Natural England Commissioned Report NECR238

An Investigation into the Management of Catch Dykes in The Broads

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

Catch dykes (at the break of slope between floodplain and upland) have been given little attention in studies of wetland hydrology.

They can play an important role in the transmission of nutrients, interrupt the hydroseral succession on the valley side, and impact groundwater supply to the valley sides and/or floodplain fens. This work has confirmed that catch dykes may have significant implications for the management of wetland sites nationally and internationally.

The intention is to use this work to implement restoration of valley side hydrology on sites impacted by catch dykes.

This contract reviewed the role of catch dykes, developed a decision-making process for addressing issues, categorised Broads' catch dykes, designed management options and developed a number of case studies to inform the theory.

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Natural England Project Manager - Adrian Gardiner, Lead Adviser

adrian.gardiner@naturalengland.org.uk

Contractor - Mike Harding, Associated Ecologist www.ohes.co.uk

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An Investigation into the Management of Catch Dykes in The Broads

by OHES on behalf of

Adrian Gardiner
Natural England
Norfolk Local Delivery Team
Natural England
Dragonfly House
Norwich
NR3 1UB

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OHES Environmental Ltd.

1 The Courtyard

Denmark Street

Wokingham

Berkshire

RG40 2AZ

www.ohes.co.uk

SUMMARY

Catch dykes are watercourses that often exist at the break of slope between the 'upland' and the floodplain. Other names include landspring dykes or interceptor drains. Their function is to pick up and remove surface and groundwater flows between the upland and floodplain.

The project aims to investigate the functional role of 'catch dykes' within the Broads with a view to identifying options for their future management, based on characteristics observable by desk research or fieldwork. The report is intended to be a briefing, an evidence base and a guide to studying, assessing and developing remedial actions for catch dyke managers. It contains a wealth of information that those involved in catch dykes can use in project investigation and planning. Around two-thirds of the report are the case studies and additional data in the Appendices.

The project touches on a wide range of disciplines; landscape history, geology and soils, hydrology and fen eco-hydrology, water quality and wetland ecology. These subjects are individually complex and their application to catch dykes especially so. The relevant literature is reviewed (Section 2) and scopes out the main issues which catch dykes raise. These can be broadly grouped as:

1. Change of groundwater quality experienced by floodplain wetlands.
2. Depletion of the wetland water balance.
3. Direct drawdown of the wetland water table.
4. Delivery of nutrients and other agrochemicals.
5. Generation of acid sulphate pollutants.

The degree to which these five issues are manifest in a wetland depends on entirely site-specific circumstances that require individual fieldwork and assessment. However, it is clear that many sites are likely to experience multiple issues. Some impacts may be severe and others quite subtle. The conclusions of the review section are borne out by the Case Studies. It is clear from the review that the importance of catch dykes has been underestimated.

It is difficult to demonstrate clear evidence of the above issues on a particular site in any but the most extreme case. Four reasons are suggested:

- Catch dykes have been in existence for a very long time. A wetland will have become adjusted to the prevailing conditions. It is difficult to hindcast the type and condition of the wetland prior to catch dyke creation.
- The issues are complex and interrelated. The overall impact may consequently be difficult to identify, let alone to separate out the individual impacts of specific issues.
- Site management may produce shifts in vegetation which modify impacts of catch dykes. Scrub encroachment on the margins (where catch dyke impacts are likely to be strongest) obscures potential vegetational changes.
- There is little effective monitoring that can pick up changes to key plant communities.

Without such evidence it may be difficult convince landowners and funders to take action.

Section 3 outlines a decision making process for catch dyke managers to assess impacts and to determine remedial measures. Three stages are then explained in more detail:

> **Stage 1: Desk and Field Research**. The information required is scoped.
>
> **Stage 2: Defining the Problem:** A range of tools are provided to assess the type of catch dykes, assess its risk and assess potential impact on WetMec type and ecological feature.
>
> **Stage 3: Developing Solutions**: a series of decision webs leading to possible remedial solutions are described.

A series of maps of Broadland catch dykes that border fens has been produced (Section 4 and Appendices 3-5). They describe the catch dyke type, the soil association it runs through and the Hydrology Of Soil Types (HOST) classification for the soil type. These all determine the potential of the catch dyke to cause problems for the wetland, and the kinds of solutions that might be appropriate.

Section 5 provides a summary of a wide variety of solutions that could be adopted in different contexts. They are the end-points of the decision webs developed in Section 3. A summary table assesses their pros and cons and the range of factors to consider when applying them. There are drawings for solutions where they require engineering.

Sections 6 and 7 provide an overview of New Environmental Land Management Scheme (NELMS), Defra CAP reform reports and the potential for funding engineered management solutions and the vegetation and land management solutions.

Seven case studies are presented. They are Upton Fen; Sutton High Fen with Catfield Fen; Mrs Myhill's Marsh and Catfield Dyke; Decoy Carr; Limpenhoe Meadows; Ebb and Flow Marshes; and Barnby Broad. They illustrate a number of issues and consider a wide range of management solutions. Most involve levelling and soils fieldwork although lack of upland landowner permission prevented this at Sutton/Catfield and Barnby Broad. The case studies confirmed the methodologies developed in the previous sections and underlined the need for individual site study and fieldwork. Some sites are heavily constrained by upland land use, the catch dyke often being important in maintaining field drainage. Others were less constrained, such that comprehensive remediation could be considered and the full wetland to dryland hydrosere restored. Where appropriate, potential remediation is suggested, including maps, but it is emphasised that in all cases further work and stakeholder discussions would be required.

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FIGURES AND TABLES

1. AIMS OF THE REPORT

The Brief issued by Natural England summarises the overall purpose of this work:

The project is to investigate the functional role of ‘catch dykes’ within the Broads with a view to identifying options for their future management based on their characteristics.

The report is intended to be a briefing, an evidence base and a guide to studying, assessing and developing remedial actions for catch dyke managers.

The Brief further breaks this down into five aims, around which the report is structured:

1. Investigate the role and function of catch dykes based on a summary of the available literature (Section 2);
2. Develop a decision process/ matrix for identifying management options for catch dykes, based on the characteristics of the dykes and the characteristics of the neighbouring land (Section 3);
3. Based on the decision process, identify the potential for taking forward different options throughout the Broads, including the identification of potential trial sites for the next two years (Section 4);
4. Identify potential methods for the retention/ removal/ part removal of catch dykes (Section 5);
5. Identify management options for the upland land, where catch dykes are removed/ part removed (Sections 6 and 7)

Following tender, these aims were supplemented by the use of case studies taken from the Broads which test “in the field” the various conclusions and recommendations made above.

2. THE PURPOSE AND FUNCTION OF CATCH DYKES: A REVIEW

2.1 What is a Catch Dyke?

Catch dykes (alternatively known as landspring dykes, catchwater drains or less commonly interceptor drains) have no formal definition, but their function is summarised in these names. They are usually at the break of slope between the flat floodplain and the rising “highland”, and their purpose is to intercept run-off from the higher ground and to pick up the line of shallow groundwater input to the valley bottom. Their intention is to improve drainage of the lower slope of the upland and of the flat floodplain land.

The intercepted water may be discharged directly to a larger drainage channel at a lower level, by passing the floodplain. More commonly, the catch dyke is connected to the floodplain dyke network, whether it be a grazing marsh or fen system. On grazing marshes in the Broads, the dyke system tends to be drained directly by pumps, whereas in fens it is not. There are many exceptions to this pattern, especially where small areas of fen are incorporated in drained marshes, usually in sumpy hollows or along the highland margins. Where a system is pumped, the catch dyke can be very effective at lowering groundwater and intercepting surface water inputs. Where the system is gravity drained, with base level determined by the river, the drainage function is weaker and the catch dyke water is often recirculated on the floodplain. Some fen catch dykes can discharge to surrounding, lower level grazing marsh dykes in what is a hybrid system, as at Upton Fen on the Bure, but there is usually some kind of sluice in place to prevent catastrophic drainage of the higher level fen.

The context of catch dykes is therefore highly variable across Broadland, and the hydrological functioning often complex. However, the defining characteristics remain its position at the break of slope (or thereabouts) and its function of collecting and redistributing valley margin surface and groundwater. It is only these characteristics which separate it from other kinds of dykes, and make them of particular importance in terms of the eco-hydrology of the Broads valleys.

Catch dykes can be small or large features. Most in the Broads are “standard” dyke size, but where they are integral to regional arterial drainage they can be much larger watercourses with consequently greater impacts. Perhaps the longest recorded catch dyke in England is the Car Dyke on the western margin of the Fen Basin which stretches 140km between Cambridge and Lincoln (Rackham 1986). Very large catch dykes include the Military Canal along the northern margin of the Romney Marsh (Cook 1999) and the Cut-Off Channel which passes along the eastern margin of the Fen Basin. The latter was dug in response to the 1953 floods and can intercept flows from the Little Ouse, Lark and Wissey Rivers, discharging to the Great Ouse at Denver (Godwin 1978). This catch dyke is connected to the chalk below and has been implicated in reducing groundwater and drawing down seepage flows in Breck edge fens such as Lakenheath Poors Fens (ELP 2008) and Pashford Poors Fens (ELP 2009). Catch dykes can, then, be very significant agents for regional water resource management.

Catch dykes were sometimes used for irrigation. The best documented examples are catchwork meadows, an uncommon form of water meadows. Cutting and Cummings (1999) summarise them:

“Catchwork irrigation systems were employed from at least the early seventeenth century on valley sides where streams or spring waters could be diverted into a flood dyke (*catch dyke*) running along the contours. This would overflow, the water flowing into further channels, and ultimately returning into a tail drain or directly to the parent stream”.

However, such systems were characteristically on steeper gradients than typical of the Norfolk Broads, with examples described by Cutting and Cummings (1999) in Nottinghamshire and Exmoor. Wade Martins and Williamson (1999) note that water meadows of any sort were very rare in the east of England, and rarely managed on similar principles. They were used to irrigate for hay crops rather than the traditional West Country practise of encouraging an early spring bite. In Norfolk, water meadows were a later, nineteenth century development – including one entire catchwork system at Mileham and one with a catchwork element at Castle Acre. Water meadows of any sort were still a small-scale and minor development, largely centred around tenant farms of the Holkham Estate. Wade-Martins and Williams (1999) suggest that the lack of development of irrigated meadows is due to the much more subdued topography here compared to the West Country, making such systems impractical and uneconomic. Even so, it is likely that in the Broads, similar principles were used to capture and redistribute upland water around the floodplain, perhaps promoting mowable fen crops. The map of dykes in the catchwork water meadow at Clipstone Park, reproduced in Cutting and Cummings (1999) looks much like any map of Broadland marshes.

2.2 Historical Context

There appears to have been no specific study of the history and development of catch dykes *per se*, only the history of drainage schemes of which they may have been a part. See Cook and Williamson (1999) for reviews of wetland drainage in Romano-British, medieval, post medieval and more modern eras, or regional studies such as Godwin’s (1978) account of the Cambridgeshire fens or the accounts of the Broads in George (1992) and Williamson (1997). The following draws on these and other sources.

We should not assume that catch dykes are a recent innovation – they may have been affecting valley margin wetlands for centuries. Wholesale reclamation of wetland areas is known from at least Romano-British times, with evidence for schemes from these areas being described in detail for the Cambridgeshire fenland, the Somerset Levels and the Gwent Levels by Rippon (1999). Neither should we assume such ancient engineering would have been on a small scale - the Car Dyke referred to above is thought to have been a Roman creation from the times the silt fens were first reclaimed (Cook and Moorby 1993). Catch dykes were part of the range of drainage techniques readily available to land managers by medieval times. The only piece of technology lacked by then were pumps (Taylor 1999) which may have first arrived from Holland at the start of the fifteenth century. Wetland reclamation for arable use (often thought to be the last phase of wetland reclamation) is also an age-old practise, with Silvester (1999) recording the conversion of Norfolk Marshland to grow cereals in mid-Saxon times.

The design and subsequent management of catch dykes would have been affected by four groups of historical processes:

1. **Semi-natural changes in ground water levels and surface flows** at the upland margin, associated with changes in climate and changing sea levels. Their function would have been most critical when water tables were at their highest. Evidence suggests that in the Broads the valley margins and the headwaters were much wetter in the nineteenth century, for instance.
2. **Changing land use on the upland margin**. Hydrological processes (both generation of flows and water quality) would have been strongly affected by at least three factors:

- Wholesale alteration of the principle land use from semi-natural habitats to arable, intensive livestock, or development, for instance.
- The particular agricultural practise used, including crops grown, rotations, ploughing practises and fallowing, stocking densities, management of the catch dyke margins.
- Land drainage practises including surface grips and under-drainage.

Agricultural improvements which increase discharges to catch dykes may often be older than commonly thought. Field under-drainage is one example (Cook and Williamson 1999), with schemes already widespread and large in size in the eighteenth century. Bush drains - shallow trenches backfilled with faggots of brushwood, straw and then soil – date from 1649 (Williamson 1999). Because of its expense it was used mostly on arable land, but it could be "thorough" i.e. networks in fields ensured comprehensive drainage. It is thought it was first used for thorough drainage in Essex and then spread to Suffolk and Norfolk. With progressive improvement in technology, land drainage was made more and more effective.

Williamson (2014) has recently shown for the headwaters of the Little Ouse river how changing catchment practises including land drainage significantly increased discharge of water to the floodplain, requiring the first setting up of a formal drainage authority in the area in 1880. The intensity and efficiency of land drainage correlates with agricultural profitability, decreasing markedly in depressions. Phillips (1999) records the availability of substantial Government loans for land drainage, peaking between 1850 and 1875 – note the correlation of dates with William's findings in the Little Ouse. Phillips (1999) states "By the late 1840's underdrainage had emerged as the outstanding agricultural improvement of the day".

As Norfolk was known to be a centre for land drainage improvements, these historical processes are likely to have been significant factors around the margins of Broadland which were even then important cropping areas. Much of the slope above valleys is Grade 1 arable land. Under-drainage would only work effectively if the receiving water course – the catch dyke – worked effectively with a significant freeboard.

3. **Changing floodplain management practises.** Management as turbary, litter crops, grazing land, sedge crops and reed crops may all have required varying hydrological management to maximise profit from the enterprise. Management of any particular fen compartment may vary over time, as for instance, turbaries terrestrialise and are taken into fen crop management. The degree to which catch dykes played an active part in facilitating such changes most likely varied from site to site and also according to the hydrological skills of the site managers.

4. **Changing context of artificial land drainage.** Land use change in the Broads is frequently driven by the evolution of comprehensive land drainage (George 1992, Williamson 1997). Progress of land drainage has been technology-led (Cook and Moorby 1993). Large scale schemes started with the major Dutch inspired or designed drainage schemes of the mid-seventeenth centuries which involved integrated drainage channel networks linked with pumps, which were at first wind-driven. These often small units were gradually amalgamated as wind pump technology improved with steam, diesel and then electric pumps, progressively providing greater pumping power. This, more than any process, facilitated land use change on a comprehensive scale, including for the first time in many places, extensive arable cultivation spreading from the upland to the floodplain. Especially after WWII, agricultural intensification linked such comprehensive schemes with comprehensive in-field drainage and wholesale changes to land use and farm management practises. The drained marshland bore the brunt of the impacts but schemes were not restricted to mineral soils.

Cook and Moorby (1993) recognised three types of wetland based on the degree of drainage:

- Primary wetlands, largely undrained, represented in Broadland by in-tact fenland. These areas can include catch dykes, but they are modest in effect and they do not provide for major land scale change.
- Secondary wetlands, subject to significant, usually pumped, drainage but where high water tables are typical and integral to the farming systems. These can still be of high conservation interest but are typically wet pastoral systems represented in the Broads by grazing marsh.
- Tertiary wetland, comprehensively drained where control of water levels is near-absolute and the landscape is akin to polders. Their management is highly intensive and usually arable.

Secondary and tertiary phase wetlands may be very old – the Halvergate Marshes are thought to have been reclaimed between the thirteenth and seventeenth centuries (George 1992) while areas of Romney Marshes were arable in the early medieval – 11th-13th century.

These four groups of historical processes do not act in isolation. At any particular site, some or all may co-vary in a bewilderingly complex way, sometimes one process cancelling or mitigating the impact of another, sometimes reinforcing each other. Consequently, the function and the usefulness of a particular catch dyke is likely to alter significantly over time, perhaps changing from a vital function to dereliction and back again. In particular, the cycle of agricultural prosperity and depression can cause rapid reclamation or abandonment of wetlands (Phillips 1999). The great depression of 1870-1939 caused the abandonment and reversion of much former wetland (Taylor 1999), a process that would not have left the Broads untouched.

Understanding this historical complexity on a site by site basis would require painstaking and detailed historical study. The experience of Williamson (2014) is that many of the processes referred to above are not frequently documented, a point emphasised by Silvester (1999), and the detailed history is therefore largely lost[1]. The Broads seems relatively little studied in this respect. Most of

[1] Although some of the larger historical estates and village charities may have retained more information in their archives.

the studies of early land drainage concentrate on the coastal wetlands and Cambridgeshire fens (see the series of historical studies in Cook and Williamson 1999).

The above historical context provides two important conclusions:

1. Next to the rivers and arterial drains, catch dykes are the most important watercourses in the floodplain in terms of driving land use change. Their location at the break of slope, picking up springs, groundwater and run-off, and their critical role in enabling efficient under-drainage of the shallow arable slopes, can determine whether land can be converted to arable or not. Their integration into pumped schemes allows fens to be drained and for intensive land management to spread across the floodplain.
2. Catch dykes, and their impacts on the adjacent wetlands, are likely to be very old. The issues they raise are not recent. However, the more recent intensification of wetland drainage and the increasing nutrient loadings applied to the catchment will have greatly increased the severity of impact of catch dykes.

2.3 Hydrology of Catch Dykes

2.3.1 Available Information

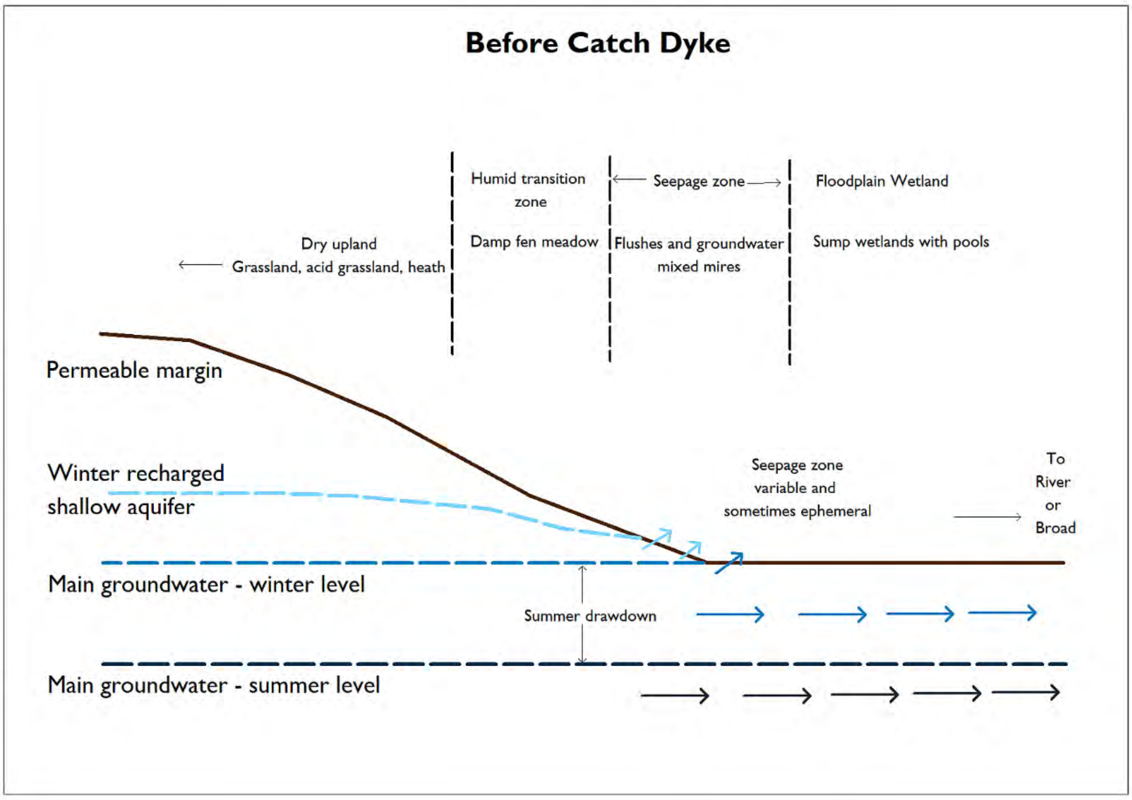
We could find no research published specifically on the hydrology of catch dykes. The impact of land drainage schemes (which incorporate catch dykes) on groundwater flows has been described by Wassen et al (1990) and recently by van Loon et al (2009) who both provide a range of examples particularly from the Dutch literature. Johansen (2011) recently reviewed some of the literature on abstraction (which can have similar impacts to catch dykes in permeable areas) and Wheeler et al (2009) provide perhaps the best general reader in fen eco-hydrology currently available. However, none of these sources discuss catch dykes specifically.

It is possible that specific pieces of casework have involved research on particular catch dykes, but we did not locate any such documents. We consulted most of the land managers and conservation staff in the Broads area but this was not productive. The following extracts what is relevant from the sources available.

2.3.2 Water Quantity and Water Flows

Impact of Catch Dykes in Permeable Soils and Shallow Geology

In terms of water flows, the generalised hydrological impact of catch drains is summarised in Figure 1, before and after cutting of the drain. The diagram pertains to locations where groundwater flow is likely to be significant, for instance from shallow aquifers of permeable soils and geological strata. Fieldwork for the case studies showed this to be the most common situation in the Broads.



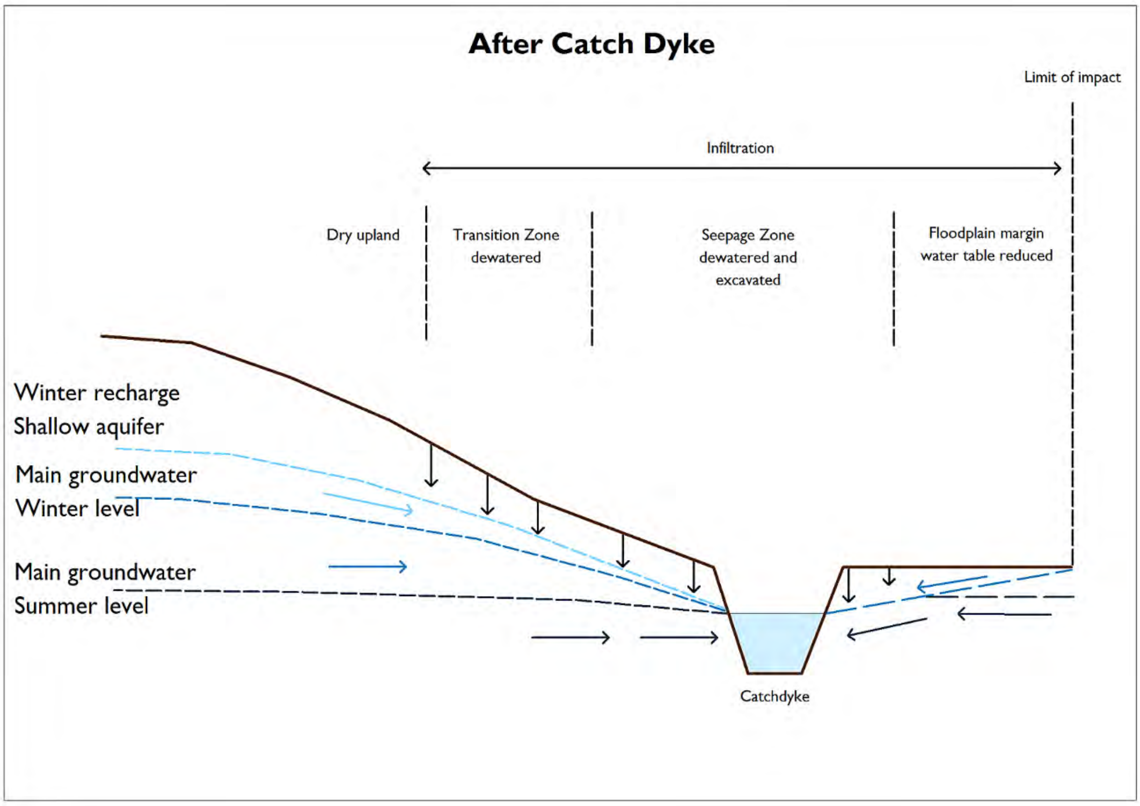


Figure 1: Impact of a Catch Dyke in Relatively Permeable Geology and Soils. Assumed moderate to low dyke water level

Van Loon (2010) has proposed two main mechanisms for groundwater flow to the margins of floodplains (Figure 2). The Exfiltration Model occurs where a significant volume of groundwater flows out on a regional scale as a result of artesian movement across a broad front. It generally involves surface discharge ("exfiltration") of groundwater. The Throughflow Model assumes intense or localised groundwater outflow from the aquifer towards the highland/floodplain margin, causing a surplus of groundwater in the shallow sub-surface. This is mostly discharged laterally through loose valley peats. Any surface discharge is spatially extremely restricted. The general absence of extensive groundwater and seepage fens in the Broads floodplain suggests Exfiltration sites are likely to be restricted to headwater valley fens. The Throughflow model is more likely to be characteristic of Broadland.

