cones of depression that form in the groundwater system is not known but during test pumping in 1987 at an average rate of 860 m^3 d (licensed rate is currently 800 m^3 d) a water drawdown of 12.56m was observed at Ludham Road (Alston) (AMEC 2012) and thus their effect can be large. Such cones of depression during pumping will intercept water moving from up gradient hydraulic head areas within the groundwater catchment and also reverse flow away from the fen and to the borehole down gradient. Thus lateral flow of groundwater to the fen will be stopped and restricted to any unaffected areas of the catchment.

Box 5 (continued)	**Responses and Comments by AMEC**

The volumes of water abstracted during spray irrigation abstraction represent a theoretical loss of groundwater that would otherwise drain towards the fen. It is worth assessing how these volumes may impact on fen groundwater levels. This can be done by dividing the volumes abstracted by the fen area and expressing it as mm drawdown of water levels per day or over a period of dry weather when daily pumping may occur. Here it is assumed that 10%, 25% and 45% of the cone of depressions for Overton, Plumsgate Rd, and Ludham Rd (Alston) lie within the groundwater catchment draining to Catfield fen. The values are 0.2 mm for Overton (based on licensed daily rate of 1.2MLD), 0.5mm for Plumsgate Road (based on a licensed daily rate of 1.090 MLD), and 0.7 mm Ludham Road (Alston) (based on a licensed daily rate of 0.8 MLD). Thus the abstraction is withdrawing a combined total of 1.4 mm per day of water in terms of fen water levels. If we assume a dry weather period of 30 days this represents 42 mm or 4.2 centimetres. This is not a statement of the drawdown that will occur due to spray irrigation abstraction but gives an indication of the potential impact. Modelled abstraction effects and evapotranspiration combined could lead to a potential drawdown of over 4mm a day if not offset by groundwater inputs from beneath the fen. In comparison to the spray irrigation abstraction the AWS Ludham Road abstraction (based on a licensed daily rate of 2.27 MLD) with an assumption of 33% of cone of depression within the Catfield fen groundwater catchment area has a similar value - 1.5 mm per day or over 30 days 45 mm or 4.5 centimetres.

This narrative and analysis, although a theoretical modelling exercise based on a number of assumptions, illustrates clearly the potential impact of groundwater abstraction on Catfield fen. The analysis and values used in estimating the extent of the groundwater cones of depression and their location in relation to the groundwater catchment draining to the fen are based on information in the AMEC (2012) report.

The above argument can be summarised as:

- the development of a cone of depression prevents water that would normally flow towards the fen from doing so;
- the calculations presented estimate that at the end of a dry month the combined effect of the three cones of depression associated with spray irrigation would be equivalent to a change in Crag (?) water level of 4.2cm;
- the AWS Ludham Road cone of depression causes a change in Crag (?) water level equivalent to 4.5cm;
- the dominant loss from the internal system at Catfield fen during times of low water will be through evapotranspiration (likely to be in the order of 3mm per day or 9 cm over 1 month) that effects the upper layer of the Fen, although losses from open water bodies will be much higher.

The calculation is that if these effects materialised that in a dry (drought?) month a total effect of 17.7cm may be seen (of which >50% is due to natural effects of evapotranspiration).

The method used to estimate these effects is extremely simplistic and appears to be based on some misleading assumptions:

1. Steady state conditions prevail i.e. no account is taken of water in storage and that the effects will occur instantaneously.
2. We note that the calculations are "*not a statement of the drawdown that will occur due to spray irrigation abstraction but gives an indication of the potential impact".* However the potential impact is calculated by converting a volume into an equivalent area under the Fen. This calculation is incomplete as it ignores the storage capacity of the Crag – in fact if storage is correctly applied then the "potential" impact could be up to an order of magnitude greater.
3. There is "*no vertical leakage of fen waters to the groundwater system. If this does occur it will heighten falls in fen water levels during periods of drought stress*". This is a worst case position and exaggerates the change in Crag water levels whereas leakage from overlying formations would reduce the effect. As mentioned above there would not necessarily be a one to one relationship between changes in Crag water levels and Fen water levels.

Box 5 (continued) **Responses and Comments by AMEC**

4. The calculations also use some unrealistically large parameters:

   a. The cones of depression have a radius of 750m. This is supported by the 12.56m drawdown in the Ludham abstraction borehole. This is the drawdown in the well and not the drawdown in the aquifer and effect of well losses is not taken into account.(drawdown in the aquifer will be much less);

   b. The cones or depression are circular whereas in reality they will be more elliptical extending up the hydraulic gradient;

   c. The percentages used are therefore on the high side (*assumed that 10%, 25% and 45% of the cone of depressions for Overton, Plumsgate Rd, and Ludham Rd (Alston) lie within the groundwater catchment draining to Catfield fen*) and appear at odds with the statement *"It should also be noted that the majority of these assumed cones of depression in the case of Overton and Plumsgate Road do however lie outside of the catchment area";*

   d. The abstraction volume assumes that 50% of the total annual licensed amount (over a 6 month period) is taken in just the one month.

The above calculation therefore use an extreme set of worst case assumptions. It is quite reasonable to assume that the cones of depression are much smaller (therefore the percentages will be much less) and the abstracted volumes in a month will be much lower. In addition any change in water levels will result in a dynamic response in the aquifer and any body of water connected to it and a large part of the effect will be compensated for by changes in flow (vertical and horizontal), leakage, changes in storage etc. A much more realistic change in the water level will therefore be significantly less than 4.2cm. However if the volume is correctly converted to a level and assuming a conservative 10% storage in the Crag, then a theoretical change of a few centimetres could be a correct estimate.

We do however note the stated concern about the AMEC report is that it is considered to be based on "*inadequate data and is very challenged in a complex site such as Catfield Fen*" and places too much "*reliance on modelling*". Therefore the above "*theoretical modelling exercise*" which uses the same data should be viewed in the same light.

Nevertheless any small change in Crag water levels at the end of a dry month needs to be put in context of:

- How will a few centimetres change in water level in the Crag translate to a change in Fen water level?
- The equivalent changes in the Fen water level will be much less (it is a higher storage system) so may be a few millimetres;
- What is the significance, if any, of a change in order of a few millimetres?
- The significance of this change may depend on the antecedent conditions and water levels;
- What is the likelihood of a dry month in a dry year – once every 10 years?
- What damage does a change of a few millimetres cause every 10 years?

We do not expect this very small change in water level to be significant. Each year fluctuations due to evapotranspiration may be at least twice as much.

Addressing AWS Ludham then the same comments applies to the calculated 4.5cm and therefore the theoretical change in Fen water levels will be very small.

In conclusion the above approach does highlight the importance of an agreed conceptual model and the need to consider the overall water balance to the fen and to assess the effect of conflicting and interacting processes that control water levels. It has suggested that in extreme circumstances there may be some very small effect due to abstraction but under normal conditions these effects will be negligible.

The question that remains is that in extreme conditions will these potential changes of a few millimetres affect the Fen?

Box 5 (continued) **Responses and Comments by AMEC**

2.2 Too little emphasis given to the potential role of irrigation in the critical summer months

The Report fails to address the potential effect of irrigation in the critical summer months when rainfall is low and evapo-transpiration high. At these times groundwater accounts for a very significant proportion of Catfield Fen's water supply.

We have considered information relating to all periods of time.

Appendix G5 highlights this lack of analysis. The combined effects of irrigation as compared to the public water supply needs to be shown on at least a weekly not a six monthly basis. Both draft and final Report have downplayed the potential effect of irrigation as compared to the public water supply. In this respect the Report is unbalanced.

This point was noted at the meeting on the 23 April and an additional plot will be added to Appendix G.

2.3 Too much reliance on modelling which is based on inadequate information and is very challenged in a complex site such as Catfield Fen

2.3.1 Catfield Fen is a complex site

Sharpin's 2010 report states "Given the complex hydrology of the area, it is not possible to use standard analytical solutions to accurately estimate the drawdown in the Crag beneath Catfield Fen that results from abstraction under licences 0141C and 0144B".

