Catfield Fen: a synthesis of recent studies.

This paper provides a concise summary of recent work at Catfield Fen, Norfolk. It draws upon a report commissioned by the Environment Agency (AMEC 2012), which reviewed the hydrology of the Fen and sought to assess the sensitivity of the site to water abstraction, and other recent reports. The motivation of the AMEC report was concern expressed at the time by Natural England, and the owners of Catfield Hall Estate, Mr and Mrs Harris, that the site was 'drying out'. This followed earlier concerns, expressed in letters by the former land-owner, Mr McDougall, to the National Rivers Authority in June 1991 and English Nature in August 1993. In the latter, Mr McDougall outlined his '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'. These concerns were shared by a respected local ecologist, Mr Alec Bull, (letter November 2010) and the Norfolk and Norwich Naturalists' Society.

In evaluating the work completed at Catfield Fen to-date, insufficient attention has been paid to the wider environmental context of the site, and the need for an interdisciplinary approach that embraces the difficulties in: i. understanding and quantifying the hydrology of the Fen (reviewed inter alia by AMEC, 2012); and ii. determining the ecological implications of any change in the hydrology. To achieve the second goal, analyses of the functional hydroecological relationships (between vegetation communities and hydrological parameters) is essential, but within a wider context that recognises the dependence of an isolated wetland nature reserve on hydrological processes within the associated surface-water and groundwater catchment. This integrated approach, linking hydrology and ecology, is particularly important given that in some cases it may take many years for the ecology of a site to respond to hydrological change (Grootjans & van Diggelen, 2009) and hence the timeline over which any change (whether hydrological or ecological) occurs is fundamental, yet frequently difficult to establish.

Long-running and continuous time series of key environmental parameters **and** vegetation records from regular quadrat surveys are essential in developing the hydroecological tools required to understand, manage, and where necessary, restore wetland ecosystems. Unfortunately, although research at Catfield Fen has been described in a number of studies over the past 60 years (e.g. Jennings, 1952; Wheeler, 1978; Giller & Wheeler, 1986a; 1986b; Gilvear et al. 1997), much of the available environmental data is temporally and spatially isolated (and in some cases lacks specificity). This is problematic when seeking to identify the interdependence between hydrology and ecology at Catfield as the vegetation data were not collected with a view to establishing whether vegetation change has (or is) occurring (Mr Bull; letter: Nov. 2010). Moreover, much of the work has been largely descriptive in nature, whole those models that have been developed to-date, focus solely on the regional groundwater catchment. Hence, the modelling 'toolbox', available at Catfield lacks a strong ecological focus, although there should be scope to develop a coupled hydrological – ecological model of the site that would enable the evaluation of specific scenarios.

Notwithstanding these problems, analysis of local rainfall and evapotranspiration (estimated by MORECS) indicate that that there is no clear trend in climate at Catfield, and hence other explanations of the changes observed at the site are required (AMEC, 2010).

Irrespective of whether it is accepted that Catfield Fen is 'drying out', it is significant that groundwaters are abstracted at three points in the immediate vicinity of Catfield for public water supply (Ludham) and for spray irrigation of farmland (the Alston and Overton licences). These points of abstraction apparently lie within Catfield's groundwater catchment area, which is relatively small (i.e. ~2km^2). The key questions therefore are: i. does local groundwater abstraction have an impact on the hydrology of the Fen? And, ii. what is the impact of the hydrological change on the ecology of the Fen?

The groundwater abstractions are licensed by the Environment Agency who commissioned ENTEC and subsequently AMEC to develop a regional groundwater model to quantify the effects of groundwater abstraction at specific points across North Norfolk. Given the scale of the model, this has a relatively coarse resolution (model cells are 200 × 200 m) and inevitably there will be uncertainties in model output. Equally challenging, however, is predicting with confidence, the impacts of individual changes in the hydrological regimen (and water balance) on the ecology of specific points of the Fen given that there are likely to be: i. changes in wetland water level (predicted by the model with respect to datum; while the water table depth below the surface is of more interest for the ecology); ii. changes in the hydroperiod (or the water-table regime), depending on the magnitude of abstraction and the distance of the point of abstraction from the point of interest; iii. changes in the hydraulic gradient (in particular the strength of the upward groundwater flux at points where groundwater discharge would normally occur and which explains the original presence of wetland in areas where precipitation by itself would be insufficient for saturated conditions to persist); iv. changes in the direction of water movement; and v. changes in the relative importance of the principal water sources: precipitation and groundwater (in some cases supplemented by river-water).