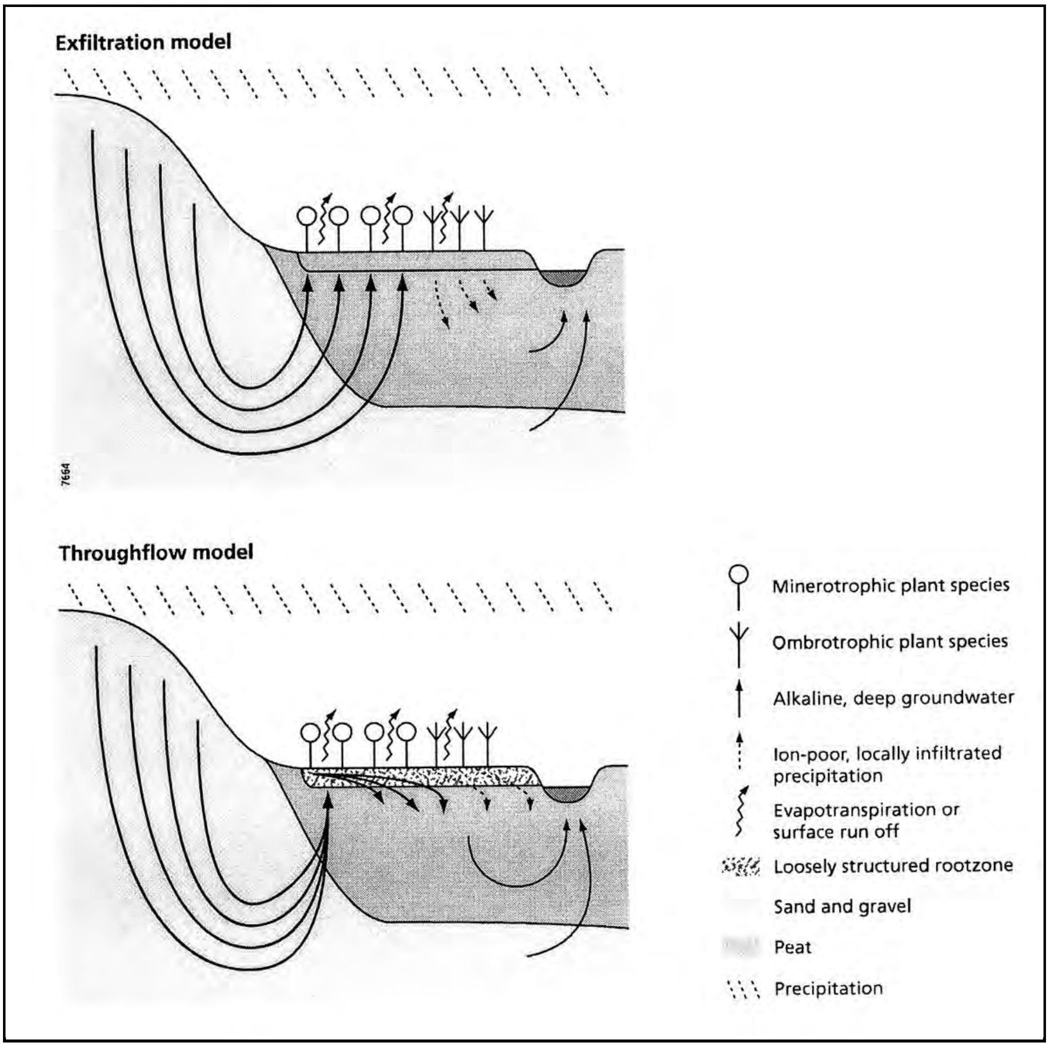


Figure 2: Exfiltration and Throughflow Models of Valley Marginal Hydrology.
Taken from van Loon (2010).

The Throughflow Model also explains how shallow peat cuttings towards the upland margin could be fed by groundwater, supporting stable water tables and providing the water quality they require (Giller and Wheeler 1986, Wheeler 1978). In both Exfiltration and Throughflow systems, catch dykes are likely to be dug along the valley margin where groundwater movement is occurring. They can therefore intercept the flow, although the proportion of flow intercepted is dependent on the exact pathways of the groundwater. If the ditch is mis-placed (perhaps behind the line of strongest groundwater upwelling) or is not dug deep enough, some groundwater flows could at least partially by-pass the ditch. George (1992) records that in reclaiming grazing marsh, a Landspring Dyke was always used to intercept the principle springs in the floodplain, but that some sites "..defied all attempts to drain them". Presumably groundwater continued to move under the Landspring Dyke to the floodplain via deeper aquifers. Such intractable areas were often left as fens – a type example being Upton on the Bure, which also appears to be a classic Throughflow site.

The Exfiltration/Throughflow split in ecohydrological functioning is fundamental to understanding the array of detailed mechanisms which operate in particular wetlands. This broad split is one of the fundamental divisions in Wheeler et al's (2009) detailed typology of wetland mechanisms described below.

A detailed field hydrological study by van Loon et al (2009) provides an example of how drainage can affect a Throughflow wetland. They compared an area of drained fen (which included catch dykes) near to the floodplain edge with an area of undrained fen which lay downslope, and along a nearby lake margin. The relationship was much like a Broads valley transect, but the two sites were disconnected by other land between them. The research showed that surface ditches in the drained fen directly dewatered the lake side fen and also intercepted groundwater destined for the fen. Interception further depleted the water balance of the undrained fen and may also affect hydrochemistry. It created an infiltration zone in the latter, rather than a receiving site for groundwater throughflow. The drained wetland was clearly located on the discharge zone of a once extensive Throughflow wetland (Figure 2).

Van Loon et al (2009) used this example to suggest that drainage schemes could in this way be a significant cause of the fragmentation and degradation of fen systems. By depleting groundwater inputs, catch dyke systems operate in a similar way to the dewatering caused by groundwater abstraction (e.g. Fojt and Harding 1995).

The degree of groundwater lowering and capture is therefore determined by the freeboard, the bed depth of the catch dyke, and its flow. The latter determines the rate of removal of groundwater from the system. Significant freeboard directly drains adjacent fen areas, the extent of impact depending on the dyke water level and the permeability of the fen substrate.

Impact of Catch Dykes in Impermeable Soils and Geology

Where soils and shallow geology are impermeable, the groundwater component is reduced or removed and surface water flow becomes the dominant water pathway. Overland or near surface flows are more rapid and higher in volume, as water does not percolate downwards to temporary groundwater stores. In these situations, water levels in the catch dyke and the floodplain is likely to be much more responsive to rainfall events so that the system is more "flashy". Because of the lack of storage in these systems and the higher energy in the water movement, more materials are transported from the highland. Because water is moving quickly, silt and particulates will be more significant than on more permeable substrates.

Impermeable soils are rare in the Broads catchments, most being at least slowly permeable, even on the interfluves. They are more frequent in the Waveney and parts of the Yare where the chalky boulder clay drift forms the main soil parent material. Certain land uses reduce permeability, as do certain farm practises. Under-drainage greatly increases the speed and volume of run-off and therefore the flashiness of a ditch. At Upton Fen, rapid overland flow and rapid discharge of land drains, both carrying eutrophic water, required construction of an entirely new catch dyke, specifically to intercept run-off. This took place in a permeable catchment. Upton Fen is one of the project Case Studies.

Impact of Catch Dykes With High Water Levels on Wetland Water Balance

Note that even if sluices maintain a minimal freeboard, if there is a significant draw in the catch dyke toward a base drainage level, the dyke will still intercept ground and surface water from the upland. Such inputs will be drawn off to the drain outlet, rather than discharging to the wetland. Carrying away these volumes could affect the water balance of at least the most proximate fen communities. Although the high water level in the dyke prevents direct drainage of the adjacent fen, its water table will still be drawn down more severely by evapotranspiration, and less buffered by dry periods, as there is no recharge from groundwater.

With a catch dyke in place, the upland can *only* contribute to the floodplain if (a) the wetland boundary of the dyke is at least semi-permeable, allowing some water to permeate into the wetland (b) there is significant head gradient from the highland to the floodplain which "pushes" the water across the dyke and into the wetland (c) there is no draw of water down the dyke which effectively neutralises the head described in (b) and (d) some groundwater is able to by-pass the drain as described above. In practise, once a catch dyke is in place, and there is flow on the dyke, it is likely that only by-passing the dyke is likely to offer significant recharge to the wetland. Consequently, sluicing a catch dyke will not ensure passage of groundwater, it will only stop direct drainage of adjacent wetland. Figure 3 illustrates this.

Note that once a catch dyke has been dug and become established, it might always form a groundwater flowline, especially if there is a significant down-valley gradient. In-filling the dyke, so that the pre-existing groundwater flows are entirely reinstated, requires removal of the dyke boundaries (which will have become blinded by silt), ensuring the fill has the same permeability as parent sub-soils and the installation of impermeable barriers within the fill material which prevent down-valley flow.

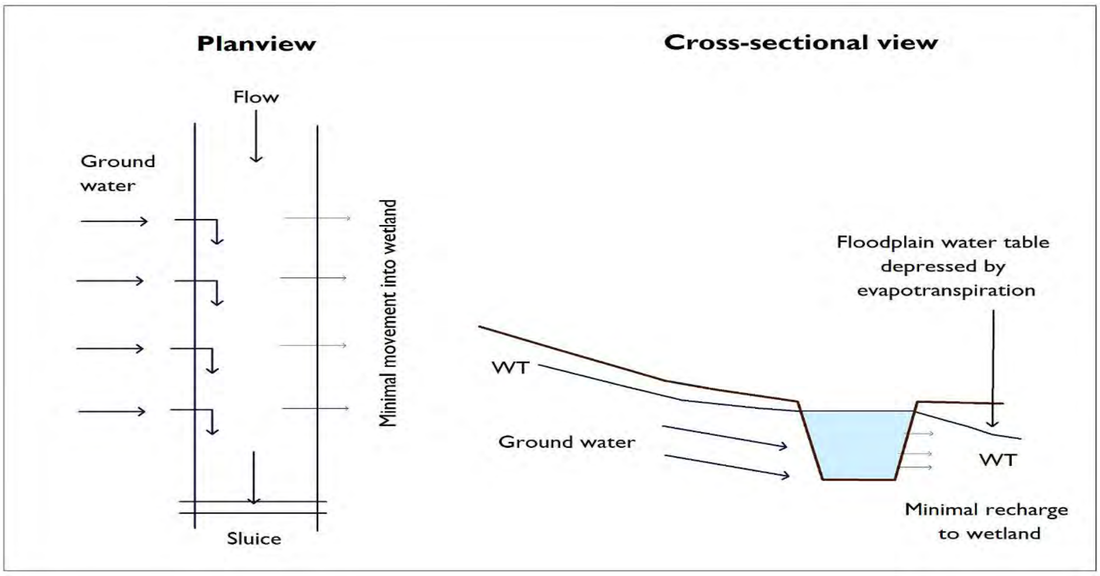


Figure 3: Impact of Catch Dyke on Groundwater Recharge of Floodplain Wetlands.

The Role of Groundwater Modelling In Understanding Impacts

Groundwater modelling has been used effectively to study impacts of dykes and drainage schemes – see for example Johansen et al (2009), and van Loon et al (2009), who cites other examples. However, note that both studies found it necessary to use a horizontal model resolution of 5m x 5m to obtain effective results. This level of detail is largely unheard of in the Broads and the UK in general. Regional models will not be useful in studying fen sites in enough detail for either impact assessment or designing remedial measures.

The Role of WetMecs in Understanding The Influence of Catch Dykes

Evaluating the impact of a catch dyke on a fen or wetland feature depends on a good hydrological understanding of the catch dyke, but also a good understanding of how that wetland feature functions hydrologically and ecologically. The simple models presented above provide a good generalist framework, but site specific work requires a more detailed approach.

The best system to describe wetland functioning developed so far is the WetMec system (short for Wetland Mechanism) developed by Wheeler et al (2009). Each WetMec describes an assemblage of hydrological characteristics that determine functioning, and this is usually linked to a characteristic ecology. WetMecs can be applied at a variety of scales, from small wetland patches to whole systems, recognising that a wetland system may be composed of more than one WetMec type. Crucially, wetland sites are not viewed as a single type (such as Catfield Fen is a floodplain fen, or Smallborough Fen is a groundwater fed valley fen), but are understood as inter-linked hydrologies functioning together, often affecting each other.

Wheeler et al (2009) identified 20 WetMecs, and provides detailed hydrological and ecological information for each. In Broadland, the most common types are WetMecs 5-9.

They are either surface water fed fens (5 and 6) or groundwater fed (7-9) with larger sites containing perhaps both. Rarely, groundwater flow to the wetland may be strong enough to express water at the surface where Exfiltration conditions (Van Loon 2010) exist as seepages. Seepage wetlands in the Broads are mostly WetMec groups 10, 11 and 13, but are mostly uncommon, small in extent or degraded - often converted to WetMecs 7-9 by drainage, often involving catch dykes. The complete list of WetMecs follows.

WetMec Group: Ombrogenous Bogs And Related Mires

The first two WetMecs are currently absent from the Broads. WetMecs 3 and 4 exist in fens with surfaces fed by rainfall, although water from the catchment may be important in providing a water table which supports the Ombrotrophic surface – acting in effect as an aquiclude.

1. **Domed Ombrogenous Surfaces (‘raised bog’)**
2. **Buoyant Ombrogenous Surfaces (quag bogs)**
   - 2a: Ombrogenous Quag
   - 2b: Ombrogenous Quag (Ground Water-Fed Basin)
   - 2c: Ombrogenous Quag (Surface Water-Fed Basin)
3. **Buoyant, Weakly Minerotrophic Surfaces (‘transition bogs’)**
   - 3a: Bog-Transition Quag (± closed basin)
   - 3b: Bog-Transition Quag (± open basin)
4. **Drained Ombrotrophic Surfaces (in bogs and fens);**
   - 4a: Drained Ombrogenous Bog
   - 4b: Drained Ombrotrophic Fen

WetMec Group: Surface Water-Fed Floodplains

5. **Summer-Dry Floodplains**
   - 5a: Rarely Flooded Floodplain
   - 5b: Alluvial Floodplain
   - 5c: Winter-Flooded Floodplain
   - 5d: Floodplain Sump
6. **Surface Water Percolation Floodplains**
   - 6a: Solid Surface Water Percolation Surface
   - 6b: Grounded Surface Water Percolation Quag
   - 6c: Surface Water Percolation ‘Boils’
   - 6d: Swamped Surface Water Percolation Surface
   - 6e: Wet Surface Water Percolation Quag
   - 6f: Surface Water Percolation Water Fringe

WetMec Group: Groundwater Floodplains (Poorly Defined)

7. **Groundwater Floodplains**
   - 7a: Groundwater-Fed River Fringe
   - 7b: Groundwater Floodplain
   - 7c: Groundwater Floodplain on Aquitard

WetMec Group: Groundwater-Fed Bottoms

8. **Groundwater-Fed Bottoms with Aquitard**
   - 8a: Groundwater Percolation Bottom
   - 8b: Groundwater-Distributed Bottom
9. **Groundwater-Fed Bottoms**
   - 9a: Wet Groundwater Bottom
   - 9b: Part-Drained Groundwater Bottom

WETMEC Macro-Group: GROUNDWATER-FED SURFACES

This assemblage of wetland types includes WetMecs 10-17. They are mostly relic features in the Broads, potentially converted to other WetMec types through drainage and land use change, although some extant examples have been identified.

WetMec Group: Seepage Slopes

10. Permanent Seepage Slopes

- 10a: Localised Strong Seepage
- 10b: Diffuse Seepage

11. Intermittent and Part-Drained Seepages

- 11a: Permeable Partial Seepage
- 11b: Slowly Permeable Partial Seepage

WetMec Group: Seepage Basins And Bottoms

12. Fluctuating Seepage Basins

- 12a: Fluctuating Seepage Basins with permanent standing water
- 12b: Fluctuating Seepage Basins with winter standing water, summer water table sub-surface or near surface
- 12c: Fluctuating Seepage Basins with shallow winter standing water, summer water table sub-surface or near surface
- 12d: Fluctuating Seepage Basins, winter ‘wet’, summer ‘dry’
- 12e: Fluctuating Seepage Basins with winter standing water, ‘dry’ by early summer

13. Seepage Percolation Basins;

- 13a: Seepage Percolation Surface
- 13b: Seepage Percolation Quag
- 13c: Seepage Percolation Water Fringe
- 13d: Distributed Seepage Percolation Surface

14. Seepage Percolation Troughs

15. Seepage Flow Tracks

- 15a: Topogenous Seepage Flow Tracks
- 15b: Sloping Seepage Flow Tracks

WetMec Group: Groundwater-Flushed Bottoms

16. Groundwater-Flushed Bottoms

- 16a: Groundwater-Flushed Bottom
- 16b: Groundwater-Flushed Bottom + watercourse inputs
- 16c: Groundwater-Overflow Bottom

WetMec Group: Groundwater-Flushed Slopes

17. Groundwater-Flushed Slopes

- 17a: Groundwater-Flushed Slopes
- 17b: Weakly Groundwater-Flushed Slopes
- 17c: Distributed Groundwater-Flushed Slopes
- 17d: Groundwater-Flushed Flow Tracks

WetMec Group: Troughs, Basins And Bottoms With Limited Or Indeterminate Groundwater Supply (Or None)

NB: These are analogues of the groundwater-fed WETMECs 14, 15 and 13 (respectively), and differ from these primarily in groundwater supply being apparently much less important, or absent, or in some cases not known. Wheeler et al (2009) record that all are mainly recorded in NW England and Wales. Their occurrence in the Broads is unlikely but not impossible.

18. Percolation Troughs
19. Flow Tracks
20. Percolation Basins
20a: Percolation Quag
20b: Percolation Water Fringe

Wheeler et al (2009) emphasise that field definition of WetMecs can be difficult due to their inter-grading and overlapping nature and the close association of different WetMecs within the same wetland area. Some have tried to map WetMec types (OHES 2013) but this is fraught with difficulty as hydrology does not operate to hard boundaries unless they are major dykes, rivers or similar. Many have topographical relationships – for instance Permanent Seepage Slopes (WetMec 10) lie upslope of Groundwater Flushed Slopes (WetMec 17), whereby groundwater discharging from the seepage slope flushes laterally through the permeable lower substrate because a shallow aquitard (such as a clay base) prevents downward percolation. Wheeler *et al* note that some WetMecs need further definition – of particular relevance to the Broads is the poor separation of Groundwater Floodplains (WetMec 7) and Groundwater Fed Bottoms (WetMecs 8 and 9).

WetMecs 8 and 9, Groundwater-Fed Bottoms (Throughflow wetlands in the sense of Van Loon 2010) are especially relevant to this study as (a) they are the most common type in permeable catchments, which is most of central and northern Broadland and (b) catch dykes are likely to intercept upland shallow groundwater flowing into the wetland. Wheeler et al (2009) comment for WetMec 9 "Many examples are now drier than was once the case, because of over-deepening of watercourses or a lowering of groundwater levels in the connected mineral aquifer." WetMec 9 is split according to impacted and non-impacted forms (9a and 9b).

An important distinction is made by Wheeler et al (2009) between WetMecs 8 and 9 (Groundwater-Fed Bottoms) and WetMecs 10-17 (Groundwater-Fed Surfaces). In the former, lateral groundwater enters the wetland but largely remains sub-surface (Throughflow wetlands). It contributes to the water balance and to the soil water chemistry but does not create surface seepage. In WetMecs 10-17, upward pressure and/or topography promotes surface expression of groundwater, even if sporadically, or seasonally, allowing the development of true seepage mires (Exfiltration wetlands). In Broadland, WetMecs 8 and 9 are the most common form of groundwater driven wetland; true Groundwater Fed Surfaces are rare, with Seepage Slopes (WetMecs 10 and 11) rare or absent. It is likely that many of the base-rich and very diverse former turf ponds are WetMec 12 Fluctuating Seepage Basins. This

WetMec may have been "engineered" by the excavation of the pit within a Groundwater Fed Bottom (WetMec 8 or 9). Infill of the pit through terrestrialisation may threaten long-term sustainability of the feature. Examples of WetMec 13 Seepage Percolation Basins have been documented (e.g. 13c and 13d at Upton Fen, Wheeler et al 2009,13b and 13c at Mrs Myhills Marsh, Hickling, OHES 2013) but remain uncommon in the Broads.

A conclusion of the case studies, and of a review of Wheeler et al's WetMecs, is that groundwater as an eco-hydrological component of Broads floodplains has long been underestimated. The Broads fens are commonly characterised as driven by their topographical relationship with river and river flooding, but discharge to the floodplain margins of groundwater may be very significant. This is likely to be especially so prior to surface water drainage schemes, especially those including catch dykes.

Another kind of fen under-appreciated in the Broads is the ombrotrophic fen surface, fed largely by rainwater (WetMecs 3 and 4). There are no raised bogs in Broadland, but there are very many parts of floodplain and valley margin fens which are not sustained by catchment water. A surface may be raised above the catchment water table through drainage (lowering of the groundwater table) or through the autogenic growth of the fen surface. Autogenic growth may be through peat accumulation or through the growth of hummock vegetation often associated with bog mosses. A third example of isolation would be low permeability peats in areas not regularly flooded by rivers. They are not surface water fed but the humified, often uncut peat, prevents lateral movement of groundwater. These conditions can develop in the interior of fen compartments, where plant communities then depend on winter recharge and summer rainfall.

Many ombrotrophic surfaces can be summer dry because evapotranspiration exceeds rainfall, or because of direct effects of drainage. They are then associated with plant communities typical of dry substrates, often of lower interest for conservation. Some surfaces can be very wet, partly because they overlie a high catchment water table acting as an aquitard, and partly because of the ability of *Sphagnum* or a spongy surface peat to retain rainfall. These wetter examples can give rise to communities of high conservation value, often sphagnacious, perhaps including *Dryopteris cristata* fen.

The so called "mixed fens" where acid communities are mosaiced or intermixed with calcareous communities are of particular ecological and hydrological interest. They occur where base rich groundwater tables (sometimes including seepages) are overlain, often as patches, by ombrotrophic communities which have raised themselves above the base rich water table. The processes of initiation have not been unpicked, but it is possible that some ground surface variation (which could simply be vegetation tussocks) may be required to seed the ombrotrophic conditions. The community is rare in Broadland but there are examples in the Case Studies from Catfield Fen, Upton Fen, Limpenhoe Meadows and Barnby Broad. They are hydrologically sensitive because small drainage works, lowering the underlying water table, can drain the ombrotrophic surface. It is possible then for WetMecs to be vertically layered in some circumstances, as well as spatially variable.

2.3.3 Water Quality

No specific studies of water quality in catch dykes were found. We can infer from the wider literature that catch dykes can affect water quality in a number of ways.

Impact of Catch Dykes on Different Types of Groundwater

Catch dykes will intercept shallow groundwater (see Figure 1) and therefore the chemical contribution such groundwater makes to floodplain wetlands. The most significant impacts are where upland seepage is markedly calcareous or acid.

In situations where calcareous aquifers formerly discharged to the wetland, interception by catch dykes could cause a significant shift in bases and pH as floodplain water tables become dominated by rain and perhaps river water where it is not isolated, both being nearer to neutral in composition. For example, Van Loon et al (2009) demonstrated that ditch drainage causes upward groundwater movement to be replaced by downward rainwater infiltration. A regime of mineral replenishment to the rooting zone is replaced by downward leaching and depletion. This has been recorded in studies of groundwater abstraction (Harding 1993, Fojt and Harding 1995). Van Loon et al (2009) demonstrated how lenses of base poor water can form in peats over base rich groundwaters (Figure 4). In addition, soil water in such situations is more static with less flux, reducing redox, which is also deleterious to some important plant communities. Overall, the change in water chemistry could have significant impacts on fen vegetation. A system previously characterised by plant communities of calcareous water moving through the subsoil, can become characterised by those typical of base-poor water infiltrating downward and then becoming immobile.

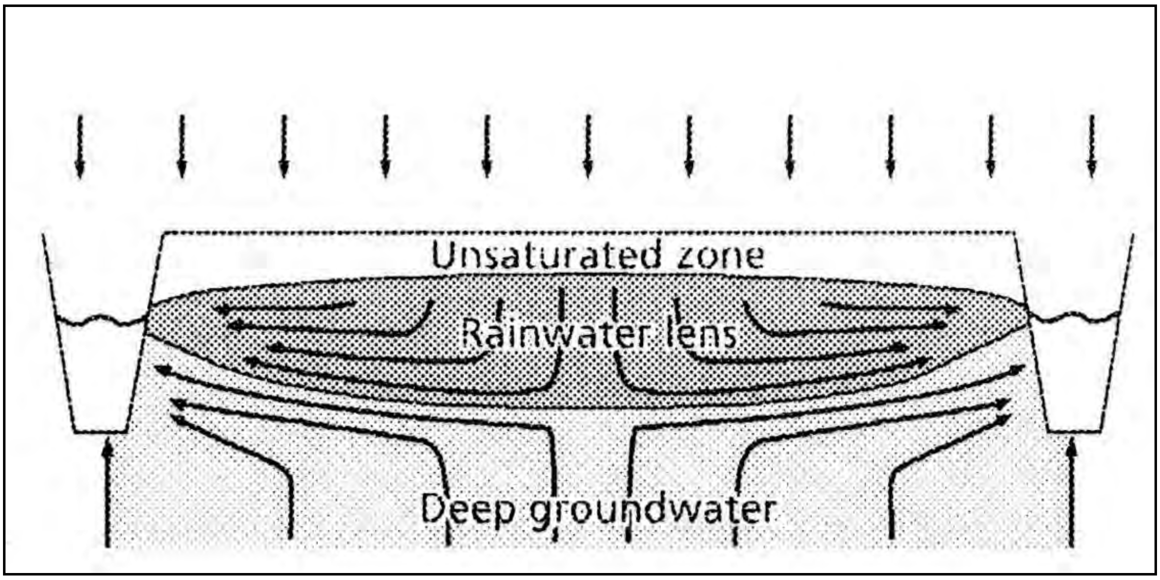


Figure 4: Creation Of Rainwater Lenses Over Groundwater Tables.
Taken from Van Loon et al (2009).

Rarely, catch dykes may be especially significant where they intercept near-surface, acidic groundwater being released by decalcified sands. Such shallow sand aquifers can generate base-poor surface flushes giving rise to acid (and even *Sphagnum*-based) mires. In some locations, especially in headwaters, where sands overly chalk or other calcareous substrates, acid flushes can overlie a calcareous base conditions giving rise to so called "mixed mires". Such features are hydrologically very fragile (Harding 1993), as (1) the volume of such discharges is very small because the contributing acid aquifer is shallow (2) the acid discharge can be seasonal and short lived because it depends on discharge of low volume winter storage of rainfall and (3) mixed mires depend on a delicate balance of emission from shallow base-poor and deeper calcareous aquifers. The system is therefore very easily disrupted, as shown in the before and after diagrams in Figure 1.

Where shallow groundwaters drain near-neutral substrates, the impact of a catch dyke is likely to be much less, as the groundwater is closer to that of the balancing sources.

Catch Dykes, Harmful Chemicals and Nutrients

The role of catch dykes in routing of harmful chemicals can be complex. Damaging elements include particulates and dissolved macro-nutrients, especially N, K and P. Agrochemicals and applications of manures on land upslope of catch dykes are at risk of entering wetlands which are often dependent on maintenance of low nutrient soils. Release of toxins to the environment is also a major problem in the Broads when acid sulphate soils have been drained. Acid sulphate substrates (which can be peat or mineral sediments) are surprisingly widespread with notable concentrations in the Thurne, Ant, mid-Yare and mid-Waveney. They are found mostly in coastal, deltaic and estuarine sediments. Sulphates in sea water and iron in sediments combine to form Pyrite (FeS_2). The process takes place in waterlogged and reducing conditions, in the presence of bacteria and organic matter. It is reversed by drainage, when oxidation takes places, causing extreme acidity and release of toxic iron and aluminium ions and the creation of ochre as suspended sediment. The distribution of Pyrite, vertically in the profile and areally across a region, can be extremely variable (Hazelden 1990). The Broads Authority (1981) surveyed the distribution of prone soils, with the data remapped by George (1992), Figure 5. The impact of drainage of these soils has been well documented (see George 1992, Dent 1986, 1992 for general accounts, and ELP (2001) for impacts and remediation in the Brograve catchment).