We agree.

If this comment stands it would suggest that the above "stockade theory" may not be reliable.

2.3.2 There are problems with the base data

The Plumsgate Road analysis in the Report is now largely based on Theis analysis. However, the Report states:

"Test pumping of the Plumsgate Road abstraction borehole in 1985 provided data that was difficult to analyse due to the unusual behaviour of water level variations in the observed drawdowns which was considered to be due to the complex geology in the area which did not fulfil the assumptions of conventional analytical techniques adopted to determine aquifer parameters."

We agree - it is unwise to make firm statements based on such fragile foundations.

Our overall conclusion relating to Plumsgate is based on the wider data set not just the 1985 pumping test data.

2.3.3 The modelling assumptions have changed significantly over time

Comparison of the assumptions made in the 1996 Licence Application Determination Report compared to the Report merely confirms one instance of this. In 1996 English Nature reported

"Of particular concern is Catfield Fen which they consider is already significantly affected by water abstractions in the vicinity".

In 2005 Natural England stated they considered SSSI Unit 3 to be in favourable condition whilst Unit 11 was in unfavourable recovering condition.

The 1996 Report commented "there is a predicted drawdown of 6 – 11 cm at this site". The Report now gives the figure as "negligible", the difference being entirely due to assumption changes.

The FOI act information supplied to Dr Mason by us included clear suggestions that Environment Agency Staff were seeking to reduce the calculated effect of abstraction to below certain levels. There is no evidence in the Report that Dr Mason has pursued or considered this issue.

Changes in conclusion since 1996 may reflect the application of better science.

The remit of the AMEC report did not include the investigation of the approach or actions of the Environment Agency.

Box 5 (continued)	Responses and Comments by AMEC

2.4 ***Insufficient emphasis is given to the malfunction of the monitoring equipment and consequent inadequacies of the data in the Report***

It is fair to conclude from the draft Report that as far as Plumsgate Road is concerned the monitoring equipment is either in the wrong place or "has not been good enough quality to assess the impact of groundwater abstractions".

The Ludham Road monitoring devices have also exhibited a history of unaddressed malfunction.

See T Harris' original submission to Dr Mason for details – Appendix K in the Report

The following comments seem appropriate:

- The deficiencies in the data are not properly recognised in the Report;
- There are few firm "facts" only interpretations - the recognition that Dr Mason has changed his analysis in each of the three reports he has produced confirms this;
- In a complex site such as Catfield it will always be difficult to prove or disprove "correlations" particularly when the effects of abstraction are likely to be diffuse and take place over time, so that one wouldn't expect to see a direct effect from abstraction;
- No attempt has been made mathematically to assess correlations – the Harrises would like to assess whether this might not be possible and seek access to the core data.

Any limitations of the data are acknowledged.

We are not clear what correlations should be assessed?

2.5 ***Comments on main abstraction sites***

i. Plumsgate Road

The definite conclusion in the Report's conclusion is not merited being based on modelled and unreliable data and assumptions. The Report clearly highlights the importance of Type 3 water in summer and the direct connectivity with the Crag on the eastern part of the site. In these circumstances it would be surprising if abstraction had no effect and Mike Harding's paper confirms that a very few centimetres can be damaging, particularly if it happens year after year. In a complex site such as Catfield Fen, the effects of abstraction are likely to be diffuse and take place over time.

ii. Ludham Road

It agreed that the Ludham Road abstraction is having an effect on the SSSI, the only question is "How much?"

It is not accepted that it necessarily only has a "small localised effect". The recovery noted emphasises the good conductivity under Catfield Fen which is relevant when considering the overall potential effect of abstraction on the Fen. Mike Harding's paper confirming that only a very few centimetres effect can be damaging is also relevant.

iii. PWS

We agree with the Report's comment that:

"The impact from the PWS source may be relatively widespread since it has been abstracting continuously since 1973 and the amount of the drawdown could be several centimetres".

iv. Overton

We agree that the considerations are similar as for the Alston licences.

Our conclusions with respect to these abstractions are given in Section 7 of our report. We do not think the Overton licence is of any significant concern.

Box 5 (continued) **Responses and Comments by AMEC**

3. Overflow of dyke water over the southern bund

We accept the evidence presented in the Report for this but do not consider that this is either a new or potentially major issue because:

- there is no evidence that the condition of the bund has changed materially over the last twenty years – in fact there are mature trees growing on it;
- inspection of the data suggests that the overflow only occurs at high levels of water in the internal system when it is effectively "full";
- the Report states that "for most of the monitored period water levels in the internal system have been higher than the external system" – confirming that the bund is effective in restraining water overflow from the internal system;
- the critical period is the summer when the southern bund is of little relevance;

NB reed cutters, including Andy Hewitt who is quoted in the Report, have consistently over the last twenty years pushed for opening the sluices in spring to allow water to flow from the internal system. They have been criticising present water management practices for holding too much water in the internal system for too long. If they had their way there would have been less water buffering in the winter months

For these reasons we consider that the southern bund overflow is unlikely to be either a new or material issue causing the summer drying.

When the bund was visited on 23 April 2012, the water level in the internal dyke was 0.53mAOD, and the depth of water within one of the breaches was about 10cm. Overflow would therefore start when dyke water levels exceeded about 0.43mAOD i.e. not just when the system is "full". Figure E33 presents a hydrograph of internal dyke water levels covering the period since 1996, and shows that winter water levels are generally between about 0.57 to 0.70mAOD. The overflow does therefore not only occur when internal system water levels are high. Water levels below 0.43mAOD only occur during the summer in most, not all, years.

During the visit on 23 April, the overflow was not accurately measured, but was roughly estimated to be at least 1 l/s. Such a flow would equate to about 86m^3/d, and, based on the estimated surface water area within the internal system (52,350m^2), could cause a daily lowering of the internal dyke of 1.7mm/d. On 7 March 2012 when the water level was 0.55mAOD, Mr Alston took a video clip of overflow which appeared to significantly higher than that observed on 23 April. The loss from the internal system will therefore be at a greater rate as water levels increases, and for much of the year may well be comparable to those losses attributed to abstraction.

We do not agree with dismissing the possibility that the overflow has an impact on the fen water levels and which may therefore contribute to the fen drying out. The fact is that the overflow is a means by which water escapes from the internal system and is lost from storage within it. There is therefore less stored water to support the internal system in summer periods than there would have been in the absence of this overflow. The timing when this overflow first began is not known but may have been before 1996 when current monitoring first began. If this is the case it could be a significant contributing factor accounting for why concerns have been expressed about the drying up of the Fen for a long time.

4. Leakage through the sluices

We accept that there may be some minor leakage particularly through the northern sluice but understand that there is a general consensus that this is unlikely to be a material cause of the drying.

Box 5 (continued) **Responses and Comments by AMEC**

5. Changes in water management

The Report is incorrect in stating that "the reason for keeping the sluices closed is to prevent Broad water from entering the internal system". The key aim of the management strategy which is approved by Natural England is to keep water in the internal system.

This has sometimes proved unpopular with reed cutters who have sought to reduce the level of water in the internal system. They would prefer less water buffering in the winter months.

It is agreed that the sluices are kept closed in summer to protect both the quality and quantity of the water in the internal system but this is most unlikely to be a significant issue. As Wheeler commented in 1986:

"Internal system dykes are largely isolated from the external system, except at times of complete surface flooding and occasionally during summer low water when water was allowed to enter from the external system." There are few opportunities owing to the prevailing summer water levels.

Overall there has been little material change in the water management system over at least the last thirty years and it is most unlikely to be a cause of the drying.

As noted above "*there is spring water discharging on to the Fen from the Glebe and possibly from other sources*" therefore have these inputs changed?