In addition to these points, that relate specifically to the Fen hydrology, equally important to quantifying the impact on the Fen is to determine the consequences of any hydrological change on the flora and fauna. This cannot be predicted as a simple function of the water level change; many wetland species can tolerate a wide range of water-table conditions, but they are likely to vary in the degree to which they tolerate prolonged wet or dry periods. Also important will be variations in nutrient input, pH, and vegetation / fen management.

Given this context, this paper first provides a short summary of Catfield Fen which reviews recent work on the hydrology (including the hydrogeology and sedimentology) of Catfield, before summarising the key conclusions of three unpublished published ecological studies of the Fen. The paper concludes with a comparison of the situation at Catfield with some wetlands in the Netherlands, which have experienced similar problems in recent years, and which have been restored successfully.

Catfield Fen.

Catfield Hall Estate covers 122 ha and forms part of the ~742ha Ant Broads and Marches Site of Special Scientific Interest (SSSI), and falls within an area that is designated a Special Area of Conservation (SAC), a Special Protection Area (SPA) and a RAMSAR site (in the latter case, the 4,623ha of Broadland are recognised as a wetland of international importance). The River Ant is one of the five principal rivers that cross the Norfolk Broads, and the Ant Broads and Marshes represent (according to the SSSI description) 'one of the most extensive remaining areas of undeveloped primary fen habitats in Britain, and is considered to form the finest example of unpolluted valley fen in Western Europe'. The associated fen vegetation is diverse: the SSSI includes the 'only known sites for several plant communities and uncommon species that were once more widespread in Broadland'.

Catfield Fen forms part of a wider expanse of floodplain fen adjacent to the River Ant and Barton Broad. The Fen was one of a number of East Anglian wetlands investigated in a study examining wetland sensitivity to groundwater abstraction (Gilvear et al. 1994), and the hydrology of the site is described in detail by Gilvear et al. (1997). As reviewed more recently (AMEC, 2012), the Fen is hydrologically complex and is largely sustained by precipitation and upward groundwater flow through a 'leaky' clay layer that lies beneath the recent alluvial and organic deposits across much of the floodplain, and which limits water movement to (and from) the underlying Norwich Crag aquifer. The Crag underlies the whole of the Fen at depth and forms the lower slopes of the uplands to the N and E.

At the surface, two hydrologically distinct units can be identified at Catfield. First, an 'external' unit close to the river and the Broad (generally described as the Great Fen), which is in direct hydrological continuity with the river; and second, an internal unit on the E of the floodplain. The latter is bounded to the W and S by a small embankment (the Commissioners Rond), and to the N and E by gently rising slopes of the valley-side. A network of dykes cross both units, and water movement between the internal and external units, through the Rond, is regulated by two control structures: in the N and S of the Fen. Surface-waters may also pass between both units via a low-lying bund to the S.

Stratigraphy.
Stratigraphic sections across the floodplain of the Ant in the vicinity of Catfield were described by Jennings (1952; his Figs. 22, 23 & 24). These sections, orientated across the floodplain perpendicular to the direction of the River Ant, indicated that 3-4m of bushwood peat fill the valley, grading to a Phragmites peat (1-2m) near the surface, and with an intermediate grey Phragmites-clay layer found in the majority of the points surveyed. An additional stratigraphic profile is described by Giller & Wheeler (1986b), across land within the 'external' unit and which is now managed by Butterfly Conservation (i.e. not part of Catfield Hall estate).

In May 2013, the Landscape Partnership was commissioned to undertake a hand auger survey across Catfield Fen in May 2013 with the aim of identifying and interpreting the key stratigraphic sequences within North, Middle, South and Middle Marshes at Catfield (Fig. 1).