Intensive farming on the upland can deliver significant quantities of pollutants to the catch dyke, especially if husbandry is poor, the soils are transmissive or under drainage employed. Poor water quality is rapidly passed through the receiving wetland where the catch dyke is connected to a floodplain dyke network or where there is a significant hydraulic gradient into transmissive peats of the wetland. If the receiving dykes or Broads are of high conservation value, the polluting effect can be direct and especially harmful to aquatic communities (Moss 2001, 1998). The catch dyke collects and redistributes the pollutants, unfiltered and more rapidly than would have been the case if groundwater seeped through soils and into the wetland naturally.

In terms of eutrophication, the impacts on the wetland depend on how much nutrient is exported from the soil to the wetland. The trend is to reduce farm applications and more precisely balance application with plant take up, so that there is less excess to route to the wetland. Soils vary in their capacity to absorb or pass nutrients. The case studies suggested catch dykes below intensively farmed slopes had better water quality and better plant communities than the above would suggest, although there were exceptions. Direct evidence of eutrophication is hard to find, although there is little collection of evidence in terms of water quality sampling or fen vegetation monitoring. In conclusion, then, while eutrophication from upland land use is theoretically likely, providing direct evidence of its occurrence in specific sites is more challenging.

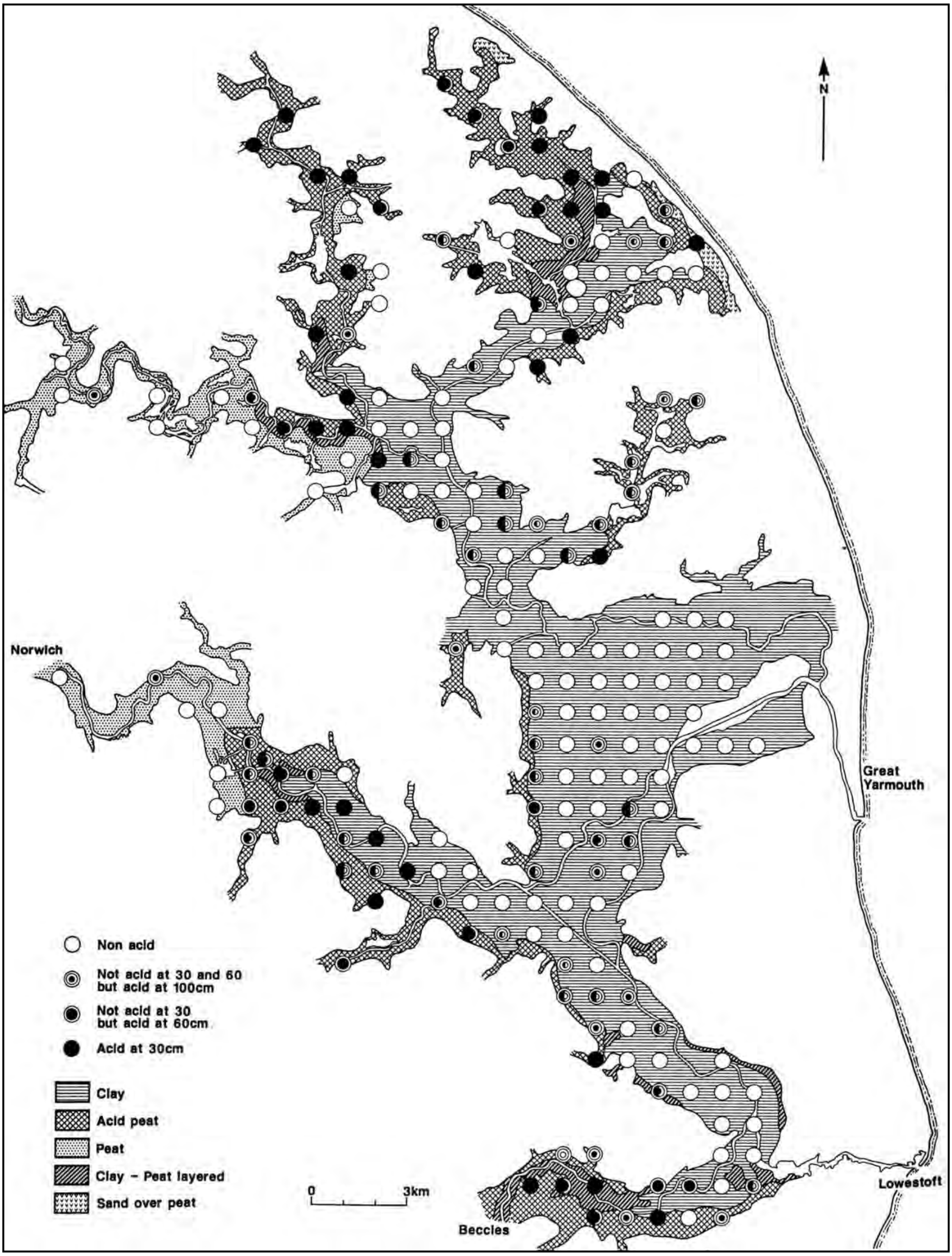


Figure 5: Potential Acid Sulphate Soils In Broadland.
From George, remapped from Broads Authority (1981)

Role of Freeboard

Water quality can be impacted even by catch dykes with very small freeboards (such as those maintained by sluices), where drawdown of the water table may be minimal. A high dyke water level does not interfere with the role of the catch dyke as interceptor. With a high freeboard, shallow groundwater seepage enters the watercourse and is mixed with the body of dyke water, homogenising water quality. The only solution here would be to infill the dyke with material that mimics the permeability of the original toeslope substrate.

If the catch dyke has a flow, with water drawn off to a lower (perhaps pumped) level, the interception of groundwater will be more significant than in a relatively still catch dyke, whether or not the dyke has a high level. Figure 3 is thus also illustrative of the impact of catch dykes on water quality as well as water balance.

Highland Margin to Floodplain Transition

Impacts on water quality are most likely to be felt on the floodplain margin, where groundwater discharge from the highland edge provides the strongest and least diluted inputs. Towards the river, other water qualities dominate and the impacts of catch dykes become less marked. The transition from highland to river (or broad), as expressed in the fen vegetation, has been well document by Pallis (1911) and Lambert (1951, 1961) for various Broads valleys. In modern times, water quality at the downstream (river) end of the hydrosere has greatly deteriorated (George 1992, Moss 2001), sometimes impacting fen communities through increases in nutrients and salinity (OHES 2013). This has been increasingly well documented, but the impact on the upland end of the classic hydrosere has been less well recognised (ELP 2011). Consequently, the classic valley side succession of wetland communities has been squeezed at both ends of the hydrosere, leaving the fen communities of the central floodplain increasingly separated from contact communities.

2.3.4 Connection With The Floodplain Dyke Network

Even “undrained” Broadland fens can have networks of ditches of varying densities. Often cut to manage water levels and to act as transport routes for fen produce, they are deeply disruptive of natural hydrological gradients.

If the dykes are open and free flowing, water circulates around the network. The water level and water quality are both homogenised by this process. Because of the influence of the dykes on compartment water tables, the dyke network can also significantly reduce natural variation in the level of water tables. A natural, topographical fall in the level of the water table to the river can be flattened by a dyke network. The degree to which internal water tables are affected depends on the hydraulic conductivity of the (usually peat) fen soils and the density of dykes.

The case studies have shown both negative and positive aspects of catch dykes connecting to floodplain dykes. Catch dykes, positioned somewhere along the toe slope, are usually topographically a little more elevated than the floodplain dykes. If all dykes are connected, and in the absence of sluices, the floodplain dykes drain down the catch dykes *and* the toe slope above and below the catch dyke. This can have significant impacts on the delivery of groundwater to the slope. Prior to any dyke excavation, this toe slope could have been a seepage area. Conversely, connection to the floodplain dykes allows more effective circulation of groundwater to the floodplain. This might benefit water quality in the dykes themselves, but could also benefit the fen communities which might be sustained by dykes. For this to be so, the volume of groundwater contributed would need to be very high, as small volumes will be diluted.

The ability of fen dykes to irrigate peats within fen compartments is dependent on two main factors:

- There must be a significant hydraulic gradient from the dyke to the fen compartment. This requires the dyke water level to be at or preferably above the fen surface. Dyke water levels even in the best fens are rarely maintained at fen surface all through summer. Ideally, fen communities should be in hollows or peat diggings to strengthen the hydraulic gradient. Evapotranspiration may depress water tables within compartments, strengthening the hydraulic gradient. Even so, overall gradients are likely to be low, meaning inflow from the dyke is also likely to be low.
- The peat substratum must have low resistance to flow, particularly at the rooting zone and just below. Peat is extremely variable in hydraulic conductivity. Loose, fresh peat that has accumulated rapidly in response to raised water levels (re-flooded peat diggings or flooded fens) can transmit water freely, whereas old, uncut and humified peat can be a significant barrier to flow. An individual site, or even compartment within a site, may have great spatial variation in peat conductivity. The dyke margin may be especially low in conductivity, due to a combination of spreading of dyke spoil with a high mineral content and heavy trafficking (dyke sides are often the best transport routes).

Sites with extensive loose surface peats are uncommon but have been described by Wheeler et al (2009) and Wheeler and Shaw (2006). However, the likelihood of a significant proportion of a fen site having dykes at fen surface level, a strong hydraulic gradient from the dyke to the compartment interior and substrates of high hydraulic conductivity from the dyke edge to the centre of the fen seems remote. Hence Wheeler et al (2009) suggest some fen sites isolated from the river have internal areas of compartment that are largely fed in mid –late summer by rainwater.

Some sites, such as Upton Fen and Sutton Fens, are thought to have loose surface peats existing over quite extensive areas. They have extensive old turbaries (Upton Fen) or loose peats arising from rapid rewetting of the fen surface (Sutton Fen). However, even in sites as well studied as these, Wheeler et al (2009) note that hydrological functioning is still understood conceptually and is not supported by conclusive data.

Loose, conductive surface peats must be considered a precious resource to be conserved through careful site management at all costs. Even so, it must be concluded that floodplain dykes on most sites are likely to be of limited value in irrigating fens. In addition, WetMec types that depend on this mechanism (usually a kind of “distributed” groundwater WetMec) are likely to be highly conceptual and in practise rather dysfunctional.

It must therefore also be concluded that connecting the catch dykes to floodplain dykes has limited if any benefits to floodplain fen communities, and that this benefit is probably outweighed by negative impacts on the toe slope habitats.

2.4 Geology and Soils

The characteristics of the soil, sub-soil and geological parent materials are of critical importance in determining catch dyke functioning. Understanding the soil context of the floodplain/highland margin provides indispensable information in catch dyke investigations.

2.4.1 Shallow Geology

While deeper geology such as the Chalk and overlying London Clay may influence the fen hydrogeology, catch dyke function is generally not affected. It is the shallow geology which determines soil type and hydrological function of the catch dyke and of the wetland surface. The following are the most important:

The Crag: This is the bedrock under most of the Broads, overlying the Chalk. It is a very variable marine sedimentary material consisting of mixtures of sands, gravels and some clays. It is an important aquifer both agriculturally and ecologically. Crag groundwater can move laterally to the wetland margin, or where flows are strong, upward into the wetland. The latter is probably rarer, as aquicludes above the Crag, such as marine clays and dense humified peat, can reduce or stop upward flow. For groundwater to move to the wetland, a strong hydraulic gradient is required, with the peizometric surface of the Crag water table being above the wetland surface. Where the Crag is close to outcropping, dykes or Broads can cut into the surface of the Crag, releasing groundwater to the wetland. A valley-margin catch dyke can penetrate the Crag water table, diverting some or all of the groundwater away from the wetland. Crag groundwater is important for Broads wetlands because it is generally base rich, calcareous and low in nutrients. Because of its variability, its hydrological properties require site by site consideration. The Crag is generally not a soil forming material as it rarely outcrops at ground level.

Happisburgh Formation[2] : Previously known as the Corton Formation or the Norwich Brickearth. This glacial till deposit overlies the Crag and forms the upland slope and plateaux of much of the north and east Norfolk. It is a variable mix of sand, gravel, silts and clay although the latter is usually minor. It is usually permeable, depending on clay content, giving rise to permeable soils and, with Cover Loam, is the predominant upland soil parent material on the Broads valley tops and flanks. It is a decalcified deposit, giving rise to neutral, base poor groundwater. Locally, where the Happisburgh Formation is coarse sands and gravels, groundwater may even be mildly acid.

Lowestoft Formation[2] (Chalky Boulder Clay). This calcareous till deposit is very extensive in high Norfolk and Suffolk. For this project it is significant only on the plateau and some flanks of the Waveney valley and the south of the Yare. Being essentially a clay parent material, soils derived from it are slowly permeable to impermeable. Mostly it is calcareous, but there are localised exceptions.

Cover Loam. This aeolian deposit of fine sand and silt overlies the Happisburgh Formation in a very complex pattern created by wind deposition and subsequent periglacial soil movements. It is concentrated in the northern Broads catchments. It is also permeable and yields base-poor, neutral soil waters. It is generally a minor component and should be considered as part of a single Happisburgh Formation-Cover Loam hydrological unit.

Breydon Formation[2 above] : Marine alluvium in east Norfolk has been laid down during transgressions when sea levels rose and flooded coastal valleys. It can include marine shell material. Alluvium from successive transgressions can be intercalated with peat beds. The most relevant event for this study is the Romano-British transgression which peaked at around 400AD. Marine clay was deposited in the mid and lower valleys in significant depths. In the lower drained valleys it is exposed giving rise to the clay marshes. In the mid valleys and along the margins, more recent peat deposits overlie the clay and are considered part of the Formation. Marine alluvium contacted during Case Studies fieldwork was very variable in texture, essentially clayey but with varying proportions of sand and silt.

Peat. Peat occurs on the mid and upper floodplains and on the margins in some areas of the lower floodplain as part of the above Breydon Formation. It is often intercalated with marine and other clays. The depth to first significant clay layer can be very variable from a few centimetres to many meters. A soil is only classified as a peat soil when depth exceeds 40cm (Avery 1980). In many places on the floodplain margin, the peat can be less than this, a recent capping over marine alluvium. Peat is an extremely heterogeneous material. Its chemistry may be varied due to the chemical composition of the plants that make up its structure, and from inclusions during its genesis. These may include shells, marl material, silts and clays.

Hydraulic conductivity varies enormously, with loose, fresh peats developed through recent hydroseral succession being the most conductive, and older, uncut humified peats being the least. Wheeler and Shaw (2009) report measurements of hydraulic conductivity in peats in Broadland that range over five orders of magnitude. Peat may have lower conductivity than

[2] Nomenclature (which seems to change rapidly) follows the British Geological Society *Lexicon of Named Rock Units*, https://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=HPGL.

some materials classed as clays. Hydraulic conductivity can vary with depth, as different layers are passed through. They can vary spatially, too, according to the pattern of cut and un-cut peat, or the pattern of valley infill. This three-dimensional variability in peat characteristics means simple generalisations about the eco-hydrological functioning of a site should be treated with extreme caution. All sites require detailed specific investigation. For a more detailed treatment of peat, refer to Wheeler et al (2009) and Burton and Hodgson (1987).

2.4.2 Soil Hydrological Characteristics

The way that soil moves downwards and laterally through soil is a key process which catch dyke managers need to understand. One of the most efficient ways to access this understanding is through the HOST (Hydrology of Soil Types) approach (Boorman et al 1995). HOST considered the following factors:

- ***Depth to a slowly permeable layer:*** Soil layers with a hydraulic conductivity of less than 10cm day^{-1} impede downward water flow causing saturation in upper layers. Soils with shallow depth to these layers store less water and respond more rapidly to rainfall.
- ***Depth to a gleyed layer.*** Gleying (shown by grey or ochreous mottles) indicates periodic waterlogging. Shallow depth to gleying indicates high groundwater tables.
- ***Integrated air capacity (IAC).*** This measures the volume of soil pores greater than 60 microns in the soil profile. Soil pores exceeding this threshold cannot retain water against the pull of gravity, hence water moves through soils freely. The measure is in part a surrogate for greater hydraulic conductivity.
- ***The presence of a peaty surface layer.*** This includes soil horizons with >20% humic content, often more. It does not necessarily imply raw peat - HOST assumes that peat is largely humified and therefore has relatively low permeability which facilitates surface runoff.
- ***Hydrogeological class of the soil substrate.*** This feature summarised the characteristics of a soil's parent material, especially its permeability, its aquifer bearing properties and the way that water moves down or through the parent material.

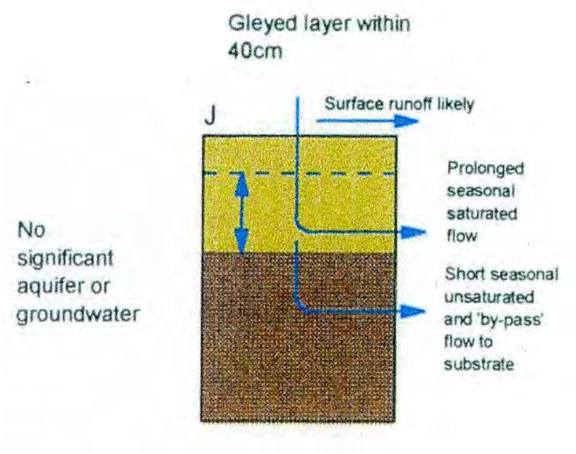
Boorman et al (1995) used data on these characteristics to construct conceptual models describing the hydrological responses of soils. Seven models have so far been recorded in the Broads, and are summarised in Table 1.

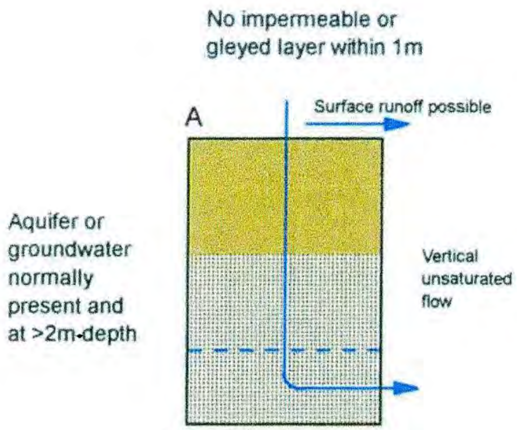
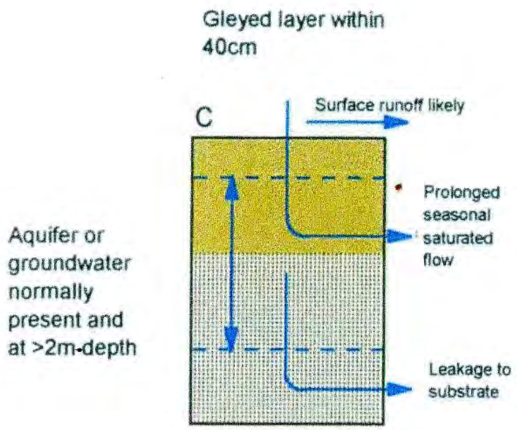
HOST classes are a further refinement of the Models, providing a more detailed description of the hydrological characteristics of UK soils, based on the dominant pathways of water movement through the soil. The system was developed to aid hydrogeological modelling of catchments and rivers and can be applied usefully here. To derive the 29 HOST Classes, the substrate hydrogeology is cross-tabulated with soil factors. The full system is shown in Appendix 1. It can be used to determine the conceptual model and HOST Class for any soil profile.

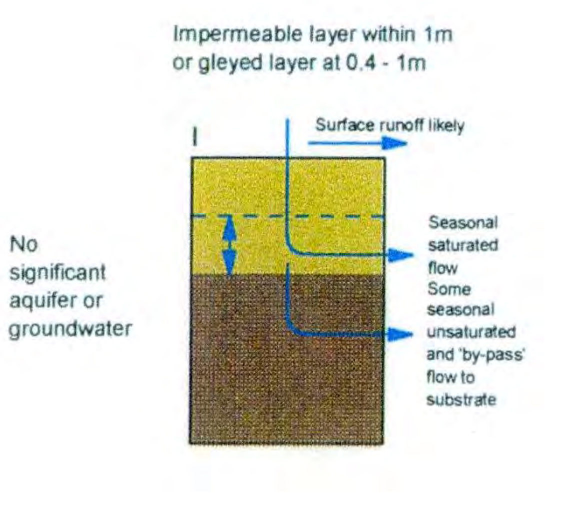
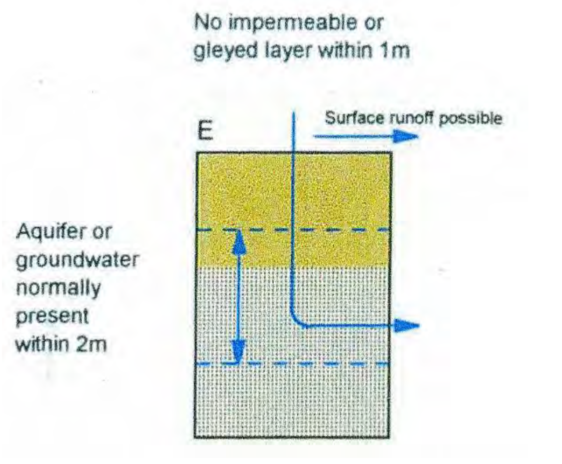
Eleven HOST Classes have been recorded in the Broads for the current report, highlighted in red in Appendix 1. They are also ascribed to the soil type and to the relevant Model in Table 1. The Table shows how the soil hydrological types are linked in terms of landscape context. Some Models and HOST Classes are very significant in the Broads, while others are minor, and this distinction is made in the table. More Host classes or models may be recorded as additional research is undertaken, but the table reflects all the more likely ones.

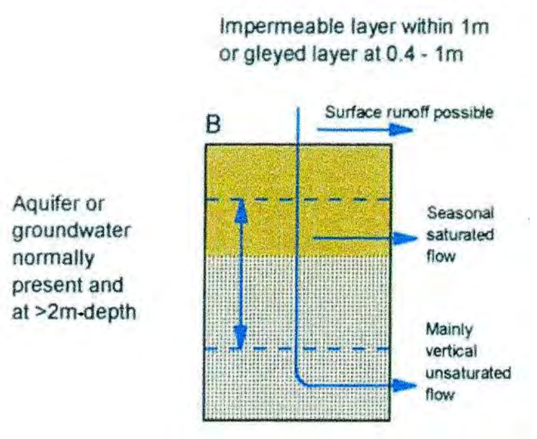
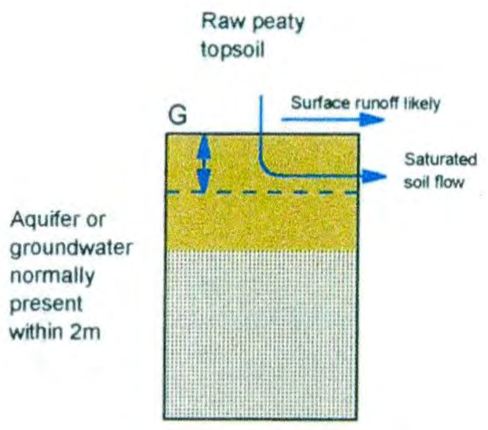
While the Model and Class can be worked out from first principles, there are published sources. Data in Boorman et al (1995) is provided for Soil Associations, which can be related to published soil maps (Hodge et al 1984). This resolution may be reasonable for catchment modelling, but the Case Studies showed that Soil Associations were not sufficient to construct reliable soil catenas and hillsope hydrological profiles. The HOST and Model for individual soil profiles are required, requiring fieldwork and identification of the Soil Series.

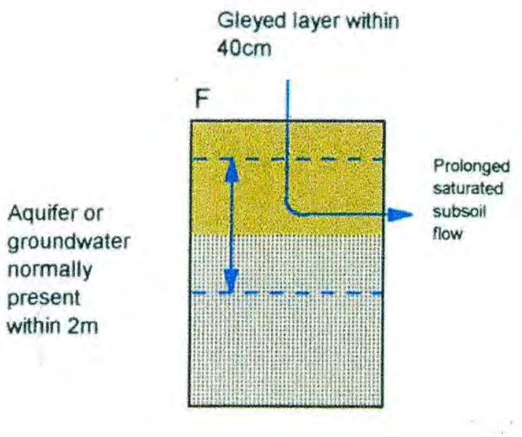
Table 1: Soil Hydrological Models and HOST Types in Broadland. Model and Host Class from Boorman et al 1995). Because Soil Associations are composed of a range of Series, which *may* have differing HOST classes and even Models, the dominant arrangement for the Association is given in bold and significant inclusions indicated in normal.

HOST Model	HOST Class	Landscape Context	Applicable Soil Series	Soil Association
Plateau tops and upper slopes				
	**24**	Chalky boulder clay plateau and some valley slope. Clayey subsoil sometimes to the surface. Although extensive in coverage in the region, its contact with floodplain margins and mid slopes is very limited and therefore of only minor importance hydrologically.	Beccles, Ragdale	**Beccles**

Slopes from floodplain to interfluves				
	**5, 6**	Valley slope locations, reaching the interfluves to the north and west of the Broads (Wick 2 area). Free draining and permeable substrates, contributing to throughflow and groundwaters in the floodplain. Usually intensive arable. Significant and extensive hydrological type.	Newport, Redlodge, Wick,	**Newport 1, 3 and 4** **Wick 2** Some parts of Burlingham 1 and 3
	**14**	Valley slopes and interfluve areas between the Ant and the Thurne, close to the more extensive Wick 2 (Host 5) association. Gresham soils have heavier textures providing poorer profile drainage and lower permeability. Locally significant.	Gresham	**Gresham**

	**18**	Valley slope between the floodplain and plateau, mostly along the southern side of the Yare. Distinguished from Class 21 by higher water storage capacity. Locally significant hydrological type.	Wighill, Burlingham, Honingham, Ashley	**Burlingham 1, 3**
	21	Valley slope between the floodplain and plateau, along the southern side of the Waveney. Distinguished from Class 18 by lower water storage capacity. Locally significant hydrological type.	Hanslope, Faulkbourne	**Hanslope**
	**7, 8**	Free draining soils closely associated with Class 5 Newport soils, but on lower parts of the slope where groundwater is found within the profile at depth. Minor component of the project area.	Ollerton (7) Aylsham (8)	Minor component of Newport 1 Minor component of Wick 2

	**13**	Located on lower (toe) slopes of the highland, often below Wick soils, where topography allows increase in groundwater level causing gleying of lower horizons. Minor component of Broadland soils.	Wickmere	Minor component of Wick 2
Floodplain				
	**11**	As Class 12, but the peat soils are pump-drained. Boorman et al (1995) note that their hydrology is closer to Models E and F because of the pumped systems. Consequently, care is needed when interpreting their hydrology when on site. Locally significant hydrological type.	Adventurers, Altcar, Mendham	**Altcar 2 Mendham**
	12	Undrained peat floodplain soils in lower and upper parts of the valley. Profiles deep. Usually underlie fen areas. Groundwater generally higher and more consistent than in the alluvial soils of Model F (Host Classes 9 and 10). Significant hydrological type.	Altcar, Adventurers, Mendham	**Altcar 2 Mendham**

	**9**	Lower valley floodplains on alluvium. Naturally high water table causing gleying high in the profile. Distinguished from Class 10 by their low hydraulic conductivity. Within the Mendham Association, it is found only on silts near to rivers in four closely related Soil Series Significant and extensive hydrological type.	Newchurch, Wallasea, Downholland Shotford, Midelney, Fladbury, Wensum,	**Newchurch 2** Locally within Mendham.
	10	Upper valley floodplains on alluvium. Naturally high water table causing gleying high in the profile. Distinguished from Class 9 by their high hydraulic conductivity. Blackwood and Quorndon Series on the lowest part of hill slope sequence, transitional to the floodplain. Locally significant hydrological type.	Hanworth, Sustead, Fordham Blackwood Quorndon	**Hanworth** Minor part of Newport 1

2.4.3 Overview of the Soils Of Broadland

Published Information Sources

The basic reference unit for describing soils is the Series, a soil profile of 1.2m or so deep that can be readily described in the field. It has a group of characteristics – texture, chemistry and hydrology – which are broadly replicated in the field and are diagnostic.