6. Process of terrestrialisation leading to general rise in the ground surface

It is agreed that neither the LIDAR nor recent Atkins studies provide any evidence of a general rise in ground surface and accept the Report's conclusion that "it appears that comparison of the available topographic survey data from different times is insufficient to determine whether there has or has not been any general trend in changing ground levels over the past twenty to twenty-five years".

As regards the Catfield Hall Estate, it is unlikely that there has been any such rise because:

- fen management practices remain unchanged, eg Middle Marsh is cut rotationally and the spoil carted away – there is an agreed, with Natural England, programme for cutting and clearance of scrub
- the level of the dykes, which are particularly relevant because of their connectivity with the crag, remain unchanged
- North Marsh and Rose Fen have, with the approval of Natural England, been cleared back to the rhizome layer but still feature the symptoms of drying.

In practice all the Marshes are cut rotationally except the Mill Marshes in accordance with the consultation and agreement of Natural England.

7. Overall conclusions

The Report is useful because it gathers together a great deal of relevant information. Particularly important are the acceptance for the first time of the following:

- that the site is drying

  Our report refers to the findings of Natural England et al. (2011) and the opinions of both Mr Harris and Mr Alston that the Fen drying out. The hydrological data (available since 1996) do not suggest either a long-term lowering of water levels (over the past 10-20 years), or that water levels at the Fen are abnormally low (in relation to O.D.). This does not mean to say that water levels are not lower than they were prior to 1996, or that terrestrialisation has not taken place, or that a combination of the two has not occurred. As mentioned above in 2005 Natural England stated they considered the Fen to be in "favourable and recovering condition" and their recent change of opinion appears to be related to an increase in scrub which could be due to many reasons.

- the recognition of the connectivity of the crag with the surface and the absence of the celebrated clay layer over large parts of the eastern side of Catfield Fen

  The available evidence provided by University of Birmingham (and included in publications by Gilvear) does not indicate that the clay layer is absent over "large parts" of the eastern side of Catfield Fen, but shows it is absent over small areas in the eastern part of the Fen and in places in the base of dykes where these have cut through the clay layer. The Final report recognises that there is a connectivity between the Crag and surface waters in these locations where the clay layer is absent, not throughout the Fen.

Box 5 (continued)	Responses and Comments by AMEC

- the importance of ground water, particularly in summer, to the Fen

The contribution of groundwater in the overall water budget for the fen is agreed.

The Report is also helpful in that it identifies the potential causes of drying which we accept. The problem is that, as the Report recognises, the site is complex which makes it difficult to come to conclusions which can be definitely proven. However, we suggest that any objective analysis of the agreed possible causes confirms that abstraction potentially plays a significant role, probably the most significant role. This is the "elephant in the room" and one which, under the precautionary principle, requires action NOW before the internationally significant site which is Catfield Fen is beyond repair – like East Ruston!

Our report does not support the statement that "abstraction potentially plays a significant role" and indeed the above stockade theory only points to a small effect in very dry conditions. The figures presented also show that the effect of evapotranspiration is twice that of abstraction.

Dr Tim Haines

22 May 2012

Box 6 Further Comments by Gilvear

RESPONSE OF PROF. GILVEAR

This document represents the reply of Professor Gilvear to AMEC's detailed response to Gilvear's previous paper summarising their areas of agreement and disagreement in Dr Mason's second draft report (the Report).

In his reply Gilvear has tried to assess the areas of common understanding of which there are many and only comment on major differences, avoiding a line by line critique with its inevitably adversarial connotations. It is hoped that this approach will be recognised as constructive and help the parties to reach a final and possibly even agreed position without too much more discussion.

The basic principle of the "groundwater stockade theory" as applied to Catfield Fen

There appears to be broad agreement that there are a number of groundwater cones of depression, or part cones within the small groundwater catchment of Catfield Fen and that they will be reducing flows in the Crag towards Catfield Fen. There is some dispute as to the extent of these and it is acknowledged there is uncertainty in their size – be it smaller or larger than assumed. The level of water table drawdown in the Crag is also not known in detail and is appreciated that the drawdown in an abstraction borehole will be more than in the aquifer. The "stockade theory" and the calculation of water depth losses expressed as mm per unit area on Catfield Fen and a month pumping at maximum daily abstraction rates are not disputed by AMEC / Mason. However, it is suggested that this basic water budgeting approach is simplistic and we agree and do not suggest that the water loss calculations expressed in millimetres per unit area on Catfield Fen would not necessarily match the actual water table drawdown on the fen. The calculations were undertaken to highlight the potential significance of spray irrigation. Modelling never will match reality! Indeed it is highlighted by AMEC that a millimetre loss of water when translated in to groundwater will create much more than a millimetre change in head in the Crag. Our calculations suggest that abstraction could be withdrawing a combined total of 1.4mm /day of water in terms of fen water levels. It should also be noted that in a dry summer, abstraction albeit not every day, may be on-going over several months through spring and summer and so the total "water loss" over the summer could be much greater than highlighted and equivalent to the annual abstraction licence volume. AMEC suggest that a summer month with no effective precipitation is a 1:10 year event without any evidence and this is clearly not the case. One or more summer months with negative effective precipitation and high soil moisture deficits are the norm.

Conclusions

1. Both sides accept the theory of the modelling approach of the other, i.e. both the "cones of depression theory" and the "stockade theory".
2. Both sides accept that modelling can never be an exact science particularly in a complex site as Catfield.
3. Both sides accept that the data is either deficient or not available to make definitive statements.
4. The main areas of disagreement appear to be:
   i. the Report includes no acknowledgement of the "stockade" theory and of the potential loss of lateral water flow to Catfield Fen from the local catchment area.
   ii. the AMEC response dismisses the potential effect of the "stockade theory" as a "once in ten year issue". Gilvear sharply disagrees.
   iii. the Report draws definitive conclusions particularly about the Plumsgate Road abstraction which Gilvear does not believe can be reconciled with the evidence.

Box 6 (continued) Further Comments by Gilvear

The hydrology of Catfield fen and groundwater hydrological connectivity

The broad conceptual model of how Catfield Fen functions hydrological is accepted by both parties, including the fact that there are groundwater inputs and some level of hydrological connectivity between the Crag and the fen. It is also universally accepted that the hydrology is complex and thus caution is needed in interpretation of data and model output. Thus there is agreement that the relationship between Crag and dyke and fen water levels is difficult to ascertain with a high degree of confidence. Thus, for example a 1:1 relationship between Crag water levels and dyke water levels cannot be assumed but neither can a ratio close to one be ruled out. Also in the fen peat a 1mm loss of water could equate to slightly more than a millimetre fall in water table. The uncertainty primarily relates to the level of water flow between the Crag and fen and the role of clay layers in precluding flow. AMEC appear to be of the view that the absence of clay is localised. Even if localised there is the possibility of significant flow in the vicinity and its effect to be felt more widely much like the plughole on a bath. Also it is acknowledged there are springs discharging water on to the fen. There are also no blockages in the dyke system and on North Marsh, Long Fen and Rose Fen in particular there are good connections by foot drain between the marsh and the dykes and thus for any water loss at one point to create a hydrological change elsewhere (e.g. a change in flow direction in the dykes). The map produced at B5 in the report clearly shows that North Marsh, the vast majority of Middle Marsh, about half of South Marsh and the whole area to the north and east of the Broad are "uninterrupted peat deposits". These are not "small areas in the eastern part of the Fen". There is then disagreement in the level of hydrological connectivity between the fen peat and Crag and thus significance of a reduction in groundwater flow towards the fen and water levels.

Conclusion

Both sides basically agree on the facts. There is a degree of disagreement about the level of hydrological connectivity between the fen peat and Crag and thus the significance of a reduction in groundwater flow towards the fen and water levels.