Six transects, orientated in an E – W direction (perpendicular to the river Ant) were surveyed by hand auger. Approximately 30% of the cores were over 18th or 19th Century turbaries, which varied considerably in depth, and in contrast to the earlier surveys (Jennings, 1952; Giller & Wheeler, 1986a) no true brushwood peat was encountered. It also proved impossible to determine accurately the boundary between the Middle and Lower peat from the survey data. Significantly, the Norwich Crag was encountered at a depths of 15cm below the surface to the E; but the depth of the Crag increased to >165cm below the surface to the W. The hydrological implications of the stratigraphic survey have yet to be fully considered, but it is likely that the presence of turbaries will facilitate lateral movement through parts of the fen. The proximity of the Norwich Crag to the surface in the E, explains some of the water chemistry data (described below); and it is likely that in some places the dykes that cross the fen will be closely connected with the Crag. The survey also revealed the discontinuous nature of the Breydon Formation Clays (Jenning's clay layer, intermediate between the brushwood and phragmites peat); they have been partially removed by turf digging (and rhizomes and leaf material in the clay may affect their permeability). However, there was no evidence, in the May 2013 survey, of a clay layer immediately below the alluvial / organic depots, which directly overlies the Norwich Crag. This could reflect the limited depth to which it was possible to hand auger, but importantly, some of the lower samples collected, comprised upto 50% sands and gravel, indicating the presence of highly permeable deposits at depth.

On the basis of the May stratigraphic survey, a new conceptual model of the hydrology of the Catfield Hall fens can be advanced, that draws together the surface stratigraphy, with information from local boreholes (Fig 2). The schematic cross-section indicates the inferred relationship between the alluvial / organic deposits with the underlying geological units (the Crag, the lower permeability tertiary London Clays and the Chalk), and potential lines of preferential horizontal and vertical water movement. Inevitably, the latter will vary spatially and temporally, depending upon the relative water levels in individual sedimentological units, and the permeability of each unit (and any intervening layer). It is quite likely therefore, that the hydraulic gradients will vary across the site: in some cases the centre of a particular fen unit may be higher than the water level in the adjacent dyke, and in other cases lower – depending upon the strength of any upward groundwater flux, and the balance between recent precipitation and evapotranspiration (although there appears to have been some confusion in this respect in some summaries of the hydrology at Catfield).

Hydrochemistry.
The limited hydrochemical data available from Catfield can be interpreted in the context of the schematic diagram in Fig. 2. These data are reviewed in AMEC (2012) who distinguish four surface-water types:

I: waters with a significant rainwater component, and which could also be influenced by Crag and/or Broad water (mainly sampled from the internal unit, and largely from ponds and the surface, as opposed to the dykes).

III: waters sampled in the dykes or close to the E margins of the Fen, and having a chemistry that suggests a significant input of groundwaters from the shallow and/or middle Crag.
II: a mixture of Type I and III. These waters were sampled from both the internal and external units; and including waters from the dykes and the fen surface.
IV: waters that show evidence of pollution (e.g. potential contamination from septic tank effluent – inferred from a sample collected on the margin of the Fen at Fenside).

AMEC (2012) suggest that the chemistry of Crag groundwaters differs through the aquifer. Waters associated with the deep Crag have low SO_4 concentrations, and a high Ca/Mg ratio; whilst those from the shallow Crag have high SO_4, Mg (and nitrate) concentrations, and lower Ca and HCO_3 concentrations. Middle Crag waters appear to be intermediate, but with occasionally higher Ca and HCO_3 concentrations than the deep Crag groundwaters, and AMEC (2012) hypothesise that the type III waters, sampled at Catfield, may include waters derived from the middle Crag. The Crag groundwaters also tend to have moderate to high Fe concentrations, which may (but not necessarily) result in ochre precipitation. Giller & Wheeler (1986a) note that high values of total and extractable Fe 'were recorded from sites close to the upland margins' (p. 112).

Significantly, AMEC (2012) appears not to review pH data, although some data are probably available for some of the dipwells monitored by the Environment Agency. In their earlier study, Giller & Wheeler (1986b) were able to distinguish between 'poor-fen' sites at Catfield, where the pH was low (water pH<5.9; peat pH<4.7) and' rich fen sites' where the pH was ~6.5.More recent spot measurements at Catfield Fen by Dr Aat Barendregt in June 2013, revealed a higher range in pH: in Middle Marsh pH ranged from 4.85 to 5.56, with a much higher pH in a sample from the adjacent dyke (7.5). A water sample from North Marsh north was similarly high (6.9). The limited data available indicate that pH varies over several orders of magnitude across Catfield, and detailed analysis would probably reveal a clear spatial trend, although some temporal variation in pH can also be expected.