Soil Associations are groups of Soil Series that are regularly found in close proximity in a particular landscape situation. An Association may be simple, with just two Series, or may be complex with many Series, although a few Series are usually responsible for most of the geographical coverage of an Association. The Association generally reflects the near-surface geology, while the Series within an Association are disposed according to location in the landscape, usually along a plateau-to-floodplain topographical sequence, referred to as a catena. Understanding the pattern of soils down the hill slope abutting wetlands tells us much about their hydrological relationships and how water, nutrients and mineral contents could be transmitted to the wetland. In planning catch dyke work, soil information at the Series level is the ideal. Association level information is much less precise, and often allows only broad generalisations to be made.

Mapping of Soil Series is rare because of the resources it requires. Consequently, Hodge et al (1984) map soils in Associations, based on geological maps, air photos and a certain amount of ground truthing. The locations of particular Series cannot be determined. A further limitation of the maps is their small scale, making Association boundaries rather difficult to plot accurately on larger maps. Association level information is useful for strategic planning or first scoping, but not for site specific case work.

There are four detailed surveys mapping Series that include the Broads (Tatler and Corbett 1977, Hazelden 1990, Corbett 1979 and Corbett and Tatler 1970) but they are each of limited extent. In detailed remediation proposals, field soil survey is required, ideally using a transect from the highland through to the mid-floodplain. The recorded profiles can then be related to published accounts to extrapolate key soil characteristics and hydrological data.

The Soils of Broadland

Appendix 2 provides a description of the Soil Associations of Broadland, with an accompanying table which summarises the Soil Series most likely to be encountered during catch dyke work. The Appendix describes parent geological materials and HOST classes associated with each Series. In the Case Studies, a range of hillslope catenas are described along with illustrative cross sections. An example is shown in Figure 6.

Most of the Broadland upland is surprisingly permeable. The plateau and slopes of the Thurne, Ant, Bure and northern valley side of the Yare are brown earths developed in Happisburgh Formation and aeolian Cover Loam parent materials. Water readily moves down the profile to a rather deep water table, possibly recharging the Crag. Towards the toe slope of the upland, the groundwater rises closer to the surface until, proximal to the catch dyke, downward water movement becomes limited, the soils become strongly gleyed and affected by groundwater. Soil texture generally remains coarse so lateral hydraulic conductivity is still high, allowing rapid passage of groundwater to the wetland. The upland soils are often Grade 1 agricultural land, intensively cultivated for arable crops. The catch dyke is often positioned at the point where peat floodplain meets the mineral upland. They are ideally placed to intercept upland soil groundwater. On the floodplain side, soils become peat dominated. In some situations, peat thickens gradually from the valley margin, usually over marine alluvium, while in other places the peat can be deep very quickly. The peat soils – Adventurers, Altcar or rarely Ousby raw peat – are extremely variable both laterally and vertically.

South of the Yare, the plateau and upper slopes are more dominated by soils formed in chalky bounder clay. They are much less permeable, and prone to surface run-off. The mid and lower slopes are more complex, with bands of very sandy permeable soils and bands of more impermeable clayey soils. The floodplain of the Waveney is also different in character to the other valleys, with Mendham Series peats which are acid-prone, with much more frequent inclusions of mineral soils associated with small streams, banks and other river features.

In all valleys, the lower open valley areas are dominated by soils developed in marine alluvium. Both calcareous and non-calcareous Series have developed. These rarely penetrate the fen areas of interest, more often giving rise to wet grassland habitats.

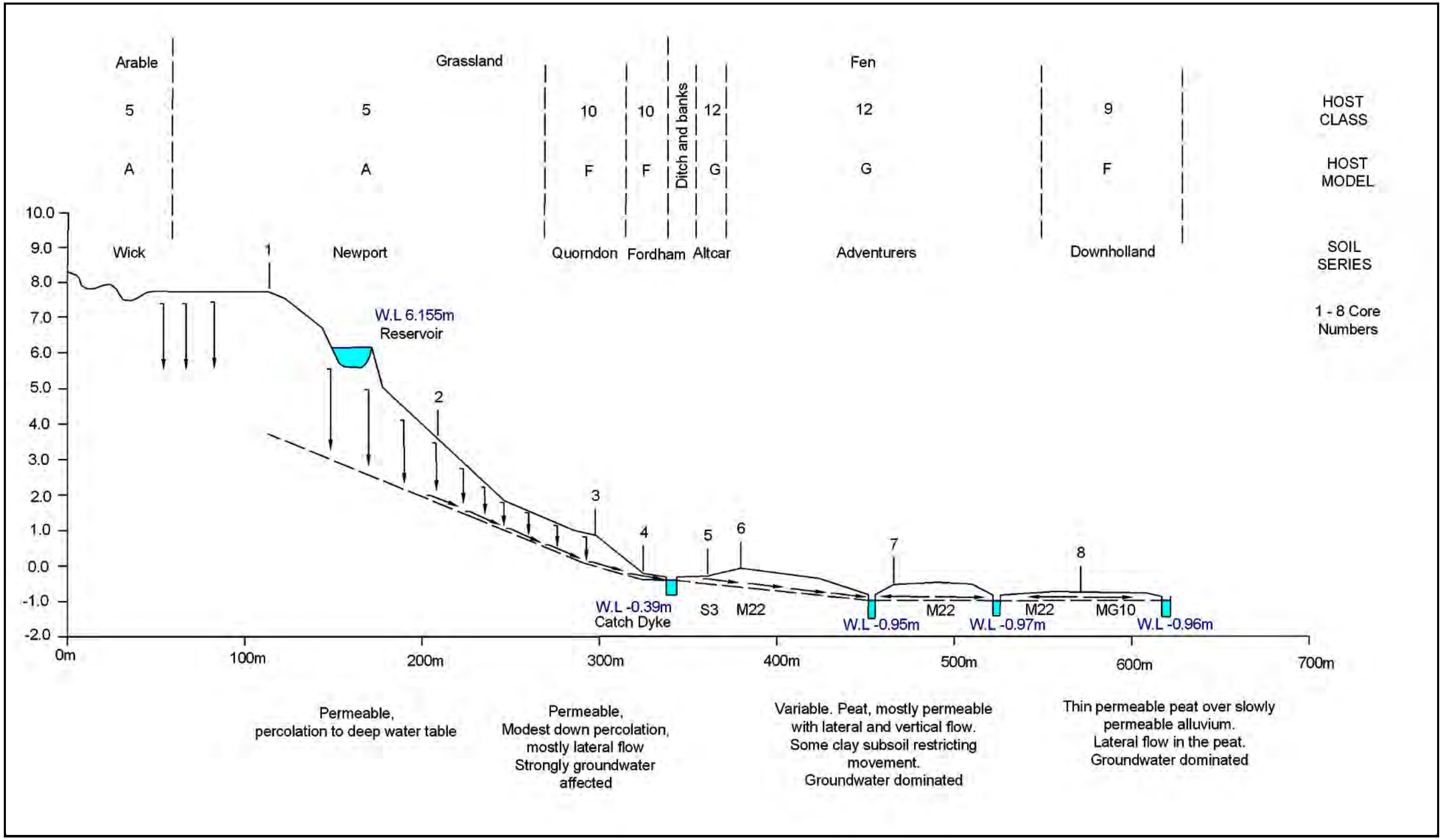


Figure 6: Soil Catena and Hydrological Sequence in a Broadland hill slope and Floodplain: Limpenhoe Marshes (west side), north side of the Yare.

2.5 Ecology and Related Land Use Issues

Once again, there has been little or no specific study of the ecology of catch dykes. There has been a lot of work on dykes in general but no sources could be found that specifically considered this type of dyke.

2.5.1 Ecological Issues

Visual inspection of maps contained in the last systematic survey of Broadland grazing marsh dykes (Harris et al 1997) shows that some uncommon species had distributions that were strongly skewed towards the highland margins. The scale of mapping does not allow determination of whether or not catch dykes specifically are responsible. Species favouring the margins of floodplains include *Hottonia palustris, Potamogeton coloratus, Ricciocarpus natans* and *Stratiotes aloides,* but many more species show no such distribution.

In terms of aquatic plant communities, end groups 1 and 2 (freshwater plant communities of high conservation value) shows a skew toward the highland margin, especially in the large grazing marshes in the lower reaches of the river. End groups 3a and 3b, meso-eutrophic communities showed no preference for the margin, mostly occupying central marsh areas. The eutrophic dyke types tended to cluster toward the river margin. These distributions suggest plant communities reflect a deteriorating water quality gradient from highland margin to river.

There is no obligate relationship between these species and communities and catch dykes *per se*, only a coincident association with water quality. Catch dykes and their immediate neighbours are simply further away from the influence of poor quality river water and more strongly influenced by groundwater.

The above general overview does not provide evidence of strong eutrophication effects from upland agriculture. However, this probably requires a much more detailed analysis of specific samples to elucidate this further.

Dykes with ecologically important aquatic plant communities are often associated with high diversity and importance for invertebrates (Moss 2001, George 1992) and other faunal groups, particularly amphibians, water voles and breeding birds of the water margin. The impact of any proposed management works on the intrinsic value of the catch dykes and its immediate network should be considered when assessing remedial measures.

2.5.2 Truncating The Hydroseral Succession

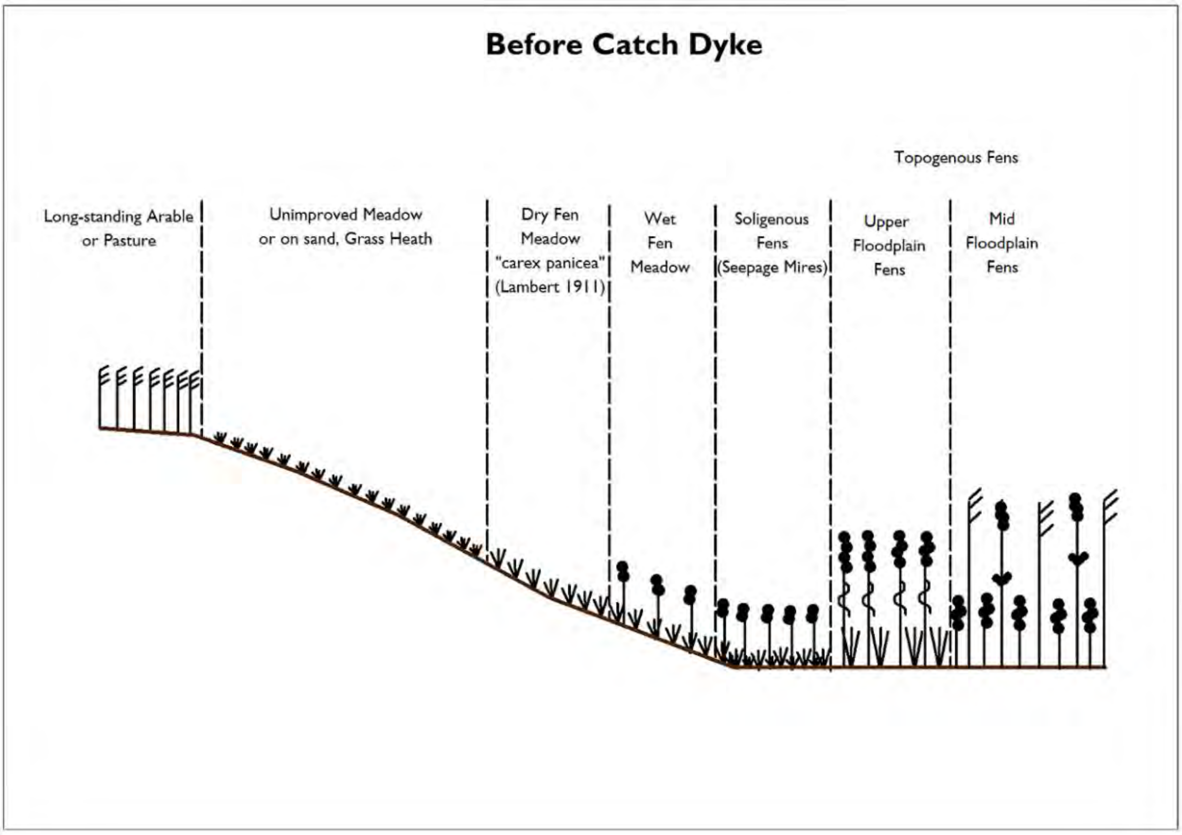
One of the most important functions of a catch dyke is that it draws a line in the landscape.

Upslope of the line, the land is “released” from its semi-natural origins to be made available for a whole range of alternative land uses, few of which are likely to have any connection with the preceding habitat.

Land above the break of slope was always vulnerable to improvement. Arable conversion is an ancient practise. However, the catch dyke and associated drainage allowed conversion to be more focused and more effective, and to be brought right up to the line of the dyke. There was no longer a gradation between improved land and wetland. The side of the dyke provides a hard boundary to the remaining floodplain habitat. The once ubiquitous seral succession first described by Pallis (1911) is now very rare indeed, with almost all of the ecologically valuable transition zones now under other land uses. Figure 7 shows how catch dykes can truncate this succession, impoverishing the margins of Broadland valleys. The inclusion of seepage and groundwater fed mires is conjectural, as they are now so rare and degraded. However, there is sufficient evidence in the foregoing review and from the case studies to justify their inclusion in the model of change. The near-ubiquity of catch dykes, and their coincident location with the landscape position of soligenous fens, means it is quite possible that these small features were obliterated as the dykes were created. Lost from the landscape before they were even recognised or described, these communities could be an important beneficiary of catch dyke restoration schemes.

2.5.3 Remediation Of Catch Dykes And Wider Land Use Issues

Catch dykes are likely to facilitate other land uses which may be well established. They may also be part of a much wider drainage network which involves a range of stakeholders with potentially different management objectives. Consequently, any remedial action will need to take into account impact on neighbouring land uses.



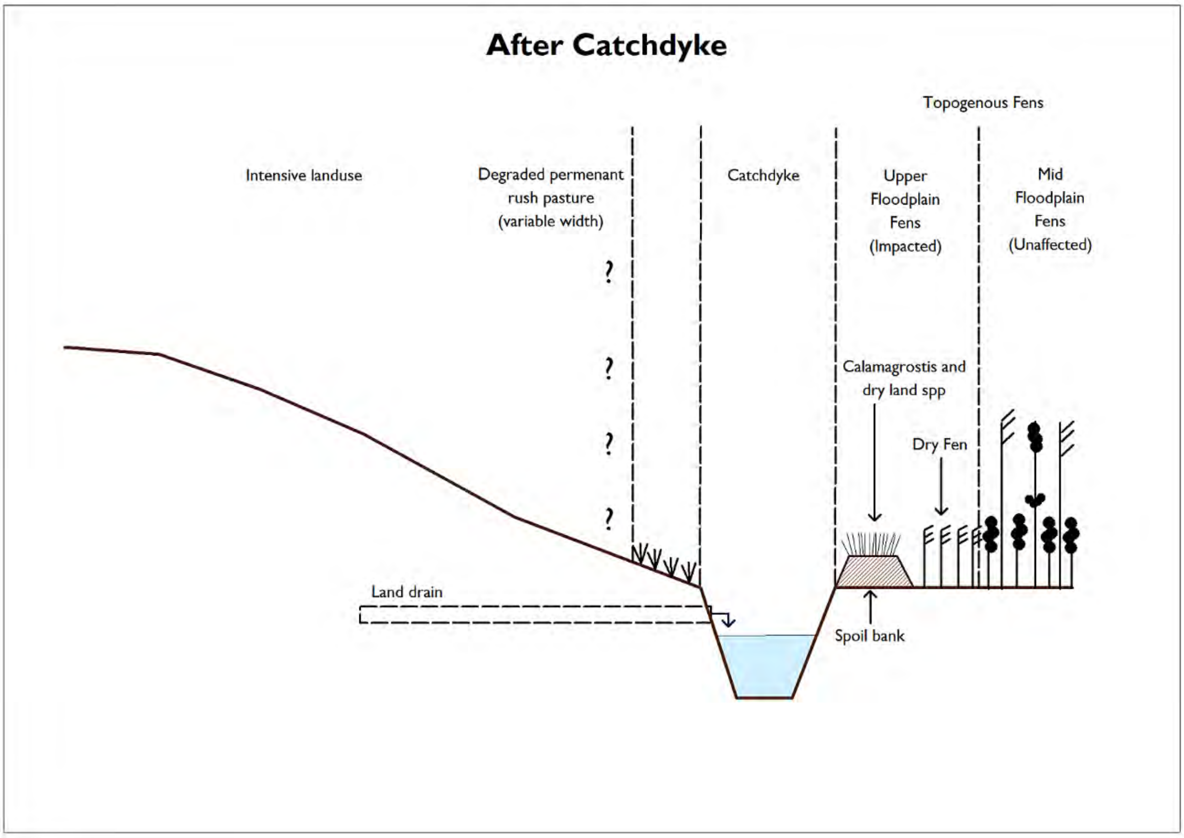


Figure 7: How Catch Dykes Facilitate Loss of the Hydroseral Succession.
Seepage mires have been infrequent.

2.6 Summary of Factors To Consider in Assessing Impacts of Catch Dykes

Factors that determine the impact of a catch dyke include:

- Permeability of the soil, sub-soil and parent material of the upland margin.
- Permeability of the soil, sub-soil and parent material of the catch dyke.
- Permeability of the soil, sub-soil and parent material of the floodplain.
- Soil chemistry and physical properties.
- Presence of an aquifer contributing to the floodplain.
- Complexity of aquifers, especially layering.
- Water quality of contributing aquifers.
- Freeboard of catch dyke.
- Flow characteristics of the catch dyke (flowing, static)
- Connection to a pumped drainage system.
- Presence of working under-drainage in the upland.
- Permeability of the catch dyke banks and bed (related in part to maintenance regime)
- Connectivity to the floodplain ditch network.
- Topographic and hydraulic gradient of the upland slope, toes slope and transition to the floodplain.
- Land use of the upland.
- Quality of land husbandry, especially silt and nutrients.
- WetMecs in the fen compartments adjacent to the catch dyke.
- The role of catch dykes in facilitating land use change and in truncating the hydroseral succession.

The review highlights further factors to be considered when devising remedial measures:

- Intrinsic conservation value of the catch dyke including presence of protected or feature species.
- Intrinsic conservation value of the ditches the catch dyke is connected to.
- Constraints such as flood defence, land ownership issues and other land uses that could be impacted by altering.

The complexity of the role of catch dykes is made clear by the above review. The individual circumstance is overriding. Experience gained from the case studies suggests that only site specific fieldwork and investigation can determination impacts and remedial measures.

2.7 Evidence of the Impact of Catch Dykes

The literature review above has shown a wealth of theoretical and indirect evidence of the impacts that catch dykes could have on wetland sites. The impacts become more compelling and more pervasive in permeable catchments with intensive land use. However, despite the wealth of such evidence, it is difficult to demonstrate clear field evidence on any particular site of the above issues, in any but the most extreme case. To adjacent land owners this may present a significant barrier to agreeing remediation works, especially any that may have an impact on their use of upland. Four reasons for this lack of apparent evidence are suggested:

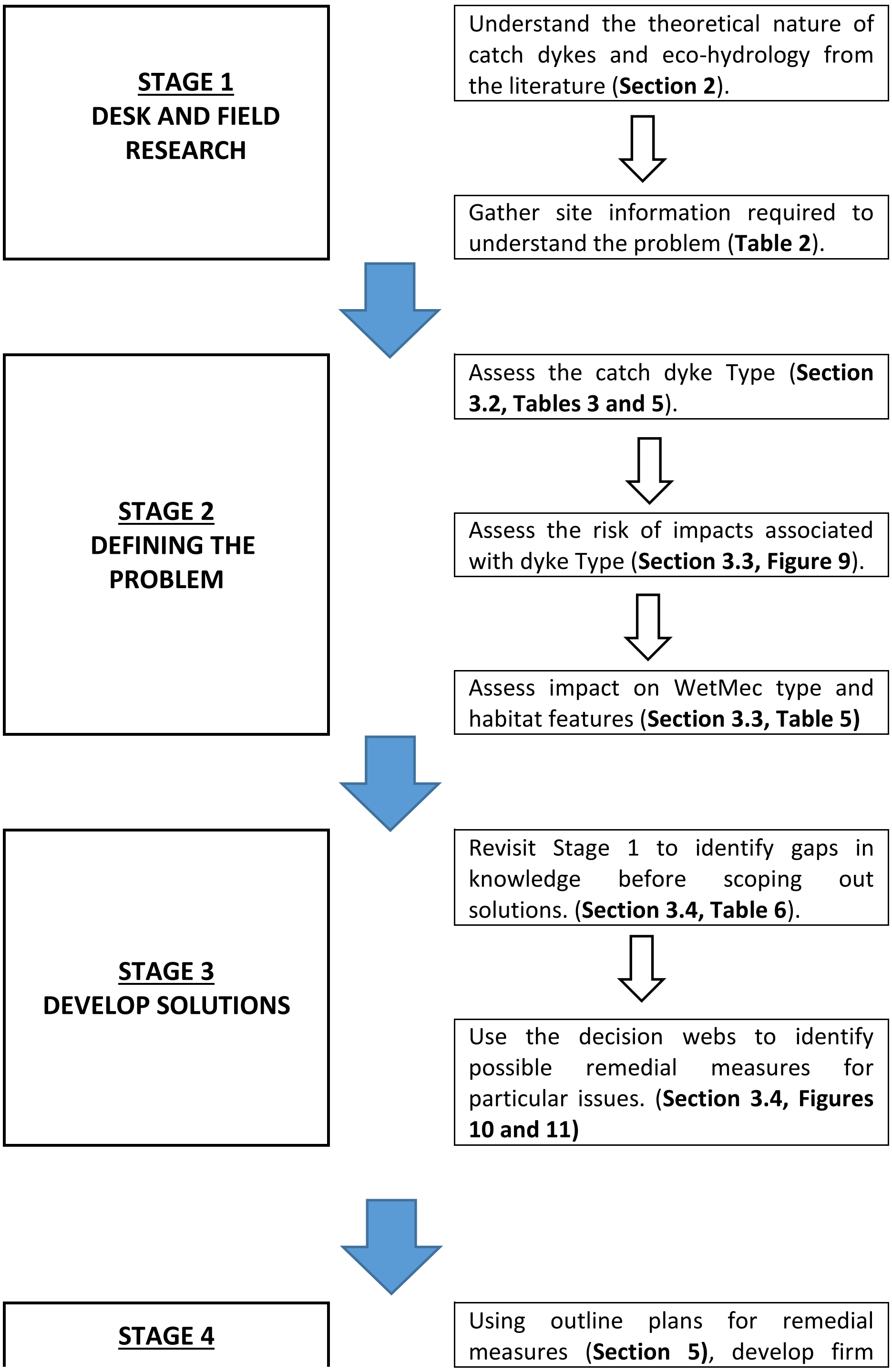
- Catch dykes have been in existence for a very long time. A wetland will have become adjusted to the prevailing conditions. It is difficult to hindcast the type and condition of the wetland prior to catch dyke creation.
- The issues are complex and interrelated. The net impact may consequently be difficult to identify, let alone to separate out the individual impacts of specific issues.
- Site management may produce shifts in vegetation which modify impacts of catch dykes. Scrub encroachment on the margins (where catch dyke impacts are likely to be strongest) obscures potential vegetational changes.
- There is little effective monitoring that can pick up changes to key plant communities.

Without such evidence it may be difficult convince landowners and funders to take action.

3 DECISION MAKING PROTOCOLS

3.1 A Decision Making Process

Despite the complexity of issues associated with catch dykes, it is possible to devise a preliminary decision making process, summarised in Figure 8, based on the classic problem and project management cycle. Stages 1-4 (Proposals) were used to provide a methodology for the Case Studies. Stage 4 (Consents), Stage 5 and Stage 6 could not be tested as they are project delivery stages.