Importance of seasonality in the hydrology and timing of drying out of Catfield fen

It is obvious to a plant ecologist, or any gardener, that the critical time in terms of water availability is in the summer. At Catfield fen in the summer months when evapotranspiration is high the contribution to the fen water balance from the groundwater is vital to the health of the fen and that any reduction due to abstraction is critical. Stating that the drawdown effect relative to evapotranspiration is not large fails to acknowledge the fact that it is an additional water loss and a double whammy in terms of inducing dry conditions. AMEC appear not to understand the growth cycles of fen communities and the critical role of any draw down during the period of growth. Harding's studies have shown for East Anglian fens a few centimetres can be critical. In a wetland where the critical factor is that the water table remains close to the surface drawdown of a few centimetres can be a significant percentage drawdown. A three centimetre drawdown could easily increase the aerobic zone by 25-30% stressing wet loving plant species and allowing the ingress of drier loving species (scrubbing up). Expressing the impact on water table drawdown is also simplistic in that water content within the unsaturated peat will also be important.

It is acknowledged that winter water levels on Catfield fen are important in terms of the fen hydrology and plant ecology together with any impacts of groundwater abstraction. Groundwater abstraction during the winter will result in less groundwater storage and a lower baseline against which summer abstractions cause a drawdown. During the winter if the water table is at the fen surface this is also similarly advantageous in terms of providing a "wet" baseline against which evapotranspiration and any abstraction impact over the summer drawdown water levels. However it is too simplistic a management approach just to store or winter rainfall and groundwater inputs to the marsh and turn it in to a lake just to try and offset natural and human-induced losses in the summer. There thus seems to be some level of disagreement in the importance of the role of the alleged breach in the Southern bund in terms of its effect on the summer hydrology. Gilvear/Riches believe the natural summer Catfield fen hydrology relates to the balance between summer month inputs of precipitation and groundwater and loss due to evapotranspiration acting upon water storage as defined as the water table being at or close to the fen surface (marginally below or short-lived and shallow inundation).

Conclusions

1. There is sharp disagreement between AMEC and Gilvear on the likely ecological importance of drawdown of the water table in Summer months. The Summer period is critical and water budgeting at the annual scale is inappropriate.
2. Gilvear suggests that the approach of the Report and comments by AMEC reflect a lack of awareness of the Harding report and its conclusions about the extreme vulnerability of the Fen habitat "to even the smallest reductions in water levels on Catfield Fen" – eg from AMEC "what is the significance if any of a change in order of a few millimetres?" and "each year fluctuations due to evapotranspiration may be at least twice as much".
3. There is some level of disagreement over the significance of the alleged breach in the Southern bund which Gilvear believes essentially represents an overflow and not relevant to the problems of Summer drying.

Leakage through sluices / changes in water management / process of terrestrialisation leading to general rise in ground surface.

It is noted that AMEC do not take issue with the Gilvear's comments included in their previous paper.

Box 7 Final Comments by AMEC with Final Comments by Gilvear

RESPONSE OF PROF. GILVEAR

The following response was provided to AMEC on the 1 June 2012. This document (original text in black) has been annotated (in blue text) by AMEC in order to move discussions towards reaching a final position.

The text in Red is Gilvear final comments dated 14 June 2012

This document represents the reply of Professor Gilvear to AMEC's detailed response to Gilvear's previous paper summarising their areas of agreement and disagreement in Dr Mason's second draft report (the Report).

In their reply Gilvear has tried to assess the areas of common understanding of which there are many and only comment on major differences, avoiding a line by line critique with its inevitably adversarial connotations. It is hoped that this approach will be recognised as constructive and help the parties to reach a final and possibly even agreed position without too much more discussion.

The basic principle of the "groundwater stockade theory" as applied to Catfield Fen

There appears to be broad agreement that there are a number of groundwater cones of depression, or part cones within the small groundwater catchment of Catfield Fen and that they will be reducing flows in the Crag towards Catfield Fen. There is some dispute as to the extent of these and it is acknowledged there is uncertainty in their size – be it smaller or larger than assumed. The level of water table drawdown in the Crag is also not known in detail and is appreciated that the drawdown in an abstraction borehole will be more than in the aquifer. The "stockade theory" and the calculation of water depth losses expressed as mm per unit area on Catfield Fen and a month pumping at maximum daily abstraction rates are not disputed by AMEC / Mason. However, it is suggested that this basic water budgeting approach is simplistic and we agree and do not suggest that the water loss calculations expressed in millimetres per unit area on Catfield Fen would not necessarily match the actual water table drawdown on the fen. The calculations were undertaken to highlight the potential significance of spray irrigation. Modelling never will match reality! Indeed it is highlighted by AMEC that a millimetre loss of water when translated in to groundwater will create much more than a millimetre change in head in the Crag. Our calculations suggest that abstraction could be withdrawing a combined total of 1.4mm /day of water in terms of fen water levels. It should also be noted that in a dry summer, abstraction albeit not every day, may be on-going over several months through spring and summer and so the total "water loss" over the summer could be much greater than highlighted and equivalent to the annual abstraction licence volume. AMEC suggest that a summer month with no effective precipitation is a 1:10 year event without any evidence and this is clearly not the case. One or more summer months with negative effective precipitation and high soil moisture deficits are the norm.

We do not consider the "groundwater stockade theory" to be other than a very simplistic way of expressing potential effects of groundwater abstraction. We agree that groundwater abstraction causes a cone of depression and that it will have some effect on the local water budget, including the area around Catfield Fen. The above calculation expresses the combined effect of the various abstractions as 1.4mm/day or 4.2 cm over a month. We consider this value to be an over estimate but allowing for the error that storage was not taken into account then a possible change in the Crag groundwater levels of a few centimetres could be used as a working assumption.

The 4.2cm figure relates to the abstraction for irrigation. There is a further 4.5cm from the PWS at Ludham

If it is assumed that the groundwater level in the Crag reduces by a few centimetres then we need to determine how much this affects the water level in the overlying peat and this will depend on the degree of connectivity between the Crag and the overlying peat (see below), the properties of the peat and the effect of other water inputs (e.g. springs discharging on to the Fen), volume of water in the dykes etc. Our view is than any change in the Fen water levels will be less than the change in Crag groundwater levels.

Box 7 (continued) **Final Comments by AMEC with Final Comments by Gilvear**

Conclusions

1. Both sides accept the theory of the modelling approach of the other, i.e. both the “cones of depression theory” and the “stockade theory”. For reasons indicated above we do not consider the “stockade theory” approach to be an appropriate method (or term) to use.

2. Both sides accept that modelling can never be an exact science particularly in a complex site as Catfield. Modelling either using empirical calculations or the use of computer models can provide a very useful insight to the understanding of groundwater systems including the area around Catfield Fen.

3. Both sides accept that the data is either deficient or not available to make definitive statements. We do not agree with the sentiment behind this general statement.