In summary, the hydrological, stratigraphical and hydrochemical data, when considered together, confirm the environmental complexity of Catfield, and while the conceptual figure (Fig. 2) provides a good context for understanding the physical system, there will be marked spatial and temporal variations in the environment across the site. These present real challenges with regards sampling, and questions will be raised concerning how representative isolated point measurements (whether water samples or 1m^2 vegetation quadrats) may be of the wider Fen. Notwithstanding these observations, the following section summarises the key findings of a vegetation survey, completed at Catfield in July 2013 by the Landscape Partnership (The Landscape Partnership, 2013), with additional comments from reports by Dr Aat Barendregt and Mr Mike Harding.

Vegetation Surveys at Catfield Fen: 2010 to 2013.

Unfortunately, there is relatively little quantitative vegetation information available for Catfield Fen that ideally could establish a time-line of ecological change at the Fen. Four quadrats were surveyed by Giller & Wheeler (1986a) in the area of Catfield Fen that is now managed by the Hall, and a wider vegetation survey was completed by Dr Jo Parmenter in August 1991 as part of the Broadland Fen Resource Survey (Parmenter, 1995) funded by Natural England and the Broads Authority. The latter included 22 quadrats on Middle Marsh (G14), South Marsh (G25), Mill Marsh East (G24) and Mill Marsh West (G23). These areas are currently managed as fen: parts of the area are variously cut for litter (marsh hay) either annually, to maintain a summer mowing marsh, or over a longer rotation, to maintain tall herb fen, reedbed and sedge beds. A resurvey of the August 1991 quadrat locations was completed in July 2013, although there are some difficulties in comparing results between the two dates: while current quadrat locations can be identified with some precision by GPS (but still ±0.5m?), former locations were not surveyed in precisely, but rather located by 6 figure grid references, and so there is considerable uncertainty as to how closely the resurveyed quadrats correspond with those surveyed formerly and errors may approach ±10m.

The resurvey considered whether certain commonly occurring plant species could be used as indicators of acidification (which might occur naturally, or as a result of changes in the water budget). Potential species included *Carex elata*, *Lycopus europapeus, Sium latifolium* (all intolerant of low pH), *Myrica gale* (broadly acidophile) and *Peucedanum palustre* and *Rumex hydrolapathum* (both broadly calciphile).

A comparison between the results of the 1991 and 2013 surveys suggests there have been:

1. **Changes in Species Diversity**

There has been an increase in species diversity in South Marsh, but two quadrats (8 in Middle Marsh and 2 in Mill Marsh East) are now dominated by a dense layer of *Sphaghum*, with an attendant loss of calciphile species

2. **Changes in occurrence of acidophiles**

There has been a dramatic expansion of *Sphaghum* spp in Middle Marsh. *Sphagnum* was present in, or close to, 2 quadrats in 1991; but 10 quadrats in 2013. There has also been an increase in the distribution of *Myrica gale* (from 4 quadrats in 1991 to 8 in 2013), which inter alia could reflect a reduction in pH.

3. **Changes in occurrence of calciphiles**

While there has apparently been no reduction in the frequency / occurrence of *Peucedanum palustre* in any quadrats, Lycopus europaeus has declined (from 10 quadrats in 1991 to 4 in 2013). The latter is associated with a relatively narrow pH range (6.78 to 5.59) and is much less tolerant of lower pH than *Peucedanum palustre.* Similarly, although there was no overall reduction for *Carex elata* across Catfield, it is no longer present in Middle Marsh.

Moroever, *Sium latifolium* is now present in / near 5 quadrats, compared with 8 in 1991 (and is no longer present in Middle Marsh), and *Rumex hydrolapathum* is now present in / near 5 quadrats in 2013, compared with 7 in 1991, and is also no longer present in Middle Marsh. Both species would respond negatively to drying.

In summary, the results suggest that there has been a trend – from higher to lower pH and / or relative drying of the fen surface between the two survey points. There has also been a marked and dramatic increase in *Sphagnum* spp – particularly in Middle Marsh – and most of the adverse changes (inferred changes in pH and botanical evidence of drying) are associated with Middle Marsh.

Discussion.