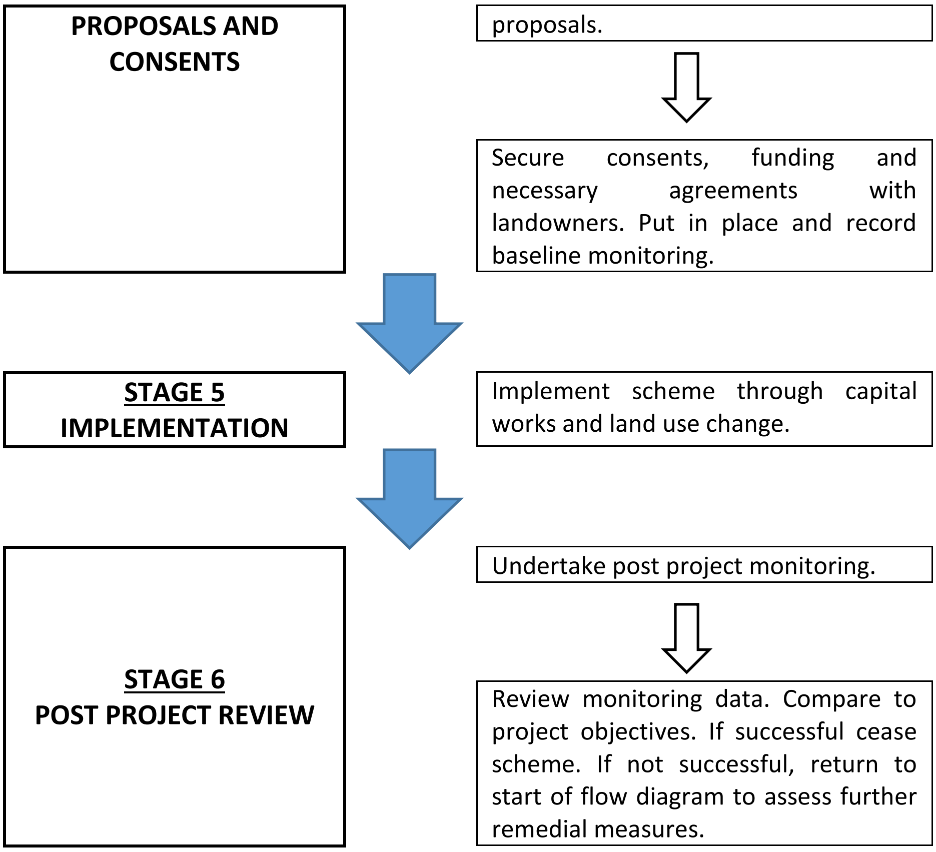


Figure 8 : Summary of Decision Making Process.

The following expands methods and approaches for Stages 1-3. The Proposals part of Stage 4 is addressed in Section 5 of the report.

3.2 Stage 1: Desk and Field Research

Preliminary desk and site investigation is required to (1) to define in detail the nature of the problem and (2) scope the constraints on remedial measures. Table 2 provides guidance on approaches and content.

The Case Studies showed Table 2 to be a comprehensive scope of work, although not all aspects were needed for what were essentially preliminary and theoretical exercises. Were any of the Case Studies to be taken forward for implementation, further work particularly on constraints and on mapping of conservation features on the fen may be required. The case studies showed just how time consuming Stage 1 can be. It may be pragmatic to undertake a "scoping" level of detail in the first instance. It may be sensible to leave very detailed work when there is a consensus for action.

Table 2: Scope of Work Needed Before Remedial Measures Can Be Selected. The issue can be scoped in a preliminary assessment, or the full, detailed study undertaken, or a staged approach used.

1. Defining the Nature of the Problem		
Understand the study area	Scope the area of interest	Through discussions with land managers and agencies, broadly scope the geographic area of concern.
	Identify the hydrological units	Identify the catch dykes and the watercourses they are connected to.
		Undertake a preliminary division of the study area into catch dyke lengths which appear to be homogeneous. These will be the catch dyke units.
Understand the dyke	Define dimensions for each catch dyke unit	Determine profile in the field with cross sections in each unit.
	Define flow characteristics for each unit.	Determine surface water flow direction and strength.
		Assess potential groundwater interaction.
		Determine connections to pumped drainage
		Determine connectivity to distributor dykes within the wetland.
		Determine freeboard, control structure and management regime
		Determine condition of channel, location and size of obstructions and impact on flow performance.
	Define nature of perimeter for each catch dyke unit	Profile silt around bed and banks – depths and permeability.
		Profile soil and subsoil in host substratum.
	Define intrinsic value for each catch dyke unit	Assess conservation interest: protected species, habitats, faunal group and designated features. Assess their condition
	Review dyke categorisation and threat for each catch dyke unit	Using the above data, review assessment of dyke type and risk.
Understand the landscape context	Understand topography for each catch dyke unit	Derive a slope and floodplain profile through levelling or existing maps.
		Locate dimensional dyke cross-section in the slope profile
		Add water management infrastructure and other key features such as floodplain water bodies, dykes etc.
	Understand substrate for each catch dyke unit	Map soil series down the topographic profiles.
		Document significant local features such as hard pans, under-drainage, peat condition, permeability.
Understand hydrological	Produce conceptual model for study area	Describe the WetMecs for the floodplain and highland margin.

functioning		Propose simple hydrological model for how the site **currently** functions.
		Propose simple hydrological model for how the site **could** function if the system were naturalised.
Understand conservation requirements	Define conservation interest in study area	Map and describe NVC communities (Broads database)
		Map and describe rare species
		Map and describe designated features
		Map and describe current condition and any known issues.
	Define conservation condition	Map and describe ideal condition, defining the aim of any remedial work.
	2. Scoping Constraints	
Nature conservation constraints	Protected species	Scope potential impacts from engineering works
		Map or describe occupancy of catch dyke for each species
	Habitat features	List designated features
Physical constraints	Drainage issues	Scope third party drainage interests including abstractions if known.
		Scope statutory interest – Main Drains, main river etc.
	Infrastructure issues	Scope assets that may be affected.
		Scope services and utilities that may be affected, statutory and private.
Social constraints	Private stakeholder issues	Scope the main stakeholders in the project.
		For each stakeholder identify their potential objections.
	Public stakeholder issues	Scope the main agency and public stakeholders in the project.
		Scope their likely position on the project, including initial consultation where uncertain.
		List the consents that may be required and the regulating agency.

3.3 Stage 2: Defining the Problem

3.3.1 Assessing The Catch Dyke Type

The most important characteristics of catch dykes and their environs are tabulated in Table 3. This table should allow diagnosis of most catch dykes. Note that some characters may need to be determined using fieldwork, unless there is up to date documentary information. Not all characteristics are diagnostic for all dykes, and a key to dyke types using critical characters is given in Table 4. Note some dykes could show a mixture of characters. In these circumstances, Table 3 should be used to identify the best fit. It is possible to have hybrid dyke types – for instance a **Severe Directly Draining Dyke** (Type 5) that is also **Ochreous** (Type 6). It is possible that some dykes do not key out using Table 4 – they should be rated **Indeterminate** (Type 8).

Table 3: Characteristics of Dyke Types. N/A indicates characteristic whose condition is not relevant to the dyke types.

Dyke Type	**Characteristics**												
	Upland				**Catch Dyke**					**Floodplain**			
	Soil permeability	Aquifer	Under drainage	Slope	Size and condition	Substrate	Freeboard	Flow	Connected to pumped drainage	Near surface permeability	Direct drawdown	WetMecs within 1Km	Connectivity to ditch networks
1.Groundwater dykes with significant direct drainage.	Medium to high	Permeable and contributing to wetland.	Absent or present (increases permeability)	Modest to significant.	Moderate-large, >1m deep, clean and open.	Permeable	>30cm	Significant flow	Yes	Medium-high	At least in near-ditch sediments	Groundwater dependent element.	Usually connected where dykes exist
2.Groundwater dykes with minimal direct drainage.	Medium to high	Permeable and contributing to wetland.	Absent or present (increases permeability)	Modest to significant.	Small-moderate, less than 1m deep, poorly maintained, silted	Permeable	<30cm	Still or minor	No, or with sluices	Medium-high	Not evident	Groundwater dependent element.	Connected ditches have sluices or other controls.
3.Surface water dykes with significant direct drainage.	Slowly permeable to impermeable	Not usually significant	Usually Present	Flat to modest	Moderate to large, >1m deep, clean and open.	Semi permeable to impermeable	>45cm	Significant flow	Yes	Usually slowly permeable to impermeable	Significant, distance depends on connectivity and substrate.	Usually topogenous types	Connected to uncontrolled ditches
4.Surface water dykes with minimal direct drainage.	Slowly permeable to impermeable	Not usually significant	Usually Present	Flat to modest	Small-moderate, poorly maintained, silted	Semi permeable to impermeable	<45cm	Still or minor	No, or with sluices	Usually slowly permeable to impermeable	Modest to 25m, barely noticeable thereafter.	Usually topogenous types	If connected, other ditches have small freeboard
5.Severe directly draining dykes	Permeable to impermeable.	Present or absent	Absent or present (increases permeability)	Flat to moderate.	Large, deep (>1.5m), open and well maintained	N/A	Significant, >60cm	Regular flow	Connected to pumped system	Permeable or connected to dense, effective ditch network.	Noticeable and significant	N/A	High connectivity
6.Ochreous	Highly to slowly permeable.	Shallow aquifers can be saline in Thurne.	Usually, especially in silty lower horizons	Modest to minor	Moderate to large, >1m deep, clean and open (unless fallen derelict)	Acid sulphate prone peats, sometimes alluvium	Significant, below sub-soil pyrite layer	Significant draw	Connected to pumped or steep gravity system	Usually high, peats	Variable, depending on connectivity and permeability.	N/A	Usually well connected
7.Redundant or derelict	N/A	N/A	None or derelict	Modest to nil	Small, not maintained, part-infilled or overgrown	N/A	Low or empty except exceptional floods	None except exceptional floods	Usually not. If connected pumped drainage no effective.	N/A	None observed	N/A	None or limited.
8. Indeterminate	Cannot be assessed on basis of documentary or walkover evidence – requires more detailed study.												

Table 4 : Key to Dyke Types.

1	Dyke with thick ochreous sediment on bed and/or in suspension	**6. Ochreous**
	Dyke may have some mild orange-red staining but not dominant	Go to 2
2	Dyke with little or no open water, or water under a skim of aquatic vegetation. Apparently dry and in-filled with silt and vegetation. Little obvious maintenance.	**7. Redundant/derelict**
	Open water on surface, or depth of water under wobbly hover. Modest siltation, maintained in the last 15-20 yrs.	Go to 3
3	Large dyke, deep (>1.5m) and wide, well maintained with significant flow or draw. Usually a freeboard of >60cm. Well connected to functioning drainage pump.	**5. Severe directly draining dyke**
	"Average" sized dyke, less than 1.5m deep, variable state of maintenance.	Go to 4
4	Upland and ditch perimeter with permeable to moderately permeable soils, with permeable to moderately permeable shallow geology. Likely sub-surface contribution to floodplain water balance.	Go to 5
	Upland and ditch perimeter in mostly impermeable or slowly permeable soils and shallow geology. Minimal sub-surface contribution to floodplain water balance.	Go to 6
5	Dyke >1m deep, freeboard >30cm, well maintained with noticeable flow, usually connected to pumped drainage	**1. Groundwater dykes with significant direct drainage**.
	Dyke 1m deep or less, freeboard <30cm, variable maintenance, still or minimal flow, not connected to pumped drainage but if so, sluices maintaining low freeboard.	**2. Groundwater dykes with minimal direct drainage**.
6	Dykes moderate to large, >1m deep, open, well maintained, noticeable flow, freeboard >45cm, usually connected to pumped drainage.	**3. Surface water dykes with significant drainage**.
	Dykes small to moderate, 1m deep or less, freeboard <45cm, maintenance variable, still or minimal flow, freeboard <45cm, not connected to pumped drainage or if so then freeboard controlled by sluices.	**4. Surface water dykes with minimal direct drainage.**

Experience gained through the case studies showed that the typology is robust, with all dykes examined being classified satisfactorily. Most case studies diagnosed Type 1 and Type 2 dykes.

This partly reflects the frequency of permeable soils and geology in the Broads, and partly the tendency to choose case studies that had "issues".

3.3.2 Risk And Impact Of The Dyke Types

Minimum impacts of any catch dyke

In terms of conservation of the hydroseral succession from dry land to floodplain, ***all*** catch dykes have an impact. As described in Section 2, even the most benign can intercept and mix groundwater moving into the floodplain, and draw a line in the landscape which facilitates the conversion of semi-natural habitat on the highland to less beneficial uses, with the contingent impacts which this may have. Hence, even a catch dyke maintained with zero freeboard could to some degree be "problematic".

The absolute minimum impact would be a catch dyke in impermeable sediments in a largely impermeable and flat valley context, maintained brim full and with a complementary, low-intensity land use on the highland, with the whole system perhaps managed primarily for conservation objectives ("nature reserve" quality). Here, any minimal impacts may be outweighed by intrinsic value of the dyke and the expense and impact of doing remedial works. However, this kind of context is rare and was not encountered during case studies. All resulted in suggested remedial work.

Risk of Significant Impact

Dyke types vary in their risk of impacts on nature conservation interest as follows:

<u>Minor Risk of Impacts</u>: Type 4: **Surface water dykes with minimal direct drainage.** With impermeable soils, minimal groundwater movement, low flows and small freeboards, the opportunity to disrupt sub-surface flows and cause direct drainage of wetland features is small. They may however still facilitate land use change upslope, and receive poor quality run-off which could then be distributed around the wetland. Land use and connectivity in the floodplain are therefore important in determining actual impacts.

Type 7 **Redundant or derelict catch dykes** also generally have minimal impacts. They have been by-passed by a presumably later floodplain dyke network, a change of adjacent land use or some other former of reorganisation of local hydrology. They play little part in the operating hydrology, but can still provide preferential flow lines for groundwater or can become operative in times of very high water tables. They can also be re-activated if a land owner decides to restore all their ditches – perhaps following a change of ownership. Because they have the potential to be transformed to another dyke type by simple maintenance, they can have significant latent risk.

<u>Moderate Risk of Impacts</u>: Ditch Types 2 **Groundwater dykes with minimal direct drainage** and Type 3 **Surface Water Dykes with significant drainage** are likely to have moderate impacts. Type 2 dykes can affect ground water flows to wetlands which are dependent upon them. The degree of impact is dependent on the nature of the groundwater flows and the location, depth and management of the dyke. Type 3 dykes do not significantly affect groundwater but can affect largely topogenous fens through drainage and reduction of the water table. Their impact depends on the degree of drainage, the proximity of the wetland features to the draw-down zone and the sensitivity of those features to reductions in water levels. Clearly the exact impacts of Type 2 and 3 dykes is highly site-specific and requires detailed investigation in the field. Both dykes can be pushed into Type 1 and 5 respectively through relatively straightforward drainage works and therefore have high latent risk.

Severe Risk of Impacts: Type 1 **Groundwater dykes with significant direct drainage** are probably the greatest concern. Because of the context, they are likely to be in locations where groundwater plays a significant role in water budgets and water quality in the floodplain. The adjacent floodplain may also be the locus of wetland types most closely associated with low nutrient water tables, with characteristic natural chemistries vulnerable to disruption. Because of their direct drainage, they are likely to most severely interrupt groundwater movements and also to directly draw down water tables. Because of the permeability of the catchment they are likely to be significant vectors for upland pollutants. This was a frequent dyke type in the case studies.

Type 5 **Severe Directly Draining Dykes** are a threat because of the draw-down in wetland water tables they cause, particularly when connected to floodplain dyke networks that extend their impacts. Because they are usually associated with comprehensive drainage schemes, the likelihood of high quality fen features remaining within the directly drained network are reduced, but fen features at some distance can also be affected. Such dykes are sometimes installed and maintained by the drainage authority. A good example would be the catch dyke maintained by the IDB at Calthorpe Broad. Where this dyke type is combined with other features, such as ochre or permeable substrates, their impact is compounded.

Type 6 **Ochreous** dykes derive their impact in part because they are associated with deep drainage (and are usually hybrid with directly draining dyke types), and also because of the potentially severe water quality impacts they bring. This mostly affects aquatic habitats of the dyke itself, but could affect wetland features in the floodplain if suitable transport mechanisms were available. A severe example of this occurred at Calthorpe Broad (Gosling and Baker 1980).

Conceptual Model for Risk

Figure 9 presents a conceptual model of the risk, relating dyke types to gradients of permeability, drainage and land use on the upland margin, the three driving axes of change for floodplain habitats.

Boundaries of the territories occupied by dyke types on the risk triangle are provisional and approximate. Hybrid dykes or those exhibiting some features of other dykes may have particularly complex territories. There may be more overlap in occupation of the space than the figure implies.

Note that the boundary of Severe and Moderate risk falls at *Pumped drainage impeded by sluices.* This is because sluices are a risky option for dealing with pumped drainage issues – the retention level can be difficult to set (often being the subject of compromise) or can amended later, and there can be seasonal variation in the retention level.

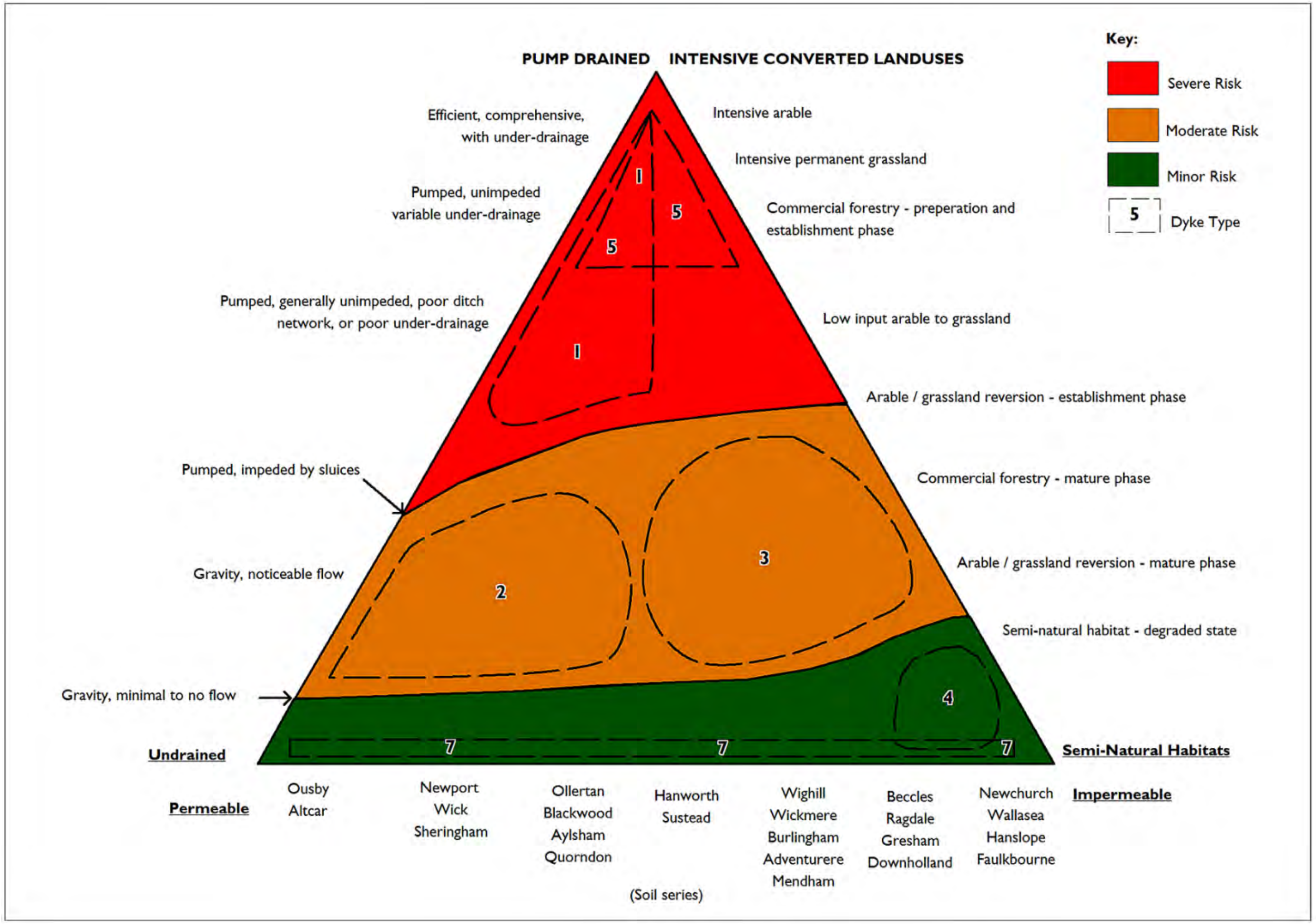


Figure 9: Conceptual Model of Risk of Impacts for Dyke Types 1-7.

Note that Type 6, Ochreous, is a Severe Risk when the indicated soil series are drained. They occupy the red area of the triangle

3.3.3 Assessing Impacts On WetMec Types And Habitats

Table 5 summarises the wetland types (adopting WetMecs, Wheeler et al 2009) and the habitat types (using NVC type) that can be impacted by changes to hydrology and land management. It attempts to map WetMec type and habitat feature onto the risk diagram of Figure 9.

The table includes many WetMecs that are rare or not currently recorded in the Broads. WetMec assessment has not been completed for the whole of the Broads so many unusual types may be present but not documented. Section 2 suggests that many groundwater and seepage dependent WetMecs may have been impacted by catch dykes and could be restored, hence they should be reflected in the table. NVC community has been used to describe habitat feature. Rare species or important faunal assemblages are not included but the approach could be extended to include them. Wheeler's *Peucedano-Phragmitetum-caricitosum*, the very rich community of Broadland turf ponds (Wheeler 1980), has been included within M9 in this table.

NVC types that are commonly accepted Habitats Directive features are indicated in bold. Some such as S24 and S25 have sub-communities with strong calcareous mire elements and are rated in European Commission (2007) as European features under the "Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae"* feature. For sake of brevity, some communities have been aggregated. "Swamp" includes S4-S23, and "Aquatic" refers to species-rich calcareous communities of dykes and fen pits and hollows, often with a significant *Chara* component.

Following on from previous analyses, it is clear that Dyke Types 1 and 5 represent the greatest threat to the widest range of WetMec types and habitat features, many of them of European significance, because of the extreme disruption they can cause to the water table in general and groundwater in particular. Ochreous dykes (Type 6) are similarly problematic where acid sulphate soils makes the system prone to generation of acid sulphate pollutants.

Note that the table indicates *potential* and *risk*, but not *severity*. The table is therefore general, and can only be used for scoping potential issues. Determination of actual impacts requires site investigations.

Table 5: Potential Impact of Hydrological and Land Use Change on Wetland Types and Habitat Features Associated with Each Catch Dyke Type. Cell contents indicate which WetMec and Feature are most likely to be affected by a dyke type, based on section 3.2 and Wheeler et al (2009). Cells colour codes are: Red = severe risk of impact, Orange = moderate risk of impact, Green = Minor risk of impact (see also Figure 9).

<table>
<tr><th colspan="2" rowspan="2">Dyke Types</th><th colspan="7">Issues: Hydrological and Land Use Change Caused by Dyke Type</th></tr>
<tr><th>Change of Ground Water Quality</th><th>Depletion of Water Balance</th><th>Direct Draw Down of Water Table</th><th>Generation of Acid Sulphate Pollutants</th><th>Generation of Nutrients</th><th>Conversion of toe-slope habitats</th><th>Conversion of mid-slope habitats</th></tr>
<tr><td rowspan="2">1. Groundwater dykes with significant direct drainage.</td><td>WetMec</td><td colspan="3">7- 9
10-17</td><td rowspan="2">Depends on upslope land management and presence of acid sulphate soils. It is not related to WetMec type so could affect any.</td><td>7- 9
10-17</td><td>10-17</td><td rowspan="4">Mid-slopes do not sustain WetMecs.

Standard agricultural reclamation threatens U1, U4, MG5 heath and grassland, depending on soil type.</td></tr>
<tr><td>NVC</td><td colspan="3">M9, M13, M14, M22, M23, M24, M25, S1, S2, S24, S25, S27, Aquatic
`</td><td>M9, M13, M14, M22, M23, M24, M25, S1, S2, S24, S25, S27, Aquatic, some swamps</td><td>M22, M23, possibly forms of M24, M25, M13 and M14 in rare favourable geology and topography</td></tr>
<tr><td rowspan="2">2. Groundwater dykes with minimal direct drainage.</td><td>WetMec</td><td colspan="2">7- 9
10-17</td><td>7- 9
10-17
(minimal risk)</td><td rowspan="2">Depends on upslope land management and presence of acid sulphate soils. It is not related to WetMec type so could affect any.</td><td rowspan="2">Not significantly changed</td><td>.</td></tr>
<tr><td>NVC</td><td colspan="2">M9, M13, M14, M22, M23, M24, M25, S1, S2, S24, S25, S27, Aquatic some Swamp</td><td>M9, M13, M14, M22, M23, M24, M25, S1, S2, S24, S25, S27, Aquatic some Swamp</td><td>If freeboard low, toe slope communities not impacted</td></tr>
</table>

Dyke Types		Issues: Hydrological and Land Use Change Caused by Dyke Type						
		Change of Ground Water Quality	Depletion of Water Balance	Direct Draw Down of Water Table	Generation of Acid Sulphate Pollutants	Generation of Nutrients	Conversion of toe-slope habitats	Conversion of mid-slope habitats
3. Surface water dykes with significant direct drainage.	WetMec	5 and 6 (minimal risk because groundwater not significant component)	5 and 6		Depends on upslope land management and presence of acid sulphate soils. It is not related to WetMec type so could affect any.	5 and 6 `	5 and 6	
	NVC	M22, M23, **M24**, M25, S1, **S2, S24, S25**, **S27**, **Aquatic,** Swamp	M22, M23, **M24**, M25, S1, **S2, S24**, **S25**, **S27**, **Aquatic,** Swamp			M22, M23, **M24**, M25, S1, **S2, S24, S25**, **S27**, **Aquatic**	M22, M23 (restricted extent of toeslope likely to preclude development of other communities)	
4. Surface water dykes with minimal direct drainage.	WetMec	Not significantly changed	5 and 6		Depends on upslope land management and presence of acid sulphate soils. It is not related to WetMec type so could affect any.	5 and 6	5 and 6	
	NVC		M22, M23, **M24**, M25, S1, **S2, S24**, **S25**, **S27**, **Aquatic,** Swamp			M22, M23, **M24**, M25, S1, **S2, S24, S25**, **S27**, **Aquatic,** Swamp	M22, M23 (restricted extent of toeslope likely to preclude development of other communities)	

Dyke Types		Issues: Hydrological and Land Use Change Caused by Dyke Type						
		Change of Ground Water Quality	Depletion of Water Balance	Direct Draw Down of Water Table	Generation of Acid Sulphate Pollutants	Generation of Nutrients	Conversion of toe-slope habitats	Conversion of mid-slope habitats
5. Severe directly draining dykes	WetMec	5- 9 10-17			Depends on upslope land management and presence of acid sulphate soils. It is not related to WetMec type so could affect any.	5- 9 10-17	5- 9 10-17	
	NVC	**M9, M13, M14**, M22, M23, **M24**, M25, S1, **S2**, **S24, S25, S27**, **Aquatic** some Swamp				**M9, M13, M14**, M22, M23, **M24**, M25, S1, **S2**, **S24, S25, S27**, **Aquatic** some Swamp	M22, M23, possibly forms of **M24,** M25**, M13** and **M14** in rare favourable geology and topography	
6. Ochreous	Note: Because this dyke type is associated with deep drainage of acid-sulphate prone soils, which overrides the surface/groundwater division, this section mirrors that for dyke type 5					Associated with intensive land uses		
	WetMec	5- 9 10-17						
	NVC	**M9, M13, M14**, M22, M23, **M24**, M25, S1, **S2**, **S24, S25, S27**, **Aquatic** some Swamp				M22, M23, possibly forms of **M24,** M25**, M13** and **M14** in rare favourable geology and topography		
7. Redundant or derelict	WetMec	This dyke type could potentially occur in all landscape situations and hence affect all WetMec types and conservation features, but with very low risk.						
	NVC							

3.4 Stage 3: Developing Solutions Using Decision Webs

Figure 10 presents a decision web for the three main hydrological issues identified in Table 5, Figure 11 presents a web for issues of the generation of acid sulphate pollutants and nutrients. The decision path to particular remedial solutions are outlined. The remedial solutions themselves are discussed in Section 5, along with indicative drawings.