4. The main areas of disagreement appear to be:

   i. the Report includes no acknowledgement of the “stockade” theory and of the potential loss of lateral water flow to Catfield Fen from the local catchment area. The report is based on hydrogeological principles which take into account groundwater flow. The “stockade theory” was introduced after the report was written; therefore we are happy to include Prof. Gilvear’s theory as presented in the final version.

   ii. the AMEC/Mason response dismisses the potential effect of the “stockade theory” as a “once in ten year issue”. Gilvear sharply disagrees. The once in ten years was reference to extreme climatic conditions as it is acknowledged that overall rainfall is the main water input to the fen and that it rains most summers.

   iii. the Report draws definitive conclusions particularly about the Plumsgate Road abstraction which Gilvear / Riches do not believe can be reconciled with the evidence. This same conclusion as given by AMEC is drawn by NE; therefore this is one where we must agree to disagree. We are not contending this merely that the Report has downplayed the effect of Summer abstraction when the Fen is most stressed

The hydrology of Catfield fen and groundwater hydrological connectivity

The broad conceptual model of how Catfield Fen functions hydrological is accepted by both parties, including the fact that there are groundwater inputs and some level of hydrological connectivity between the Crag and the fen. It is also universally accepted that the hydrology is complex and thus caution is needed in interpretation of data and model output. Thus there is agreement that the relationship between Crag and dyke and fen water levels is difficult to ascertain with a high degree of confidence. Thus, for example a 1:1 relationship between Crag water levels and dyke water levels cannot be assumed but neither can a ratio close to one be ruled out. Also in the fen peat a 1mm loss of water could equate to slightly more than a millimetre fall in water table. The uncertainty primarily relates to the level of water flow between the Crag and fen and the role of clay layers in precluding flow. AMEC appear to be of the view that the absence of clay is localised. Our conclusions draw from the work by the University of Birmingham study (of which Prof. Gilvear was part). Even if localised there is the possibility of significant flow in the vicinity and its effect to be felt more widely much like the plughole on a bath. The degree of hydraulic connectivity between the fen and the underlying Crag via the windows in the clay is unknown. The analogy to a plughole is potentially misleading because it implies flow is downwards – also if such “plugholes” existed then the overlying water should have drained away? Also it is acknowledged there are springs discharging water on to the fen. There are also no blockages in the dyke system and on North Marsh, Long Fen and Rose Fen in particular there are good connections by foot drain between the marsh and the dykes and thus for any water loss at one point to create a hydrological change elsewhere (e.g. a change in flow direction in the dykes). Given the level of connectivity then the breach in the southern bund may therefore have a Fen-wide effect on water levels. The map produced at B5 in the report clearly shows that North Marsh, the vast majority of Middle Marsh, about half of South Marsh and the whole area to the north and east of the Broad are “uninterrupted peat deposits”. The map referred to shows the extent of the “upper clay” which is of Romano-British age and which occurs within the peat sequence. It does not refer to the clay at the base of the peat. It is surprising that this confusion has been made. These are not “small areas in the eastern part of the Fen”. There is then disagreement in the level of hydrological connectivity between the fen peat and Crag and thus significance of a reduction in groundwater flow towards the fen and water levels. Again we may have to agree to disagree on this point.

Box 7 (continued)	Final Comments by AMEC with Final Comments by Gilvear

Conclusion

Both sides basically agree on the facts. There is a degree of disagreement about the level of hydrological connectivity between the fen peat and Crag and thus the significance of a reduction in groundwater flow towards the fen and water levels.

The above text suggests that not all the facts are agreed but although there appears to be some consensus some key conclusions remain disputed.

Importance of seasonality in the hydrology and timing of drying out of Catfield fen

It is obvious to a plant ecologist, or any gardener, that the critical time in terms of water availability is in the summer. At Catfield fen in the summer months when evapotranspiration is high the contribution to the fen water balance from the groundwater is vital to the health of the fen –and that any reduction due to abstraction is critical. Stating that the drawdown effect relative to evapotranspiration is not large fails to acknowledge the fact that it is an additional water loss and a double whammy in terms of inducing dry conditions. AMEC appear not to understand the growth cycles of fen communities and the critical role of any draw down during the period of growth. Plant communities are capable of dealing with natural fluctuations in water levels caused by climatic conditions and a drought stress may develop even at times where there is no abstraction. Natural fluctuations may be at a greater scale than that from abstraction. Harding's studies have shown for East Anglian fens a few centimetres can be critical. In a wetland where the critical factor is that the water table remains close to the surface drawdown of a few centimetres can be a significant percentage drawdown. A three centimetre drawdown could easily increase the aerobic zone by 25-30% stressing wet loving plant species and allowing the ingress of drier loving species (scrubbing up). Expressing the impact on water table drawdown is also simplistic in that water content within the unsaturated peat will also be important.

A few centimetres change in Crag groundwater levels if transmitted on to the peat will (due to the higher storage in peat) result in a small change in water level. The comments from Harding is not specific about Catfield Fen and further work is needed to ascertain if "a few centimetres is critical"

It is acknowledged that winter water levels on Catfield fen are important in terms of the fen hydrology and plant ecology together with any impacts of groundwater abstraction. Groundwater abstraction during the winter will result in less groundwater storage and a lower baseline against which summer abstractions cause a drawdown. During the winter if the water table is at the fen surface this is also similarly advantageous in terms of providing a "wet" baseline against which evapotranspiration and any abstraction impact over the summer drawdown water levels. However it is too simplistic a management approach just to store or winter rainfall and groundwater inputs to the marsh and turn it in to a lake just to try and offset natural and human-induced losses in the summer. It would seem that over winter it is appropriate that the water storage across the fen is maximised as it provides a potential buffer to a dry summer. We are not aware that recharge over the winter months is compromised by abstraction? There thus seems to be some level of disagreement in the importance of the role of the alleged breach in the Southern bund in terms of its effect on the summer hydrology. Gilvear/Riches believe the natural summer Catfield fen hydrology relates to the balance between summer month inputs of precipitation and groundwater and loss due to evapotranspiration acting upon water storage as defined as the water table being at or close to the fen surface (marginally below or short-lived and shallow inundation). The importance or otherwise of the bund is an area where we have to disagree. Our view is that the bund was not originally designed to leak/overflow at this point, therefore the fact it now does must have some effect on the surface water levels across the site.

Box 7 (continued)	Final Comments by AMEC with Final Comments by Gilvear

Conclusions

1. There is sharp disagreement between AMEC and Gilvear on the likely ecological importance of drawdown of the water table in Summer months. The Summer period is critical and water budgeting at the annual scale is inappropriate. We conclude from your comments that that you now only consider drying out in the summer months to be important? I have not yet had the opportunity of a discussion of the Mason Report with Natural England
2. Gilvear / Riches suggest that the approach of the Report and comments by AMEC / Mason reflect a lack of awareness of the Harding report and its conclusions about the extreme vulnerability of the Fen habitat "to even the smallest reductions in water levels on Catfield Fen" – e.g. from AMEC / Mason "what is the significance if any of a change in order of a few millimetres?" and "each year fluctuations due to evapotranspiration may be at least twice as much". The significance or otherwise of a small change in water levels needs advice from others more qualified in this area
3. There is some level of disagreement over the significance of the alleged breach in the Southern bund which Gilvear / Riches believe essentially represents an overflow and not relevant to the problems of summer drying. If the breach is an overflow then the principle of an overflow is to either control water levels at a certain maximum desired level and/or allow excess water to "escape". This would imply that when water is "overflowing" that the fen water level has reached its desired (maximum) level and cannot rise anymore. This may not be important in the summer when water levels fall but could be important in the winter/spring as the overflow may stop water levels being has high as they could before they start to fall.

It would appear that the working assumption that a change in Crag water levels of a few centimetres my result in a change in Fen water level of a smaller amount is agreed but the significance of that change in terms of the Fen ecology is disputed. Our view it that the natural seasonal fluctuations are of at least this order of magnitude (or greater) and that the ecology is tolerant of these changes. We consider that the ecology should also tolerate the effect of an occasional further change in water levels. It should be borne in mind that in each year, depending on the winter recharge, the water level at the beginning of summer may be quite variable.

Leakage through sluices / changes in water management / process of terrestrialisation leading to general rise in ground surface.

It is noted that AMEC do not take issue with the Gilvear comments included in their previous paper.

The other reasons suggested by AMEC need to be taken into consideration and their significance assessed as part of the long term management of the fen.

- changes in water management – to be discussed with NE
- leakage through the sluices – agreed unlikely to be a significant factor.
- terrestrialisation – to be discussed with NE

In light of the recent comments form NE then these areas warrant further discussion.

Overall it appears that Gilvear considers abstraction to be the sole reason for the fen to be drying out. AMEC do not agree with this conclusion.