Catfield Fen is evidently a complex and diverse fen ecosystem. There are marked differences in hydrology across the, site with a huge contrast in the Chemistry (a site visit on the 5th June 2013 revealed a range in pH from 4.85 to 7.5; Ca: 1.43 to 68.06 mg/l; Mg: 1.6 to 19.17mg/l; Cl: 21.47 to 104.26mg/l; K: 1.05 to 11.38mg/l; Na: 11.1 to 55.84mg/l), and vegetation (both at species and community level). However, if a fen ecosystem is to persist at Catfield, this requires the maintenance of high water tables and buffered condition for peat accumulation to continue. High water tables prevent the invasion of other species; and in periods when water-tables fall, the soil will be oxidized leading to mineralization of the peat, releasing nutrients (and CO_2 to the atmosphere) and resulting in eutrophication. This will stimulate the growth of other species leading to what in the Netherlands is referred to as 'accelerated succession'.

At the same time as the release of nutrients (from mineralization of the peat), there will be a change in the hydrology, with infiltration of precipitation. Given the acidity of rainfall, the near-surface sediments will be acidified, leading to a change in vegetation (i.e. to acidiphiles, or 'bog-vegetation'). When *Sphagnum* spp become established, the *Sphagnum* enhances the acidification by the expulsion of H+ ions. In addition, at a pH of ~5, phosphorus is no longer precipitated with Ca and Fe, but becomes freely available. The resulting 'positive feedback' loop further enhances acidification leading to accelerated succession.

Evidence, therefore, of what may first appear relatively small changes in the hydrology, hydrochemistry and presence or absence of indicator species (as described in the previous section) are significant areas of concern. They are outlined in a briefing paper by Barendregt (2013). These concerns were expressed at Catfield earlier by Harding (2010), as part of the Compendium (agreed with Natural England), who describes a mixed mire community where waters derived from recent precipitation overlie the groundwater table. In this situation, the calcareous tall fen species may be rooted through the shallow rainwater table and into the minerotrophic water table below, whereas the surface bryophyte and shallow-rooted herbs may be supported by the perched rainwater table. As the two water types have contrasting hydrochemistries, an acid bog vegetation characterised by Sphagnum is found beneath a layer of rich-fen tall herbs. These are the prevailing conditions in *Dryopteris cristata* - *Sphagnum* fens found in the Norfolk Broads, for which Catfield is the type locality. As Harding highlights, their hydrochemistry is complex, it is likely to be very fragile, and susceptible to reductions in the groundwater table.

Harding and Barendregt both consider that restoration of fen systems, when they have been degraded beyond a certain point, is very difficult. For example, work on comparable Dutch systems suggests that the only sustainable process is when groundwater continues to seep up into the peat layer, thereby adding directly to the buffering capacity of the soil.

Conclusions

Catfield Fen in a site of acknowledged global significance: it forms part of an internationally recognised RAMSAR wetland, and has been described as the finest undrained floodplain fen ecosystem in Europe. The available data indicate that groundwater contributes to the water-budget of the site, and the variability in the local water-budget (including a groundwater contribution) undoubtedly account for the ecological diversity of the site.

The designation of Catfield Fen as a wetland of national, European and global significance is threatened by continued groundwater abstraction in the immediate vicinity. While the quantitative effects of individual abstractions can be estimated using a regional groundwater model, the potential error in model outputs is not known. Moreover small changes in the water-table may lead to significant change in the predominant water source at key depths immediately below the surface (i.e. within the area where plants extract water), leading to increased mineralization of the near-surface organic deposits (releasing nutrients and CO_2 to the atmosphere).

Experience from work on comparable Dutch fen ecosystems, published in the internationally recognised peer-reviewed literature (and confirmed by Dutch experts) suggests that Catfield Fen is experiencing accelerated succession. A process which is very difficult to reverse, and which can be only be managed by a cessation of groundwater abstraction in the surrounding area. These interpretations have been peer-reviewed by a leading UK wetland ecologist: Dr Owen Mountford of the Centre for Ecology and Hydrology.

Despite this evidence, Natural England apparently considers that Catfield Fen is thriving, and that the changes at the site can be attributed to natural succession. In so doing, Natural England is apparently supported by an unsolicited report produced by Dr Wheeler, which repeats his earlier suggestion (Giller & Wheeler, 1986a) of the importance of succession. This interpretation is seemingly not open to challenge, yet the facts are incontrovertible:

- The diversity of Catfield has been affected negatively in recent years, with a dramatic increase in *Spaghnum* spp, and the loss of caliciphiles, especially in Middle Marsh. This is consistent with a reduction in the groundwater contribution to the water-budget, which would be expected as a result of groundwater abstraction.