Decision webs are not presented for conversion of toe-slope and mid-slope habitats. These issues are straightforward habitat re-creation and restoration projects which have their own literature and guidance.

Note that Figure 10 and 11 are indicative and simplified. Solutions to difficult problems in complex environments, fraught with constraints, often requires great creativity and collaborative working. They do not lend themselves to simple decision models. However, Figures 10 and 11 do offer a useful guide to the main approaches and remedial measures that can be used in the most often encountered circumstances.

The remedial measures have been colour coded according to sustainability and carbon footprints. Some, usually those involving heavy engineering, are partial treatments or treatment of symptoms rather than addressing root causes. They are of dubious sustainability and involve high carbon footprints. They are often measures of last resort or temporary measures until more sustainable solutions can be put in place.

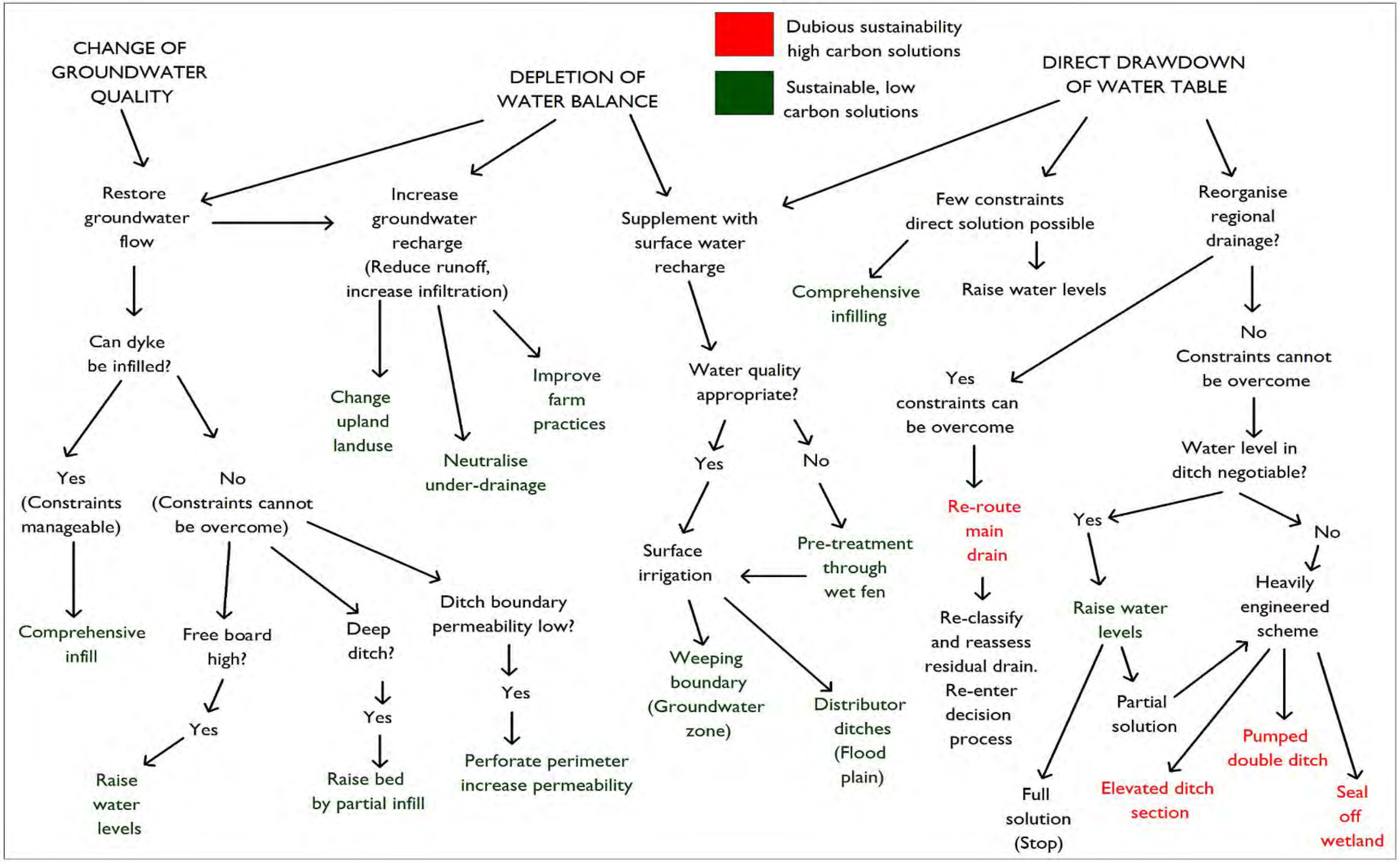


Figure 10: Decision Web for The Three Main Hydrological Issues Described in Table 5.

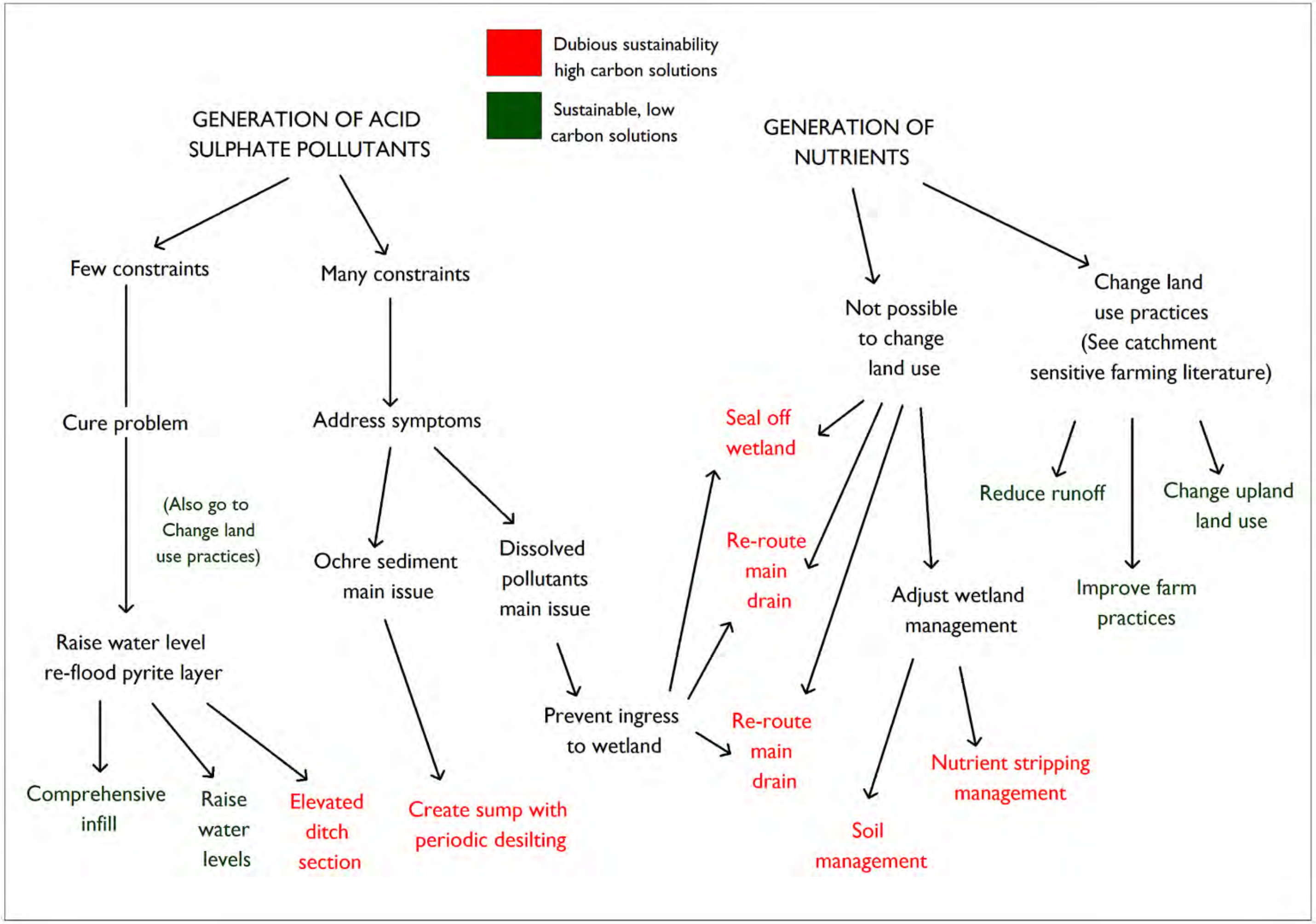


Figure 11: Decision Web for Issues of Generation of Acid Sulphate and Nutrient Pollutants

4. BROADLAND CATCH-DYKE MANAGEMENT POTENTIAL

4.1 Approach

In this section the potential for catch dykes to require remediation work is scoped. Three themes are mapped – soil context, hydrological category, and dyke type with its associated risk – to identify areas where catch dykes may be causing issues with fens and with the hydroseral succession.

Note that the limitations of desk based assessment, and of the scale of mapping, mean that this is a scoping exercise only. Experience from the Case Studies suggests local situations are much more complex and require careful individual consideration.

Maps are presented by river valley for each of the three themes. GIS layers for all three are available.

4.2 Maps Produced

Maps were compiled for:

- Catch dyke soil (Appendix 3). Here, the Soil Association upslope was mapped from published soil maps. This indicates the catchment permeability.
- Catch dyke HOST Class (Appendix 4). The dominant HOST Class for the soil association was mapped as an indication of the dominant hydrological function of the adjacent slope.
- Catch dyke types (Appendix 5). The methodology for this is described in the next section. The maps also show compartments where fen was recorded during the Fen Resource Survey (OHES 2011).

4.3 Methodology for Catch Dyke Classification

The identification of Catch Dyke type was undertaken using the following characteristics (taken from Table 3):

- Upland soil permeability
- Presence of upland aquifer
- Degree of upland slope
- Size and condition of dyke
- Dyke substrate
- Dyke connection to pumped system
- Near surface permeability of floodplain
- Direct drawdown of floodplain
- WetMecs where known.
- Connectivity of floodplain to ditch network

The soil permeability was estimated using the soil association information for each individual catch dyke and descriptions of their permeability, taken from the Soil Survey of England and Wales. The presence of an aquifer was determined using information taken from the British Geological Survey (BGS) bedrock and superficial deposits data for the area. This information was used to determine the presence of an aquifer and its possible influence / interaction with the wetland, as well as the dyke substrate and the near surface permeability of the floodplain. The presence and type of WetMecs within 1km of a catch dyke was used to help determine whether the dyke was ground water or surface water dependent, through the presence of groundwater dependent elements or topogenous types. These dyke characteristics were key for determining the classification of each dyke into one of the eight catch dyke types.

The presence and significance of the upland slope were classified using Ordnance Survey maps, as was the connection of dykes to a pumped drainage system and the level of connectivity of each catch dyke with ditch networks.

5. PROSCRIBING METHODS FOR CATCH DYKE MANAGEMENT

Table 6 summarises proposals for implementing solutions indicated by Figures 10 and 11. For some, there are illustrative figures while others such as ***Raising Water Levels*** or ***Re-route Main Drain*** are too site-specific to provide generic diagrams.

Note that many projects will require deployment of more than one measure. The intention is to present a menu of options from which the caseworker can select the appropriate ones The table can be adapted into an options appraisal format (see Case Studies for examples).

Some measures lack sustainability, as they either have high carbon costs or address only the symptoms and not root causes of problems – or sometimes both. Another problem with such measures is that once implemented, stakeholders may believe the problem is resolved and then be unwilling to look at further long-term and more sustainable measures. They should be considered as measures of last resort, or emergency interim measures, although they can have high capital costs. Such measures include:

- **Elevated Ditch Section**
- **Seal off wetland**
- **Re-route main drain**
- **Pumped Double Ditch**
- **Create sump with periodic desilting**

Table 6 does not consider risks such as budget overruns or other project management issues which are typical of any significant scheme.

The Constraints column refers to constraints operating generally for the project, not the specific measure, and indicate how much freedom decision makers need before they can consider a measure. So, for the first measure, ***Comprehensive Infill***, the constraints column of the table indicates this is only feasible when project constraints can be "Mostly overcome".

Table 6 : Summary of Catch Dyke Management Solutions

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Strongly Engineered Solutions					
Comprehensive Infill (Figure 12)	• Reduce impact of direct drainage. • Restore groundwater flows. • Remediate depletion of water balance. • Restore highland to floodplain ground profile. • Allow for full restoration of hydroseral succession. • Remediate drainage of acid sulphate soils.	Mostly overcome	High. Complete solution, no maintenance, moderate to low carbon footprint.	Aim is to match permeability of infill with that of the host soils/sub-soils. This includes layering if present. Matching lateral permeability of disturbed materials with in-situ materials is challenging, especially with peat. Highly permeable fill may form preferential groundwater flow lines down valley, capturing groundwater, hence the need to install cross dyke barriers. Must remove all silt and vegetation on the original dyke perimeter, and any ripened surface, so that infill is married to raw substrate.	Springs can “blow” fill, especially semi- or impermeable material.
Raise Bed by Partial Infill (Figure 13)	• Restore groundwater flows. • Remediate depletion of water balance. • Remediate drainage of acid sulphate soils.	Compromise solution where total infill is constrained.	High as a stand alone, but may require additional measures to provide comprehensive solution.	This solution can stop deep dykes cutting into groundwater flow to the wetland. Need to match permeability of infill with substrate, and prevent flow down the dyke with barriers. Where treating acid sulphate soils, infill must reach top of pryrite layer in sub-soil, unless combined with ***Raise Water Levels.***	Still allows direct drainage or removal of groundwater unless combined with other measures such as ***Raising Water Levels*** and ***Perforate Perimeter***.
Raise Water Levels	• Reduce impact of direct drainage. • Restore groundwater flows. • Remediate drainage of acid sulphate soils.	Useful where dyke must remain and with current dimensions.	High, as installation has low carbon footprint, and most sluices are low maintenance. A relatively low cost option.	Key is the determination of the retention level. As in-fill is constrained, use of this solution suggests compromise is needed and some kind of drainage function still required of the dyke. Base of sluice should be keyed into impermeable substrates to prevent sluice being bypassed. Unless automated, requires operative who works strictly to an agreed protocol. Design options are infinite and site-specific, hence no illustrative diagram.	Too much compromise on retention level can render solution ineffective. Key parameters are freeboard and seasonality of retention. Leakage is the other main risk.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Perforate Perimeter and Increase Permeability (Figure 14)	• Restore groundwater flows. • Remediate depletion of water balance.	Constraints significant, preventing more comprehensive solutions.	High, but some aspects will need maintenance.	Works are directed at improving flow of water from the dyke into the wetland. It is also possible to perforate the upland margin of the dyke to encourage ingress of groundwater to the dyke. Its effectiveness depends on the freeboard – it works best when the dyke is full, creating a larger seepage face. Perforation can include trenches of permeable material cutting across the dyke, mole draining the upper horizon, using land drainage to import water to the wetland and simple cleaning of the ditch face blinded by silt. Solution is most appropriate for permeable and semi-permeable substrates. It is most effective when used in combination with other measures such as ***Raise Water Levels***.	Where freeboard is low, increasing permeability may only serve to increase drainage of adjacent wetland. Measures must only be implemented below the ditch water level. Where nutrients are an issue, perforation could cause eutrophication of wetland. Other measures such as ***Raise Water Levels, Change Upland Land Use*** or ***Nutrient Stripping Management*** required to mitigate risks.
Elevated Ditch Section (Figure 15)	• Reduce impact of direct drainage. • Restore groundwater flows. • Remediate drainage of acid sulphate soils.	Applicable where constraints prevent upstream raising of water levels.	Low, as requires significant engineering, maintenance and long-term energy consumption (high carbon footprint) unless windmill is viable.	A local solution where a high water level is required but is not feasible upstream. Water is raised over a barrier by a pump and then flows to a sluice which provides the retention level. The pump is high maintenance unless automated. A windmill is possible if the lift and the flows are low, flood risk is low and wind is reliable. The system requires daily checks by a reliable operative.	Risks are the same as ***Raise Water Levels***. Additional risk is pump failure causing upstream water levels to increase.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Seal off wetland (Figure 16)	• Reduce impact of direct drainage. • Remediate drainage of acid sulphate soils • Remediate generation of nutrients.	Applicable where no change to catch dyke or to surrounding land use is permissible.	Very low. A heavily engineered solution with significant land take. Significant long term maintenance. Largely seals wetland off from groundwater. An option of last resort.	Where direct drainage or ingress of pollutants and nutrients is causing significant damage, but the catch dyke is an untouchable drainage ditch, this may be the only option. The impermeable boundary can be a grout curtain, a trench backfilled with clay or an impermeable artificial membrane. It should be keyed downwards into impermeable material to prevent subsurface leakage. The line of the membrane needs maintenance to prevent puncture by burrowing animals, vegetation or stones. After installation, the floodplain wetland is entirely dependent on other sources of water, hence not suitable for a wide range of WetMec types.	Main risks are disturbance during installation, leakage and sealing out of beneficial groundwater.
Re-route main drain.	• Reduce impact of direct drainage. • Restore groundwater flows. • Remediate depletion of water balance. • Remediate generation of nutrients. • Restore highland to floodplain ground profile. • Allow for full restoration of hydroseral succession. • Remediate drainage of acid sulphate soils.	Applicable where drainage function of catch dyke needs to be maintained but could be achieved using a different ditch route.	Low. May divert impacts elsewhere and requires significant engineering.	This is only applicable where there are sufficient resources to allow a reorganisation of regional drainage. It is only possible where topography allows the same drainage function to be provided from another ditch location. Requires a catchment wide approach with detailed planning and stakeholder negotiations, and possibly land use change in some parts of the catchment. The by-passed catch dyke will still have an impact, hence needs specific additional measures to re-naturalise the hydrosere.	The re-routed drain may have significant impacts along the new route.
Pumped Double Ditch (Figure 17)	• Reduce impact of direct drainage. • Restore groundwater flows. • Remediate drainage of acid sulphate soils.	Applicable where no change to catch dyke is permissible.	Very low. A heavily engineered, high maintenance solution with significant land take. An option of last resort.	A new ditch is cut, probably along the wetland edge, with an impermeable barrier between it and the original catch dyke, with water pumped from the catch dyke to the new high level ditch. The new ditch with maximum freeboard reduces wetland drainage and restarts throughflow to the wetland. Lifting water requires pumping, but the scheme does not have flood risk as the original ditch is not affected. If there is no impermeable barrier between the ditches, water will recirculate, requiring higher rates of pumping.	Risks the same as ***Raise Water Levels*** and ***Seal off wetland***.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Neutralise Under-drainage (Figure 18)	• Remediate drainage of acid sulphate soils • Remediate generation of nutrients. • Enable land use change and restoration of toe slope habitats.	Applicable where no drainage needed in adjacent land. Usually tied to change in land use.	High. Once completed needs no further attention.	Required work depends on type of under-drainage, and in particular the density of outfalls. Arterial drainage of small areas, or where field drains discharge to one or two outfalls, can be blocked with bentonite during a very dry period. This is quick and cheap, but the plugs could be dislodged or washed out over time. The most effective method is to run along the ditch margin with a machine and excavate a 1m wide trench to under-drainage depth, breaking up the drains and then re-compacting the fill. Care is needed to match the permeability of the parent soil when re-compacting. Over-compaction can lead to an impermeable vertical barrier being created which impedes natural groundwater flows to the wetland.	Drain plugging ineffective in long term, leading to drains re-opening. In trench treatments, over-compaction of fill leads to impedance of ground water flow.
Soft Engineering Solutions					
Weeping Boundary (Figure 19)	• Restore groundwater flows. • Remediate depletion of water balance. • Reduce impact of direct drainage.	Applicable where constraints mean a catch dyke cannot be directly remediated.	Low to medium. Requires mechanism for delivering water to weeping boundary but once installed is low maintenance.	A weeping boundary delivers sub-surface irrigation in a way that mimics groundwater seepage or near-surface throughflows. It is appropriate for groundwater dependent WetMec types. The main requirement is a water supply for the weeping boundary. Ideally, this should be from a high carrier but could be pumped. The weeping boundary itself is a zone of high permeability that seeps water into the wetland area of interest, mimicking throughflow and mitigating drawdown from evapotranspiration. Techniques are essentially those of ***Perforate Perimeter…..,*** applied to the boundary of the ditch or other delivery mechanism. Such schemes are likely to be technically difficult to achieve and require significant land take from the wetland. Water chemistry must match that of original wetland supply mechanism.	Technical complexity can lead to high risk of failure. Risk of mismatch of water quality between supplementary water and natural water.
Distributor Dykes (see Figure 20)	• Remediate depletion of water balance. • Reduce impact of direct drainage.	Applicable where constraints mean a catch dyke cannot be directly remediated.	Low to medium. Requires mechanism for supplying ditches, but is low maintenance. Creation of new dykes involves loss of fen.	This solution is applicable to floodplain WetMecs rather than those dependent on groundwater (c.f. ***Weeping Boundary***). Here, a network of surface water drains (which could be no more than foot drains) distribute water around the wetland area, direct to the surface soil horizons. Supplementary water should ideally have the same water chemistry as that which has been depleted by drainage. Density of foot drains depends on surface soil type.	Impacts habitat feature (could be positive if designed correctly). Risk of mismatch of water quality between supplementary water and natural water.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Create sump with periodic desilting.	• Remediate drainage of acid sulphate soils. • Deals with fine sedimentary ochre deposits.	Applicable where constraints mean the problem cannot be addressed, only the symptoms treated.	Very low. Deals only with symptoms. Sediment removal and disposal will continue until soil stores of pyrites exhausted. Removal from site and disposal has high carbon footprint and high expense. A temporary measure of last resort.	This measure addresses ingress into the wetland and its water bodies of semi-toxic ochreous silt which cannot be stopped at source. This may be especially problematic for water bodies downstream of pumped systems. The catch dyke itself may form the sump if it is proximal to the area of ochre generation. On-line ponds are an alternative. The sump is periodically desilted and the material removed. It requires considerable technical development, including dewatering sediment, disposal and creating access for the necessary machinery. The solution cannot address dissolved toxins such as acidity, reduced Fe and Al ions.	While the material remains in the sump, it may leach toxins into the wetland.
Pre-treatment through wet fen (Figure 20)	• Remediate generation of nutrients. • Remediate drainage of acid sulphate soils.	Applicable where constraints mean it is not possible to prevent contaminated water entering wetland.	High to medium. Soft engineering with potential habitat benefits. May require periodic "cleaning" of fen bed and removal of accumulated sediment.	This solution intercepts sediments, particulates and nutrients. It requires discharge of affected water across the fen surface allowing material to settle out and be "digested". Wide variety of swamp communities are suitable as receptors, but they should be species-poor as the discharge will promote species-poverty. Low gradients typical of floodplain swamp lends itself to the requirement this measure has for trickle-through. Key design requirement is discharge mechanism. Creation of foot drains and shallow bed grading are likely to be required. Probably most effective in combination with other solutions.	Risk that design does not provide optimal trickle through and digestion, resulting in poor quality water discharging to fen. Risk that creation or operation of treatment area impacts high quality fen.
Soil Management	• Remediate generation of nutrients. • Remediate drainage of acid sulphate soils.	Applicable where constraints mean it is not possible to prevent contaminated water entering wetland.	Low, requires significant excavation and removal of arisings. High carbon footprint.	Where nutrients or other toxins have accumulated in the top soil horizon of the fen or upland, wholesale removal can be beneficial. On mineral substrates on dry land, soil profile inversion has had success through burying the enriched topsoil. Unless source of nutrients is resolved, this measure will need to be repeated. Can be used creatively to restore wet and/or low nutrient fen types.	Stripping off the top soil structure can disrupt hydrological functioning.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Vegetation and Land Management					
Create buffer and/or nutrient stripping zone	• Remediate generation of nutrients. • Remediate drainage of acid sulphate soils.	Applicable where constraints mean it is not possible to prevent contaminated water entering wetland. Suitable for less acute problems than ***Pre-treatment through wet fen.***	Low. Does not deal with issues and requires ongoing commitment.	This is particularly suitable for toe slopes, for the interception of sediments and poor quality water before they enter the catch dyke or wetland (if the catch dyke has been infilled). It can also be used on the floodplain margin to intercept run-off if the catch dyke overflows, or to intercept shallow throughflow and poor quality seepage water. It is a low-impact form of the ***Pre-treatment through wet fen.*** It is likely to be less effective and most suitable for mild nutrient/pollutant situations.	Low risk.
Nutrient Stripping Management	• Remediate generation of nutrients.	Applicable where constraints mean it is not possible to prevent contaminated water entering wetland, or where dealing with historic eutrophication issues.	Low. Does not deal with issues and requires ongoing commitment. Requires disposal of significant quantities of cut material annually.	Reducing nutrient loadings in the soil by cropping is a long-term solution that will only work if the annual ingress of nutrients is less than that removed by cropping. It is therefore mostly suitable for depleting soil nutrient stores and where other measures have stopped further ingress. Annual cut-and-clear can be expensive especially on larger fen sites. Can have biodiversity benefits in terms of species-richness but may not be suitable for fen habitats requiring long rotation management.	Could impact faunal groups requiring low-intensity fen management.