I have never stated that abstraction was the sole cause of the drying of Catfield Fen and have consistently argued that it is a complex site about which it is unwise to make definitive statements. However, in my view any objective assessment of the evidence as assembled by Dr Mason will conclude that "abstraction" represents at least a prime and dominant "suspect" in the problem of drying at Catfield and that it is now time to recognise that fact

Dr Tim Haines

11 June 2012

As a result of the recent discussions between AMEC and Gilvear broad agreement has been reached over many of the issues and in correspondence dated 1 June 2012 just two issues remained outstanding:

"*1.* *The quantum of the effect of the stockade principle to the disruption of the lateral water flow to Catfield Fen from its relatively small catchment area;*

2. *A failure to recognise on your* [AMEC] *part the importance of summer as the key time of year and consequently the potential relevance of irrigation abstraction at precisely that time of most stress*."

The significance of summer as a key part of the years is not disputed and therefore although the potential effect on Crag groundwater levels of a few centimetres is accepted the corresponding effect on Fen water levels and the significance of this is on the ecology an area where no consensus has been reached.

Prof Gilvear has indicated that abstraction is not sole cause of the drying of Catfield Fen and therefore the other possible reasons suggested by AMEC for the drying out of the fen need to be taken into consideration and their significance assessed as part of the long term management of the fen.

10. Conclusions and Recommendations

10.1 Conclusions

This investigation has shown that Catfield Fen, comprising both internal and external drainage systems, is a complex hydrological system. There is some groundwater input to dykes near the eastern margin, rainfall input to the fen compartments as well as a mixture of rainwater and groundwater entering the compartments laterally from the dykes in some places in the west, and possibly flow in the opposite direction from the compartments to the dykes in the east where the ground surface may be slightly higher (though has yet to be verified). The dyke water levels are also subject to the ability of the internal system to retain water. At times water flows over the low bund at the southern end of the internal system, and this will affect the amount of water stored within the internal drainage system.

The possible reasons for the Fen drying out are varied and may involve several factors which are acting in combination to produce the effects described by the Compendium (Natural England et al., 2011). These might include the effects of groundwater abstraction, overflow of dyke water over the low-lying bund at the southern end of the internal system, leakage through sluices, changes in water management, and the process of terrestrialisation which could lead both to the infilling of former pond areas and to the general rise in the ground surface.

The groundwater abstractions that could affect shallow Crag groundwater levels at the Fen are those from the Ludham PWS source and from the Ludham Road borehole which is used for spray irrigation purposes. The effect of the Plumsgate Road abstraction on the Fen has been investigated and it is considered that it does not have an impact. The impact from the PWS source may however be relatively widespread since it has been abstracting continuously since 1973, and the amount of drawdown could be several centimetres. However, any such changes have not been clear from the water level data observed since 1996, and might not be expected to be seen since the PWS abstraction has been fairly constant over this period. The Ludham Road abstraction is considered to have only a small localised effect on groundwater levels near to Church Wood, the estimated drawdown being less than 5 cm, and when abstraction ceases groundwater levels return rapidly to the level that would have occurred without the abstraction. Observed data do not show any effect on water levels within the Fen. It would seem unlikely that this localised effect on groundwater levels could have a widespread effect on Fen water levels, particularly as dykes with groundwater input also occur further north near Middle Marsh where groundwater levels would not be lowered by the Ludham Road abstraction. However, whether there is an impact or not cannot be determined with any certainty until various investigations are undertaken.

A known factor in reducing water levels in the dyke system is overflow over the low-lying bund at the southern end of the Fen. Overflow through a breach in the bund was seen at this location in early March 2012 when dyke water levels were at 0.55 mAOD. These levels are not unusual in winter periods. Since any breach in a soft embankment will tend to get larger over time, it may be that the amount of water lost from the internal system has also increased over time. It may be a contributing factor to the fen drying out.

The implications of all the identified potential factors affecting the wetness of the Fen are more fully explored in Section 8.3 and in earlier Sections.

As a result of the work undertaken and recent discussions there is broad agreement on the hydrological functioning of the Fen. The effect of abstraction on Crag groundwater levels is of the order of a few centimetres although the corresponding effect on Fen water levels and the significance of this, is an area where consensus has not been reached and advice is needed from others including Natural England. It is recognised that that abstraction is not sole cause of the drying of Catfield Fen and therefore the other reasons indicated above need to be taken into consideration and their significance assessed as part of the long term management of the fen.

Box 8 Comments By Professor Gilvear (on the draft report)

Section 10 Conclusions and Recommendations

In relation to the statement that the Ludham Road abstraction will not be significant see comments elsewhere about levels of uncertainty and issues with regard to the location and effectiveness of monitoring. In my professional opinion although the statement may be the case it may also not be the case. The recommendations in the next session are testament to the fact that better located monitoring is required and there are uncertainties in existing data. As such making such a bold statement is unwise.

I do not believe that it can be said that the two factors mentioned in text are causing the drying out of the fen. This is because seepage/leakage has not been proven. It could be that they are contributing to the drying out of fen but given that there is no quantification of the volume of any leakage/seepage it cannot be used as a sole explanation of the drying out. Moreover the text itself in relation to lowered water levels states "at least to some extent" which suggests that it may be a contributing factor but there are likely to be others.

The relation to the sentence in the text "The abstraction from the Ludham PWS source may have had a small, effect on groundwater levels over the period since it started abstracting in 1973, but this cannot be identified from the observed data". I would suggest the last 9 words should say "but the data does not allow this to be substantiated".

Summary comments

The report acknowledges that:

- *(i) The site is complex*
- *(ii) There is the potential for vertical groundwater movement*
- *(iii) That some data is unreliable*
- *(iv) That the monitoring points are not sited in the best location for monitoring the impact of groundwater abstraction*
- *(v) That the water chemistry indicates that there is a groundwater contribution to the fen*

But despite these acknowledgements it suggests a solution of leakage as being the sole cause of the drying out of Catfield fen – a hypothesis which is not supported by physical evidence. The reality is that there are a number of factors leading to the drying out and groundwater abstraction cannot be ruled out.

More generally I think the report does not always acknowledge the full implications of the site complexity and issues to do with monitoring. For example, if some of the key boreholes are not responsive enough to pick-up groundwater abstraction effects, then to come up with definitive statements regarding abstraction impacts is unwise. Similarly given that the dyke system near Church Wood may be underlain by clay then one might not expect to see any immediate drawdown of dyke water levels arising from individual pumping periods but a delayed or long-term response could be apparent in the fen peats or the effect felt elsewhere.

My professional opinion is that although no evidence can be seen of individual abstraction episodes on the fen hydrology it does not mean that the fen is not sensitive to groundwater abstraction.

10.2 Recommendations

There are a number of questions that have arisen as part of this investigation, and these are addressed in the following recommendations:

1) Undertake a topographic survey which includes a re-survey of the 3 gaugeboards (TG32/701, GB-B and GB-C) and two boreholes (NTG3270P4 and NTG3270P5) on the eastern side of the Fen. These were all surveyed on the same day during the 2011 survey, and though the results appear to be correct, such is the significance of identifying surface water level differences across the Fen and vertical head differences within the Crag, that the results warrant checking. For comparison purposes, the survey should also include gaugeboards NTG3261G1 and G2, and TG32/711. Levels should also be taken of the tops of the sluices, and along Commissioner’s Rond including any low points, and across the low-lying bund at the southern end of the internal system, both east-west adjacent to the internal dyke and north south to the dyke leading to Sharp Street Fens;

2) Undertake topographic survey along three transects. These transects should measure the levels not only of the ground surface, but also the water levels and hard and soft bed levels of any pond and dykes that are crossed. The three recommended transects are:

    - An east-west transect crossing Great Fen, Commissioners’ Rond, Sedge Marshes, Fenside Marsh, Middle Marsh and the catchwater drain bordering Ballscroft;
    - An east-west transect crossing Irstead Poors Fen, Commissioners’ Rond, Long Marsh, Rose Fen, Catfield Broad, and then crossing to the catchwater drain at Church Wood, and from there to observation borehole TG32/801;
    - A north-south transect from the road near Fenside, crossing the catchwater drain, North Marsh, Middle Marsh and into Mill Marshes.