- Recent changes (in the hydrology and ecology of Catfield) are reducing the buffering capacity of the near-surface sediments, which is leading to a ‘positive feedback’ effect which will be very difficult to reverse.
- The recent growth of Sphagnum suggests that the real fen species (Carex, Cicuta, Cladium, Eleocharis, Schoenoplectus) are vulnerable, and likely to be highly threatened at Catfield in the next 10 – 20 years.

To preserve fen biodiversity it is essential to maintain landscape ecological processes, and for fens this requires: i. input from groundwater; or ii. flooding by clean river-water. Published research from work on the continent demonstrates the consequences of removing these processes: the fen will become isolated from the input of buffered water and will change to a system dependent on rainfall. It is likely that rainfall, by itself, will be insufficient to enable wetlands to persist in Norfolk (Herrera-Pantoja, et al. 2012), and hence continued groundwater flow to wetlands such as Catfield is essential for their survival.

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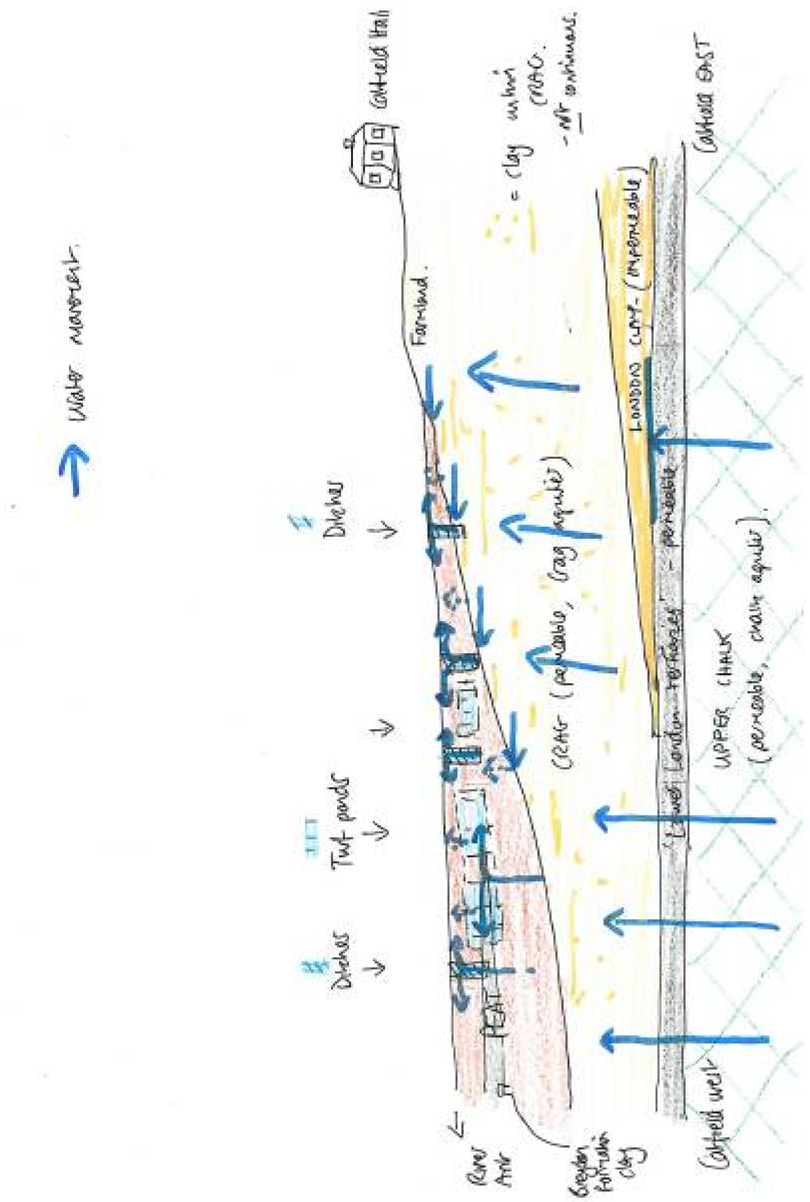

Figure 1: A conceptual representation of the hydrology of Catfield Fen (produced by Dr J. Parmenter).