Solution	Purpose	Constraints	Sustainability	Key considerations	Key risks
Change Upland Land Use	**Directly assists**: • Allow for full restoration of hydroseral succession. • Remediate drainage of acid sulphate soils. • Remediate generation of nutrients. **Facilitates:** • Reduce impact of direct drainage. • Restore groundwater flows. • Remediate depletion of water balance. • Restore highland to floodplain ground profile.	Constraints on land use must be lifted.	Very high, the optimal sustainability for both highland and floodplain.	This action facilitates many of the main drainage issues because it removes one of the main drivers for catch dyke management – maintaining a low freeboard to enable intensive management of the highland, especially on under-drained land or land with gentle slopes. Changing land use would remove many of the constraints on remedial action. It would have direct benefits for nutrient problems by reducing the addition of fertiliser and by reducing mobility of nutrients in the soil profile. Essentially the objective is to move the active land use as far down the axis of the risk triangle (Figure 9) as possible. To restore the hydroseral succession, restoration of semi-natural habitats is required.	Minimal risk.
Improve Farm Practise	• Remediate drainage of acid sulphate soils. • Remediate generation of nutrients. • Restore groundwater flows. • Remediate depletion of water balance.	Appropriate where land ownership constraints prevent land use change.	High. Changes in farm practise reduce carbon footprint and increase long term sustainability.	This element refers to a whole collection of measures which reduce the impact of the particular land use. It especially applies to land uses in the high risk zone of Figure 9, and to a lesser extent, the moderate risk zone. Measures should aim to reduce nutrient input, reduce need for under-drainage, reduce bare land phases, and reduce the freeboard required of the catch dyke. This measure is firmly within Catchment Sensitive Farming and much assistance could be gained from this programme.	Minimal risk.
Reduce Run-off	• Remediate generation of nutrients.	Appropriate where land ownership constraints prevent land use change.	High. Requires no capital works or long term maintenance.	Reducing run-off focuses on high-risk land uses (Figure 9) where land management practises lead to overland flow or high discharges from under-drainage. Run-off can deliver high volumes of silt and nutrients. It also places additional pressures on drainage infrastructure, encouraging maintenance of low water levels in dykes. Measures to reduce run-off will include some from ***Improve farm practises***, plus actions such as contour ploughing, buffer strips, increase soil surface permeability (reducing compaction) and retaining excess water on the land. This measure is firmly within Catchment Sensitive Farming and much assistance could be gained from this programme.	Minimal risk.

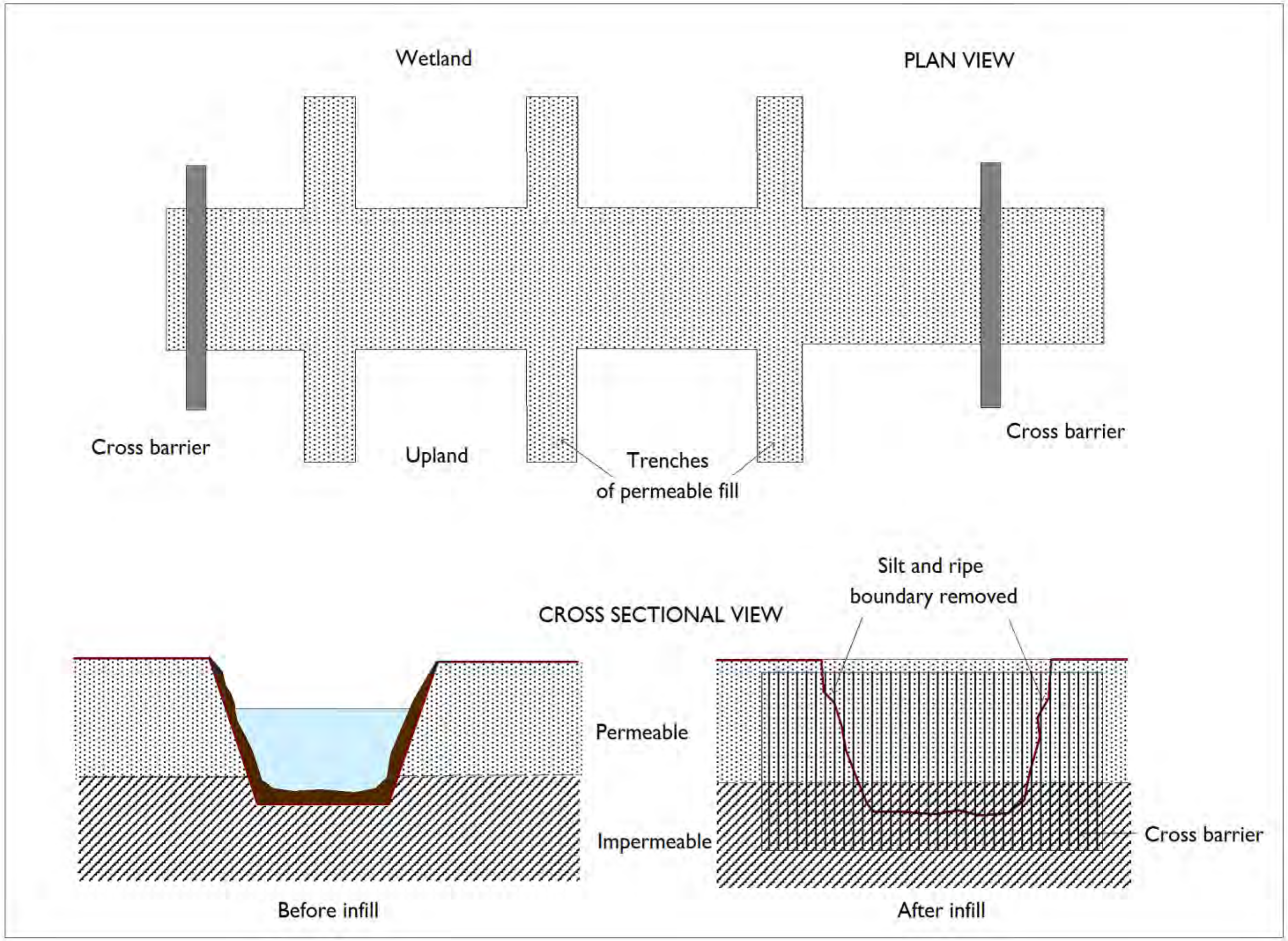


Figure 12: Comprehensive Infill

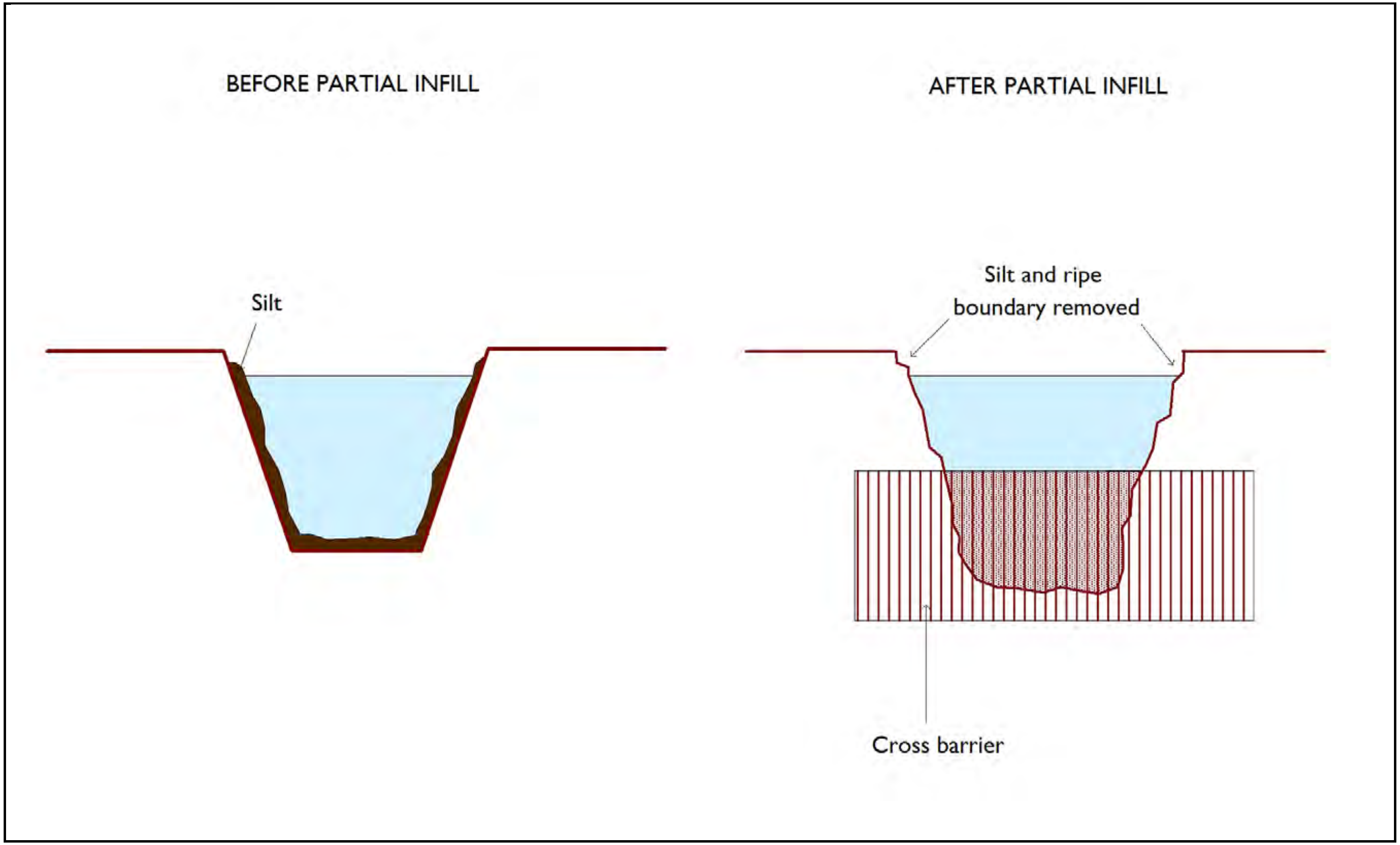


Figure 13: Raise Bed by Partial Infil

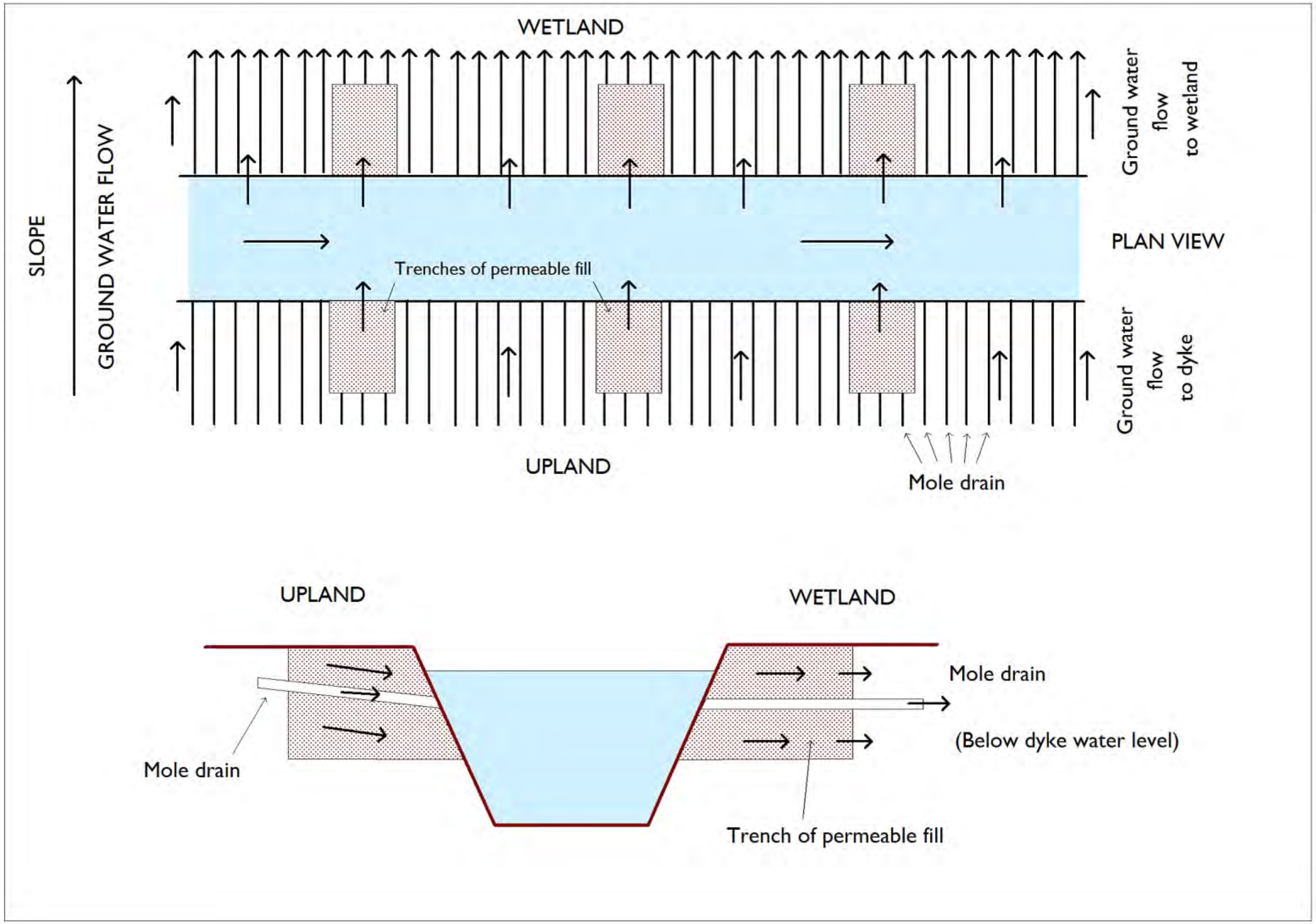


Figure 14: Perforate Perimeter and Increase Permeability

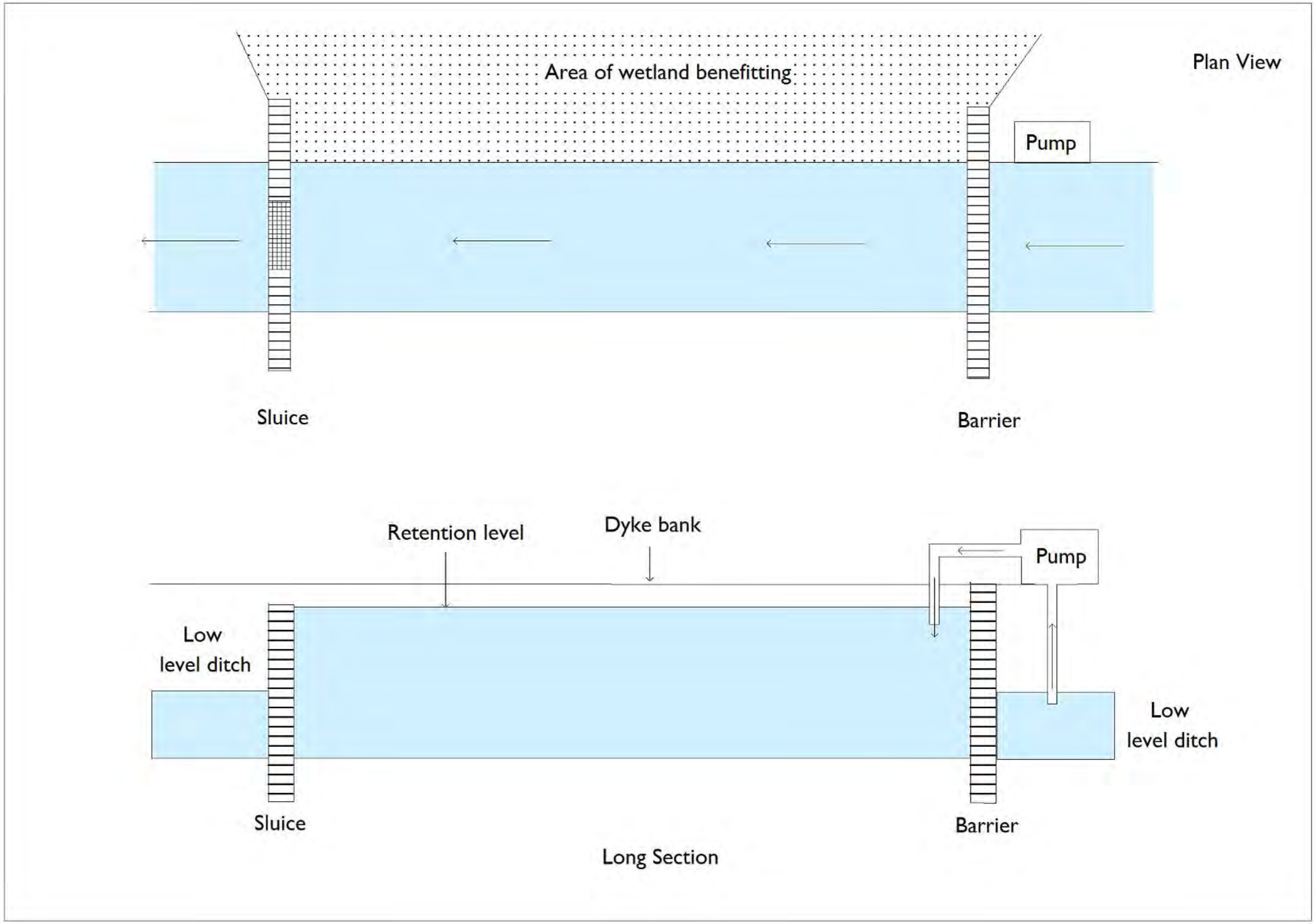


Figure 15: Elevated Ditch Section

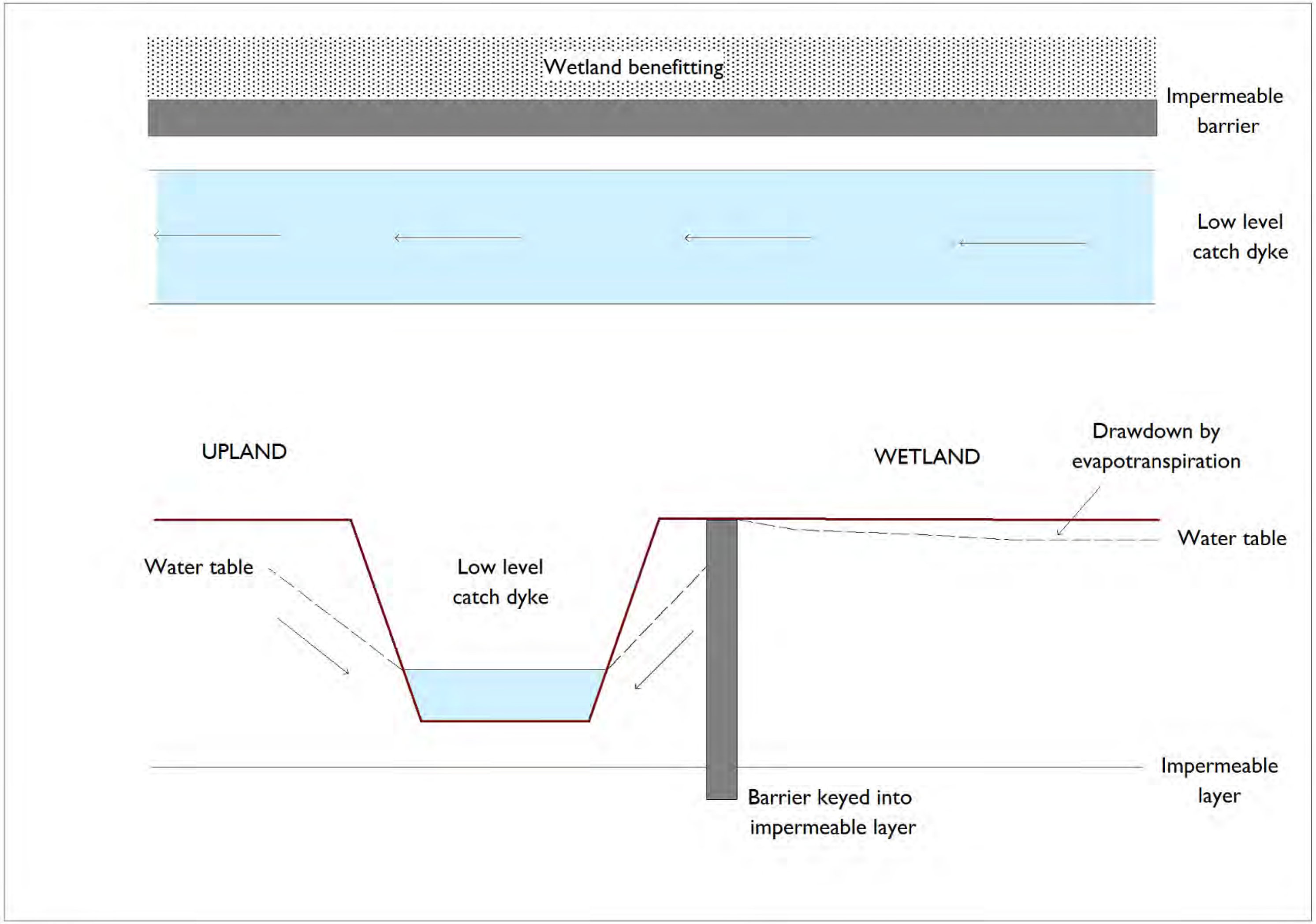


Figure 16: Seal Off Wetland. Planform above, cross-section below.