3) Undertake an investigation to identify any leakage through or around the sluices, and over (or through) the low lying bund at the southern end of the internal system. The integrity of Commissioners’ Rond should also be checked. Having identified the location(s) of uncontrolled flow out of the internal system, take steps to stop such flow taking place (for example, at the low-lying bund at the southern end of the internal system);

4) Install a gaugeboard and stilling well in the catchwater drain at Church Wood, near observation borehole TG32/801. This will monitor any impact due to the Ludham Road abstraction;

5) Undertake a survey to determine the connectivity of the dyke system and the potential for changes in dyke water levels at one location to be transmitted to another remote location within the internal dyke system;

6) Install a gaugeboard and stilling well in the wide dyke on the south side of Commissioners’ Rond, opposite gaugeboard TG32/711. This will enable monitoring of the external system at a location which is not impeded by vegetation growth as occurs at NTG3261G2;

7) Install a dipwell in Middle Marsh, probably near the area known to have bogbean;

8) Install a dipwell in Fenside Marshes if the topographic survey shows an increase in ground level towards the east. This location would be in an area where the underlying clay separates the peat from the Crag. This will probably be different to the location in Middle Marsh where the clay may be absent;

9) Install a piezometer to a depth of about 11m into the shallow Crag in the vicinity of TG32/710, near the eastern edge of the Fen, with a design similar to NTG3270P4 to the south. Similar recommendations for the installation of a piezometer and nearby dipwell were made by Entec (2010) but not implemented. The use of such installations would be as follows:

    - There would be monitoring of both Crag and peat heads at locations remote from other groundwater installations, and near to the only monitored gaugeboard on the eastern side of the Fen. This will enable head differences between all three sites to be determined and monitored over time;

    - The head difference between the Crag monitored by the piezometer, and the dyke and dipwell, can be compared with head differences observed at NTG3270P4 and NTG3270P5 at the south east corner of the Fen, and with head differences observed at the AWS Sharp Street observation boreholes. It may enable an assessment of whether a cone of depression affecting shallow Crag has developed around the Ludham PWS source;

    - Water samples taken from the three installations will help to identify the importance of any shallow Crag groundwater contribution to the dyke at TG32/710, and potentially at the dipwell location;

    - An additional option of greater expense would be to construct an additional piezometer to a depth 25 m so that the middle Crag unit can be monitored, further head differences identified with improved ability to assess the extent of any cone of depression from the PWS source, and middle Crag groundwater chemistry identified in order to determine if it contributes to the nearby dyke waters.

10) Further investigate the potential impact of the AWS Ludham source through the use of a revised groundwater model in order to assess whether its abstraction has any impact on the Fen. As part of the model development it should be able to re-create the heads within the basal, middle and shallow Crag units observed at the Sharp Street observation boreholes during the 2002 and 2003 constant rate pumping tests. Not only should peat groundwater levels within the internal system be investigated, but also shallow and middle Crag groundwater levels at the location of TG32/710 near the eastern margin of the Fen;

11) Carry out slug tests on boreholes TG32/805, TG32/815a, TG32/815b, TG32/815c in order to check their responsiveness to changes in groundwater levels. Also plumb their depths to determine whether they have been partially infilled;

12) Investigate the effects of turfing-out by looking the differences between the vegetation communities, water levels and ground surface levels at North Marsh, which was turfed-out in the 1990s, and those in adjacent compartments that were not turfed-out.

11. Bibliography and References

@one Alliance (2006). Hydroecological Investigations for WREP [AMP4 Water Resources Environment Programme]: Field Investigation Factual Report for Ant Broads and Marshes SSSI. Report for Anglian Water, December 2006.

@one Alliance (2006). Hydroecological Investigations for WREP [AMP4 Water Resources Environment Programme]: Hydroecological Desk Study for Ant Broads and Marshes SSSI. Report for Anglian Water, March 2006.

@one Alliance (2007). Hydroecological Investigations for WREP [AMP4 Water Resources Environment Programme]: Hydroecological Impact Assessment Ant Broads and Marshes SSSI. Draft Report for Anglian Water, December 2007.

@one Alliance (2008). Hydroecological Investigations for WREP [AMP4 Water Resources Environment Programme]: Signal Testing of Ludham PWS Abstraction for Ant Broads and Marshes SSSI. Factual Report. Report for Anglian Water, March 2008.

Anglian Water Authority (1986). Pump test report reference no: 34/9/2/966. Held in folder 6 for catchment 34/9. This is the pump test report for the Plumsgate Road borehole at TG 3818 2230.

Anglian Water Authority (1987). Pump test report reference no: 34/09/G/2/1045. Held in folder 7 for catchment 34/9. This is the pump test report for the Ludham Road borehole at TG 3859 2060.

Arthurton, R.S., Booth, S.J., Morigi, A.N., Abbott, M.A.W. & Wood, C.J. (1994). Geology of the country around Great Yarmouth. Memoir for 1:50,000 geological sheet 162. British Geological Survey, HMSO, London.

Atkins/HSI (2003a). AMP3 Impact of Abstractions: Catfield Fen Investigation & Monitoring Phases 1 & 2. Report for Anglian Water Services Ltd, February 2003.

Atkins/HSI (2003b). AMP3 Impact of Abstractions: Catfield Fen Impact Assessment. Report for Anglian Water Services Ltd, December 2003.

Atkins/HSI (2005). AMP3 Impact of Abstractions: Catfield Fen Supplementary Final Assessment. Report for Anglian Water Services Ltd, January 2005.

Coles, B.P.L. & Funnell, B.M. (1981). Holocene palaeoenvironments of Broadland, England. Special Publication of the International Assoc. of Sedimentologists, 5, 123-131.

Collins, F.B. (1988). A hydrochemical study of two Norfolk wetlands, Badley Moor Fen and Catfield Fen. Unpublished M.Sc. thesis, University of Birmingham.

ECUS (1997). Hydrological Project for the Fens of the Ant Valley, Norfolk. Report to Broads Authority and English Nature prepared by Van Wirdum, G., Wheeler, B., Baird, A. & Money, R. (Environmental Consultancy University of Sheffield), August 1997.

ECUS (1998). Hydrological Investigations at Sutton Fen. Report to Broads Authority prepared by Baird, A., Van Wirdum, G., Money, R. & Wheeler, B. (Environmental Consultancy University of Sheffield), March 1998.

Entec (2001). Hydro-ecological Review of European Sites within the Yare & North Norfolk Groundwater Resource Investigation Area: Ant Broads and Marshes. Final Report for the Environment Agency, Anglian Region, September 2001.

Entec (2003). Assessment of the Hydrological Impacts of Abstraction on Groundwater Fed Wetlands: Ant Broads and Marshes (Catfield Fen). Draft Report for the Environment Agency, August 2003 (never issued as Final).

Entec (2006). Habitats Directive Review of Consents Stage 3 Hydrological Impact Assessment: Ant Broads and Marshes SSSI. Report for the Environment Agency, September 2006.

Entec (2009a). Habitats Directive Review of Consents – Stage 4. Site Options Plan: Ludham-Potter Heigham Marshes SSSI. Report for the Environment Agency.

Entec (2009b). Habitats Directive Review of Consents – Stage 4. Site Options Plan: Ant Broads and Marshes SSSI/ Alderfen Broad SSSI. Report for the Environment Agency.

Entec (2010). Catfield Fen – An Assessment of Monitoring for Regulatory Purposes. Technical Note for the Environment Agency, July 2010.

Environment Agency (1998a). Licence Application Summary Report: Report relating to the application to renew time limited licence 7/34/9/G/130 (relating to the Miles's Loke borehole[now known as the Ludham Road borehole]). Unpublished report by Anglian Region, Eastern Area. Report prepared by Adrian Green.

Environment Agency (1998b). Licence Application Determination Report: Report relating to the application to renew time limited licence 7/34/9/G/130 (relating to the Miles's Loke borehole). Unpublished report by Anglian Region, Eastern Area. Report prepared by Adrian Green.

Environment Agency (2001). Licence Application Determination Report: Report relating to the application to renew time limited licence 7/34/9/G/130 (relating to the Ludham Road borehole). Unpublished report by Anglian Region, Eastern Area. Report prepared by Marion Martin.

Environment Agency (2008). Licence Application Determination Report: Report relating to the application to renew time limited licence 7/34/9/G/144A (relating to the Ludham Road borehole). Unpublished report by Anglian Region, Eastern Area. Report prepared by Alasdair Birrell.

Environment Agency (2010a). Determination Report: Report of an Application for two new (renewals) full abstraction licences AN/034/0009/008 and AN034/0009/009 under the Water Resources Act 1991 (as amended) and the Environment Act 1995. [relating to lic. nos. 7/34/09/*G/0141C and 7/34/09/*G/0144B]. Unpublished report by Anglian Region, Eastern Area. Report prepared by Hannah Goodfield.

Environment Agency (2010b). Influence of abstraction under 7/34/09/*G/0144B on Crag groundwater levels. Unpublished report by the Environment Agency, Anglian Region, Eastern Area. Report prepared by Gavin Sharpin.

Environment Agency (2010c). Interim impact assessment of Plumsgate Road and Ludham Road abstractions upon Catfield Fen. Unpublished report by the Environment Agency, Anglian Region, Eastern Area. Report prepared by Gavin Sharpin.

Ewan (2005). Hydrochemistry Water Sampling: Large Broadland Sites, September-October 2005. Report for the Environment Agency (ref: 05-60624/1).

George, M. (1992). The Land Use, Ecology and Conservation of Broadland. Packard Publishing Ltd., Chichester, 558pp.

Giller, K.E. (1978). A vegetation description of the Catfield and Irstead Fens, Norfolk. Unpubl. Report for Nature Conservancy Council, Norwich.

Giller, K.E. & Wheeler, B.D. (1986a). Past peat cutting and present vegetation patterns in an undrained fen in Broadland, Norfolk. J. Ecology, 74, 219-247.

Giller, K.E. & Wheeler, B.D. (1986b). Peat and peat water chemistry of a flood-plain fen in Broadland, Norfolk, U.K. Freshwater Biology, 16, 99-114.

Giller, K.E. & Wheeler, B.D. (1988). Acidification and succession in a flood-plain mire in the Norfolk Broadland, UK. J. Ecology, 76, 849-866.

Gilvear, D.J., Tellam, J.H., Lloyd, J.W, and Lerner, D.N. (1994). Wetland vulnerability in East Anglia; the range of validity of a generalised classification approach. Aquatic Conservation, 4, 105-124.

Gilvear, D.J, Sadler, P.J.K., Tellam, J.H., & Lloyd, J.W. (1997). Surface water processes and groundwater flow within a hydrologically complex floodplain wetland, Norfolk Broads, UK. Hydrology and Earth Systems Sciences, 1, 115-135.

Gilvear, D.J. (2010). Current understanding of the hydrology of Catfield Fen, Norfolk: Implications regarding hydrological vulnerability to groundwater abstraction. Unpublished report for Mr & Mrs Harris of Catfield Hall, 9 January 2010.

Hiscock, K.M. (2005). Hydrogeology: Principles and Practice. Blackwell Science Ltd.

Holman, I.P., Hiscock, K.M. & Chroston, P.N. (1999). Crag aquifer characteristics and water balance for the Thurne catchment, northeast Norfolk. Q. J. Eng. Geol., 32, 365-380.

HSI (1998). Hydrological Monitoring of Wetlands: Hydrological Report: Catfield Fen Site 33. Unpublished report for the Environment Agency, January 1998.

HSI/ECUS (1998). Evaluating the Impact of Groundwater Abstraction on Key Conservation Sites: Reports for AMP3: Final Report: Catfield Fen. Unpublished report for Environment Agency, Anglian Region. November 1998.

HSI (2002). AMP3 Impact of Abstractions. Catfield Fen Investigation & Monitoring Phase 1. Report for Anglian Water. March 2002.

Jennings, J.N. (1952). The Origin of the Broads. Royal Geographical Society, London. Research Series No.2. 66pp.

Land & Water Resource Consultants (LWRC)(1992). Report on Test Pumping of Catfield Fish Refuge Trial Borehole 1. Report to NRA, Anglian Region, May 1992.

Marsh, T.J. and Hannaford, J. (Eds.) (2008). UK Hyrdometric Register. Hydrological data UK series. Centre for Ecology & Hydrology. 210pp.

Metcalf, B.J. (1988). A hydrogeological study of Selected Sites in the East Anglian Wetlands. Unpublished M.Sc. thesis, University of Birmingham.

Natural England, Harris, T.C. & Harris, A.M. (2011). A compendium of ecological and eco-hydrological evidence from Catfield Fen, Norfolk, at 31st January 2011. Unpubl. report.

Norfolk and Norwich Naturalists' Society (NNNS)(2008). A Natural History of the Catfield Hall Estate. Norfolk and Norwich Naturalists' Society Occasional Publication No. 11, 152pp.

Sadler, P.J.K. (1989). The Hydrodynamics of Catfield Fen: An East Anglian Wetland. Unpublished M.Sc. thesis, University of Birmingham.

Sharpin (2010). Review of Monitoring for renewal of licences 7/34/09/*G/0141C and 7/34/09/*G/0144B. Unpublished internal Environment Agency, Anglian Region report. (Included as Appendix 4 in Environment Agency (2010)).

Surridge, B.W.J. (2004). Biogeochemical and hydrological controls on phosphorus transport in a floodplain fen. Ph.D. thesis, University of Sheffield, 233pp.

University of Birmingham (1987). The Hydrodynamics of East Anglian Fen Systems. Final Report of Phase 1, October 1987. Report to National Rivers Authority by the Hydrogeology Research Group, School of Earth Sciences, University of Birmingham.

University of Birmingham (1988). The Hydrodynamics of East Anglian Fen Systems. Interim 12 Month Report, Phase II, October 1988. Report to National Rivers Authority by the Hydrogeology Research Group, School of Earth Sciences, University of Birmingham.

University of Birmingham (1989). The Hydrodynamics of East Anglian Fen Systems, Final Report to the Nature Conservancy Council, National Rivers Authority and Broads Authority by the Hydrogeology Section, School of Earth Sciences, University of Birmingham, October 1989. [main contributors Gilvear, D.J., Tellam, J.H., Lloyd, J.W, and Lerner, D.N., though not recorded in the report].

University of Birmingham (1991). The Hydrodynamics of East Anglian Fen Systems. Phase III Report. Appendices. March 1991. Report to National Rivers Authority by the Hydrogeology Research Group, School of Earth Sciences, University of Birmingham.

Wells, C.E. & Wheeler, B.D. (1999). Evidence for possible climatic forcing of late-Holocene vegetation changes in Norfolk Broadland floodplain mires, UK. The Holocene, 9, 595-608.

Wheeler, B.D. and Giller, K.E. (1982a). Species-richness of herbaceous fen vegetation in Broadland, Norfolk in relation to the quantity of above-ground plant material. Journal of Ecology, 70, 179 - 200.

Wheeler, B.D. & Giller, K.E. (1982b). Status of aquatic macrophytes in an undrained area of fen in the Norfolk Broads, England. Aquatic Botany, 12, 277-296.

Wheeler, B.D. & Shaw, S.C. (2006). Ecohydrological site accounts for East Anglia: Catfield and Irstead Fens. Appendix 3A, pp 9-15. In: A wetland framework for impact assessment at statutory sites in England and Wales. Environment Agency, Science Report: SC030232/SR1.