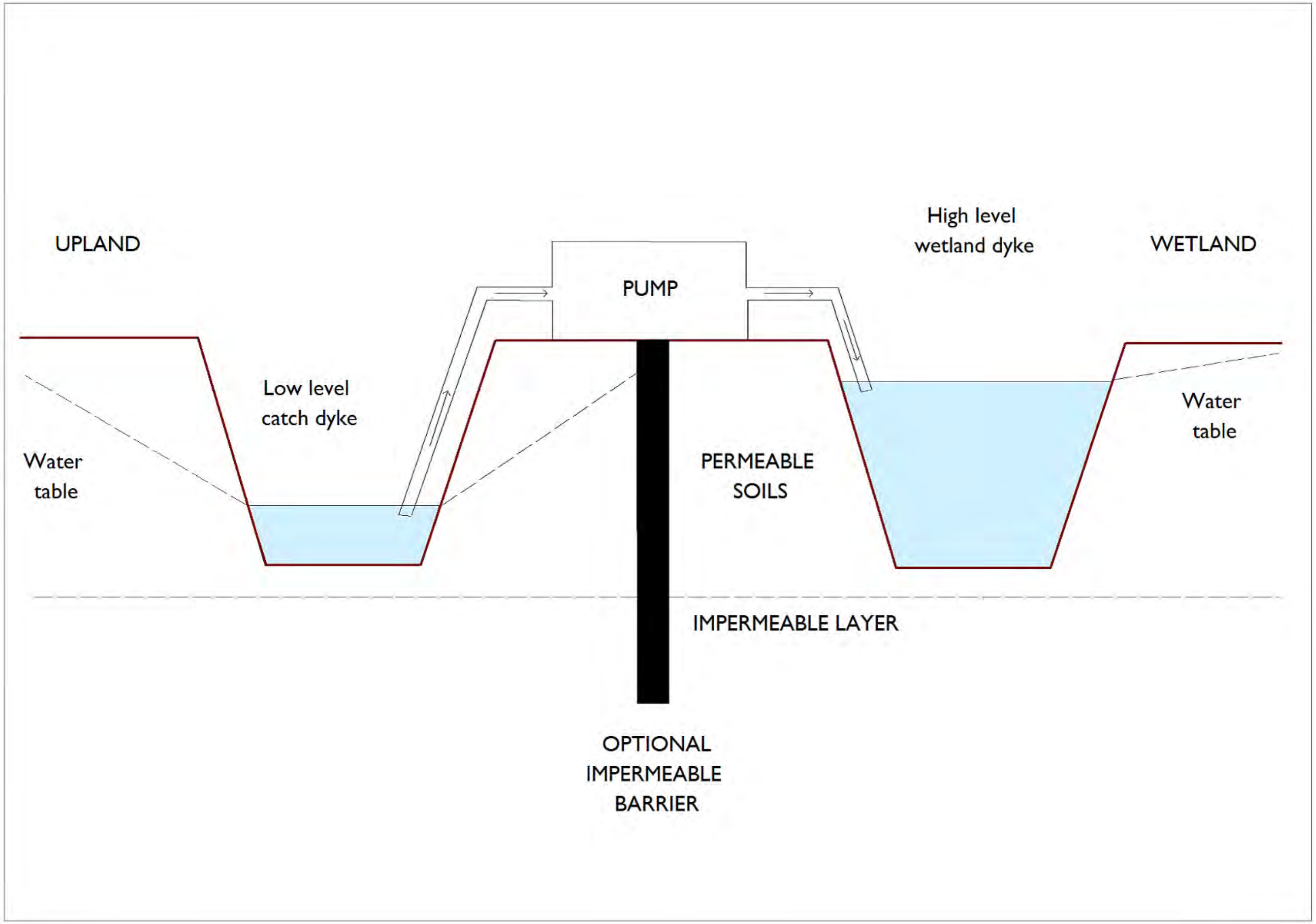


Figure 17: Pumped Double Ditch

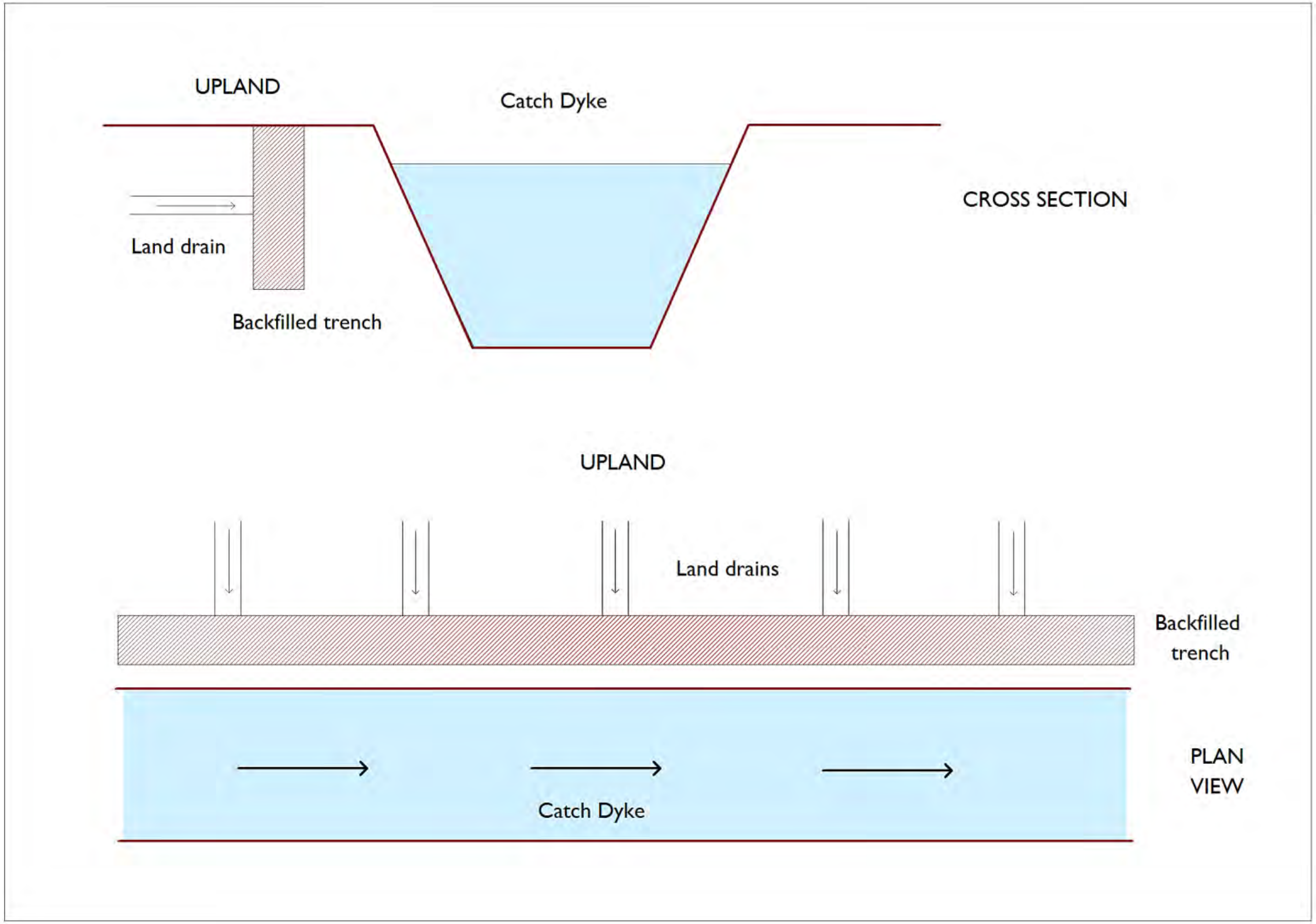


Figure 18: Neutralise Under-drainage

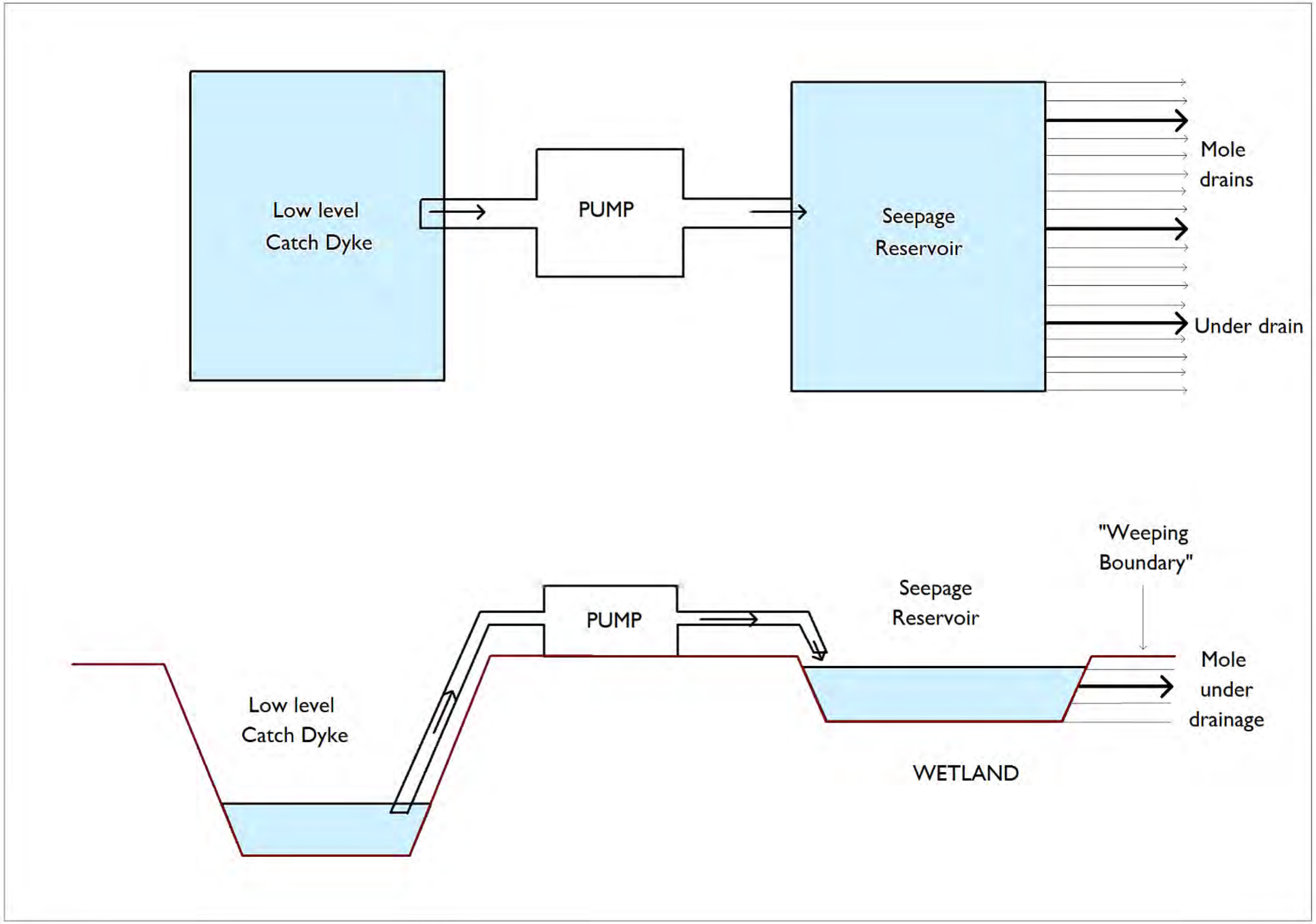


Figure 19: Weeping Boundary

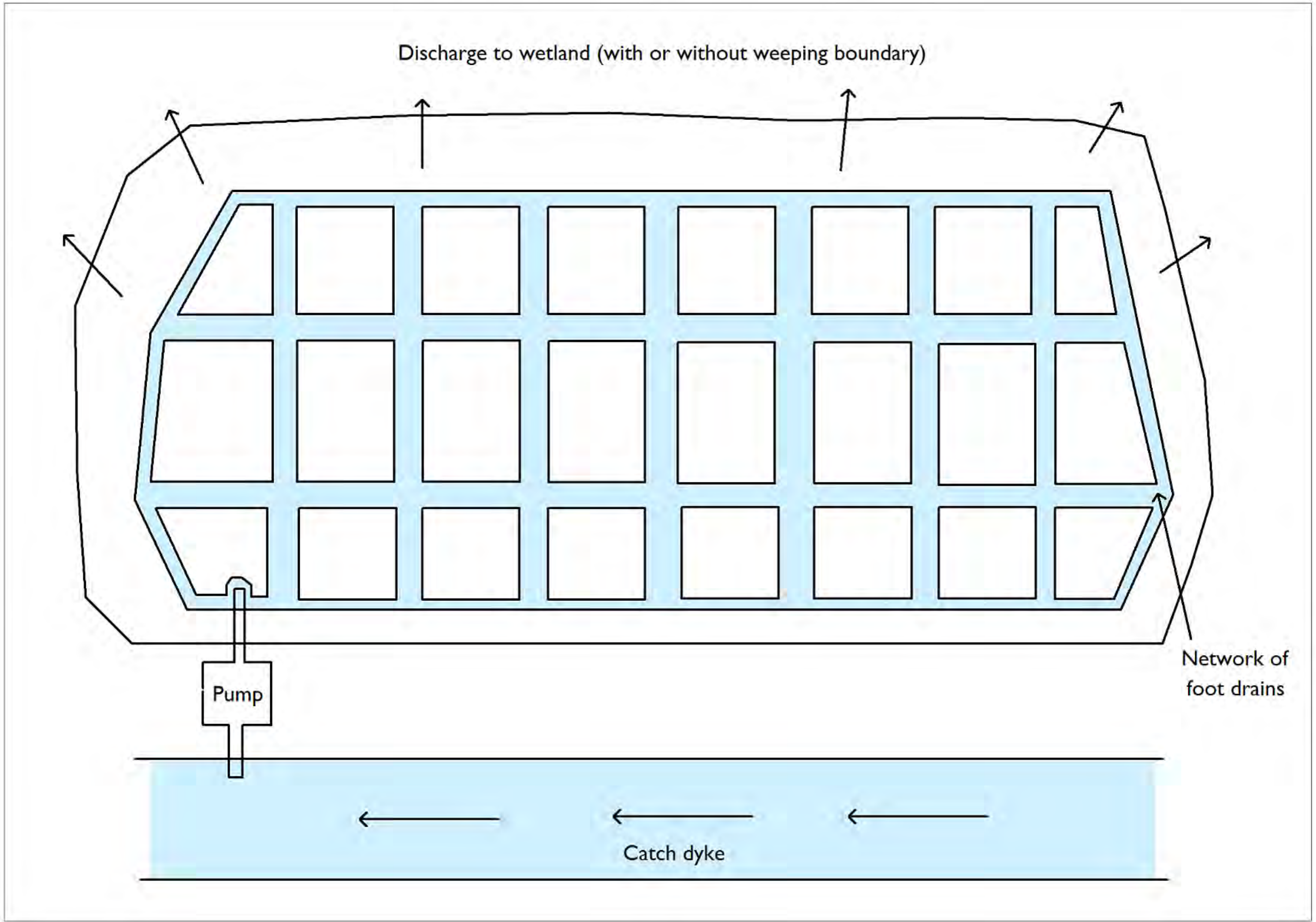


Figure 20: Distributor Dykes and Pre-treatment Through Wet Fen. The figure serves to illustrate both options.

6. ENVIRONMENTAL STEWARDSHIP OPTIONS

6.1 Scope of Considerations

The original intention of this section, and of section 7, has been to present funding options for the management solutions proposed in section 5 that were available through the agri-environment schemes operating within the Rural Development Programme. At the time of finalising this project report (November 2014), details of the New Environmental Land Management Scheme (NELMS) have not been finalised and published, and only broad comments can be made, based upon the following Defra CAP reform reports:

- Press release: New environmental scheme for farmers to prioritise biodiversity
  From: Department for Environment, Food & Rural Affairs and George Eustice MP
  First published: 26 February 2014
- Consultation on the implementation of CAP reform in England
  Summary of responses and government response
  December 2013
- Consultation on the implementation of CAP reform in England
  Summary of responses and government response on remaining issues
  February 2014
- An introduction to the new Common Agricultural Policy schemes in England
  Defra April 2014
- Policy paper: Rural Development Programme for England: outline of new programme
  Published 10 June 2014
- The new Common Agricultural Policy schemes in England: August 2014 update
- Cross compliance: lists of SMRs and GAECs from 2015 [post August 2014]
- The new Common Agricultural Policy schemes in England: October 2014 update

This section therefore addresses the potential for funding the engineered management solutions, proposed as ***Strongly Engineered*** and ***Soft Engineering*** in section 5, Table 6, based on Defra's publications to date.

Similarly, section 7 addresses the potential to fund the ***Vegetation and Land Management*** solutions proposed in Table 6, which would affect the contiguous upland and wetland margin adjacent to the catch dyke.

It is anticipated that detailed guidance on the changes to Direct Payments and Rural Development Payments will be published in the coming months; funding considerations should then be reviewed in the light of this guidance.

6.2 Funding Considerations for Engineered Catch Dyke Management Solutions

Table 7 presents a summary of the funding considerations highlighted in Table 6 for the hard and soft engineered solutions. It is apparent that the schemes require three distinct funding types:

a) Engineered construction and earth-moving
b) Capital items
c) Operation and maintenance

Table 7: Funding Considerations for Engineered Catch Dyke Management Solutions

	Solution	Funding considerations[a]
Strongly Engineered	***Comprehensive Infill***	Complete solution, requiring no maintenance
	Raise Bed by Partial Infill	Potentially complete solution, though may require to be combined with ***Raise Water Levels*** and ***Perforate Perimeter***.
	Raise Water Levels	Potentially complete solution requiring sluice installation, operation and maintenance.
	Perforate Perimeter and Increase Permeability	Potentially good solution requiring routine maintenance; typically combined with ***Raise Water Levels, Change Upland Land Use*** and possibly ***Nutrient Stripping Management***.
	Elevated Ditch Section	Local solution requiring capital investment (sluice with pump/windmill), routine operation and potentially high maintenance.
	Seal off wetland	High installation costs with significant long-term maintenance.
	Re-route main drain	Site-specific with potentially high engineering costs.
	Pumped Double Ditch	High engineering costs with significant long-term maintenance.
	Neutralise Under-drainage	Potentially effective solution when ***Change Upland Land-Use*** is applied to a significant contiguous area. Repeatable if required.
Soft Engineering	***Weeping Boundary***	High engineering costs; pump installation, operation and maintenance.
	Distributor Dykes	May require supplementary water; pump installation etc.; foot-drain costs known.
	Create sump with periodic desilting	Limited solution, treating the symptoms only. May be applicable where other, slower-acting solutions are implemented.
	Pre-treatment through wet fen	Pump installation, etc. may be required; foot-drain costs known; may require sediment management.
	Soil Management	Excavation and removal costs; may be combined with ***Change Upland Land Use*** and possibly ***Nutrient Stripping Management***.

[a] The Case Studies presented in section 8 provide examples of appropriate solutions and combinations of solutions, to address particular situations.

Engineered construction and earth-moving. As is pointed out for several of the proposed solutions, the technical precision required varies considerably between solutions and may also differ between situations and locations. As the variables affecting each situation and location – such as ease of access, clearance of scrub, soil type, depth of freeboard, cost of earth movement or disposal, and so on – are case-specific, it may not be possible to view costs on a unit-cost basis. It is also likely that engineering quotations would be accepted entirely on cost, and quotations may need to be accepted a tolerance for project over-run.

It is therefore considered that this funding type is not a suitable candidate to be covered under a scheme option, but should be addressed within a capital works plan.

Capital items. These include pumps (with their power sources) and sluices. Where sluices and water elevation is proscribed, capital outlay should reflect the necessary capacity and installation requirements to meet the specified needs. In addition, a balance may need to be met between capital and operational/maintenance costs to effect a durable solution.

Operation and maintenance. As has been highlighted in Table 6, the proposed range of solutions vary in their requirement for routine operation and/or maintenance, and in the anticipated risk of partial or wholesale failure of an engineered solution.

The degree of subsequent support for operation, maintenance and repair for a particular solution or group of solutions would therefore be managed within an implementation plan.

6.3 The New Environmental Land Management Scheme (NELMS)

Following the October 2014 Defra Update, a number of broad generalisations about NELMS have been announced:

The Basic Payment Scheme (BPS) will replace the Single Payment Scheme (SPS). To qualify, land managers must be an 'active farmer', have at least 5 hectares of 'eligible' land (i.e. 'naturally kept in a state suitable for cultivation and grazing', and possess at least 5 'entitlements'. About 30 % of this Direct Payment will be subject to three 'greening rules' covering crop diversification (number of crops grown), permanent grassland (details to be confirmed) and 'Ecological Focus Areas' (for farmers with more than 15 hectares of arable land. Further details are given in section 7.

The Rural Development Programme for England (RDP) is part of the Common Agricultural Policy, and is jointly-funded by the EU and the Government, which has announced it will spend £3.5bn over the seven years from 2014 – 2020. The programme is intended to help protect the environment, promote economic growth in rural areas, and to target improvements and maintain landscapes that underpin rural tourism, help to provide resources for farmland birds and pollinators and tackle at source water pollution. The European Commission is currently considering the UK proposals and this is expected to take around 6 months (i.e. until about March 2015). Once it has been agreed, the full programme document – setting out how the RDP will be funded, managed, monitored and evaluated – will be published on the Commission's website.

The Programme will support 3 main areas:

- managing the environment
- increasing farming and forestry productivity
- growing the rural economy

The new environmental land management scheme (NELMS) will offer:

- site specific agreements similar to the current Higher Level Stewardship (HLS) scheme
- area specific agreements aimed at targeted improvements in the wider countryside
- multi-annual agreements, normally for 5 years – but these could be longer if benefits take longer to achieve
- a choice of management options, capital items and advisory support (depending on the agreement type)
- annual small-scale grants for certain activities – such as hedgerow laying, coppicing and stone wall restoration

Defra have announced that applications would open during 2015 for an agreement which would start on 1 January 2016. The new scheme will not be underpinned by other agreements, such as with the current Higher Level Stewardship (HLS) agreements which currently have to be underpinned by an ELS agreement[3].

Defra propose to continue with similar arrangements for priority sites (the so-called "upper tier"). It would be largely analogous to HLS and retain similar processes. Because of the bespoke and complex nature of these types of agreements it would effectively be by invitation following assessment of expiring HLS and new candidate sites. Given the focus on designated and priority sites we might expect to see a high level of renewals from HLS. For "mid tier" applications, Defra intends to identify priority areas which present the best opportunities to deliver the scheme's objectives and then scoring applications to secure the best quality "offers"; high quality individual applications addressing local priorities will characterise these agreements. Consideration is being given to how best to positively recognise any group applications in the selection criteria.

The EU rules allow for investment in physical assets for non-productive investments which contribute to agri-environment climate objectives. These are commonly termed as capital items. All agreements whether priority sites or priority areas will be able to include a 2 year capital works plan alongside multi-annual scheme options. It must be essential to the achievement of environmental outcomes of the overall agreement. The environmental benefit of including the capital works would be recognised in the scoring system. The measures which can support capital grant items for water

[3] Notwithstanding, as an 'active farmer', agreement holders receive the Basic Payment, and are thus subject to Cross Compliance.

objectives have been included in the programme design and are going through the established process on verification and payment rates.

Under the current Catchment Sensitive Farming scheme, capital grants are offered with advice to some farmers. Defra are reviewing this scheme and will take into account how capital grants for water quality objectives will be available and targeted from 2015, under the Rural Development Programme.

7. POTENTIAL OPTIONS FOR MANAGING ADJACENT UPLANDS

7.1 Scope of Consideration

The original intention of this section has been to present funding options for the ***Vegetation and Land Management*** solutions proposed in section 5 that were available through the agri-environment schemes operating within the Rural Development Programme. These solutions address issues where at least partial solutions can be addressed on the contiguous upland and wetland margins adjacent to the catch dyke.

At the time of finalising this project report (November 2014), details of the New Environmental Land Management Scheme (NELMS) have not been finalised and published, and only broad comments can be made, based upon the Defra CAP reform reports listed in section 6.

It is anticipated that detailed guidance on the changes to Direct Payments and Rural Development Payments will be published in the coming months; funding considerations should then be reviewed in the light of this guidance.

7.2 Funding Considerations for Vegetation and Land Management Solutions

Table 8 presents a summary of the funding considerations highlighted in Table 6 for the vegetation and land management solutions proposed.

Table 8: Funding Considerations for Upland/Wetland Margin Management Solutions

Solution	Funding considerations[a]
Create buffer and/or nutrient stripping zone	Applied to contiguous upland/toeslopes in mild nutrient/pollutant situations; potentially suitable in combination with engineered solutions.
Nutrient Stripping Management	Applied to wetland margins affected by upland sources of contaminated water; potentially high operation/disposal costs.
Change Upland Land Use	Known costs; preferably combined with ***Raised Water Levels***.
Improve Farm Practise	Linkage to Catchment Sensitive Farming measures.
Reduce Run-off	Linkage to Catchment Sensitive Farming measures.

[a] The Case Studies presented in section 8 provide examples of appropriate solutions and combinations of solutions, to address particular situations.

The first three solutions fall clearly within the anticipated range of options though, where cutting and removal of vegetation for non-agricultural use is involved, agreements will need to consider means of disposal and the potential costs incurred.

The remaining solutions are likely to be dependent upon the outcome of Defra's review of Catchment Sensitive Farming. Notwithstanding, the intention has been expressed to dovetail any future scheme with the capital grants and multi-annual agreements offered under the new RDP scheme.

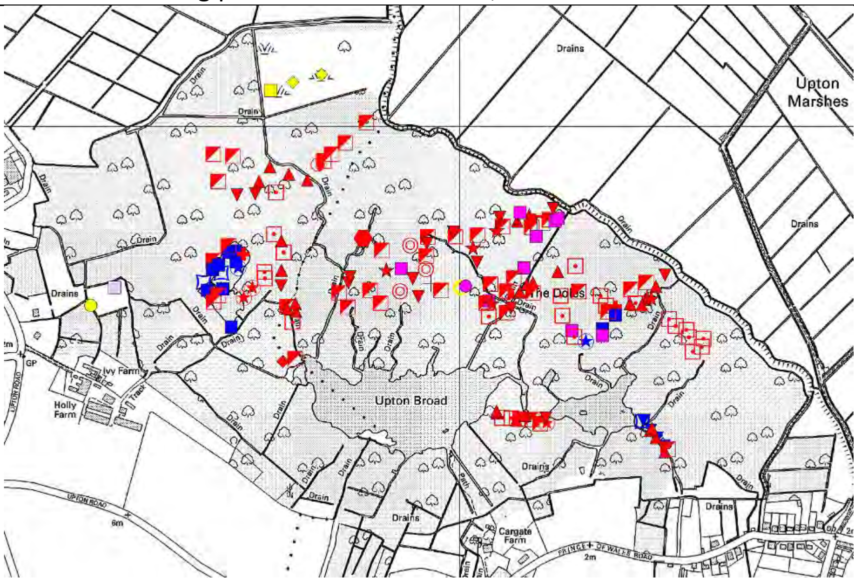
8. BROADLAND CATCHMENT CASE STUDIES

Key to NVC Community Maps

M9	S4(d)ii	S17	S26(b)	Affinity to M22-A4
M13(a)	S4(d)iii	S19	S26(b) Saline variant	Affinity to M22-M27
M13(c)	S4 BS(e)	S20(b)	S26(d)	Affinity to S2(a)-S24(f)
M22(a)	S4 BS(f)	S21(a)	S26 BS(e)	Affinity to S6
M22(a) Car nigra variant	S4 BS(g)	S21(b)	S26 BS(f)	Affinity to S24-S25
M22(a) Junc eff variant	S4 BS(h)	S21(c)	S26 BS(g)	Affinity to S24-M27
M22(a) Junc acuti variant	S4 BS(i)	S22(a)	S26(a)-S5(a)	Affinity to S25
M22(b)	S4(d)-SM24	S24(a)	OV26(b)	Affinity to S25(b)
M22(c)	S4(b)-S13	S24(b)	OV26(c)	Affinity to S25 - A4
M22(d)	BS1	S24(b) - S24(c)	OV26(d)	Affinity to S25 - M22
M23(a)	S5	S24(d)	S28(a)	Affinity to S3
M23(b)	S5(a)	S24(e)	S28(b)	Affinity to S5 - S7
M24(a)	S5(b)	S24(f)	SM13(d)	Affinity to S5(a)-S26(a)
M24(b)	S6(1)	S24(g)	SM16(a)	Affinity to S6 - S24
M24(c)	S6(2)	S24 BS(h)	SM16(b)	Affinity to S7 - S24
M25(b)	S7	S24 BS3	SM16(c)i Ag stol variant	Affinity to SM28
S1	S6-S7	S24 BS4	SM20	Indeterminate Glyceria maxima
S2(a)	BS2	S24-S25	SM23	Unassigned
S2(b)-S25(c)	S8	Eleocharis uniglumis swamp	SM24	
S4(a) Clad mar variant	S9	Myrica gale fen	MG13	
S4(a) Sol dulc variant	S12(b)	S25(a)	MG10(a)	
S4(a) Lemna spp. variant	S12(c)	S25(c)	MG10(b)	
S4(a) Ag stol variant	S13	S27(a)	OV27	
S4(b)	S14(a)	S27(b)	OV30	
S4(b) Ag stol variant	S14(b)	S27(b)-M5	Affinity to M13	
S4(d)	S14(c)	S26(a)	Affinity to M22-A3	

8.1 Upton Fen

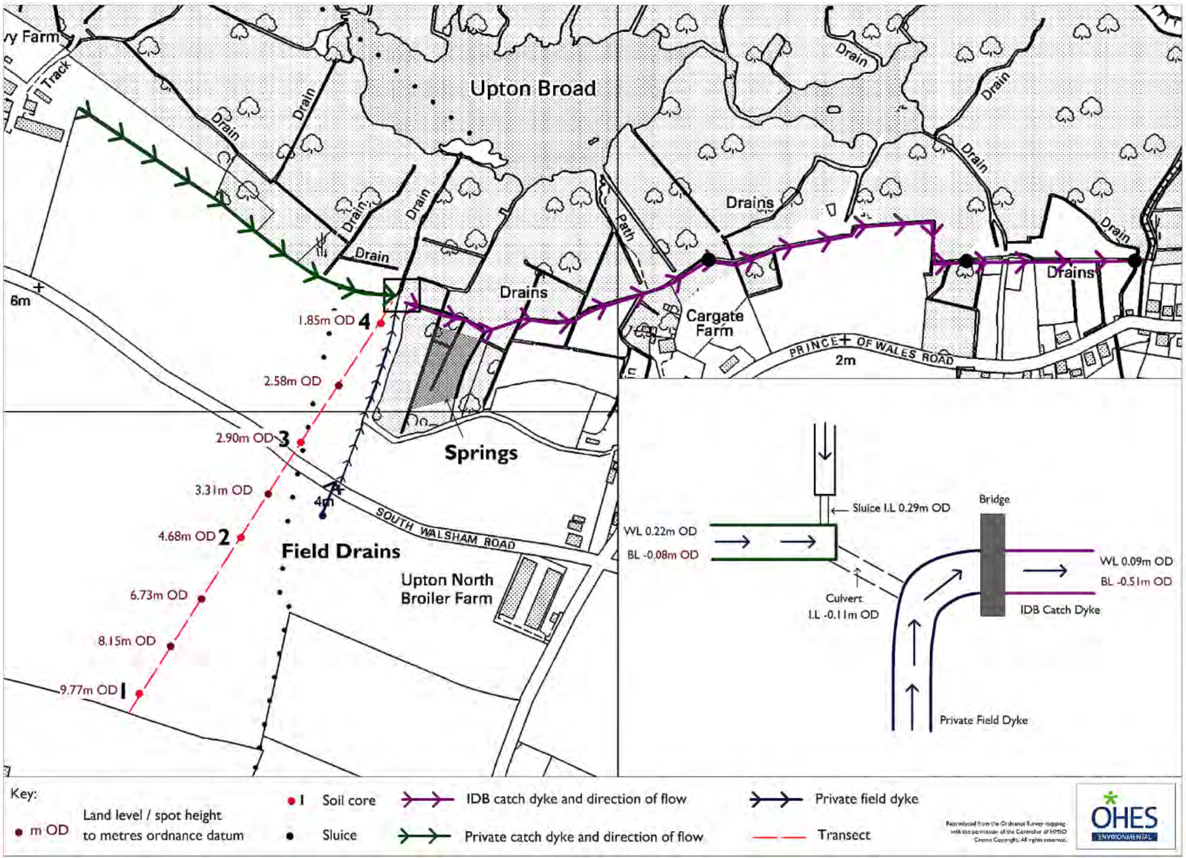
8.1.1 Defining the Nature of the Problem

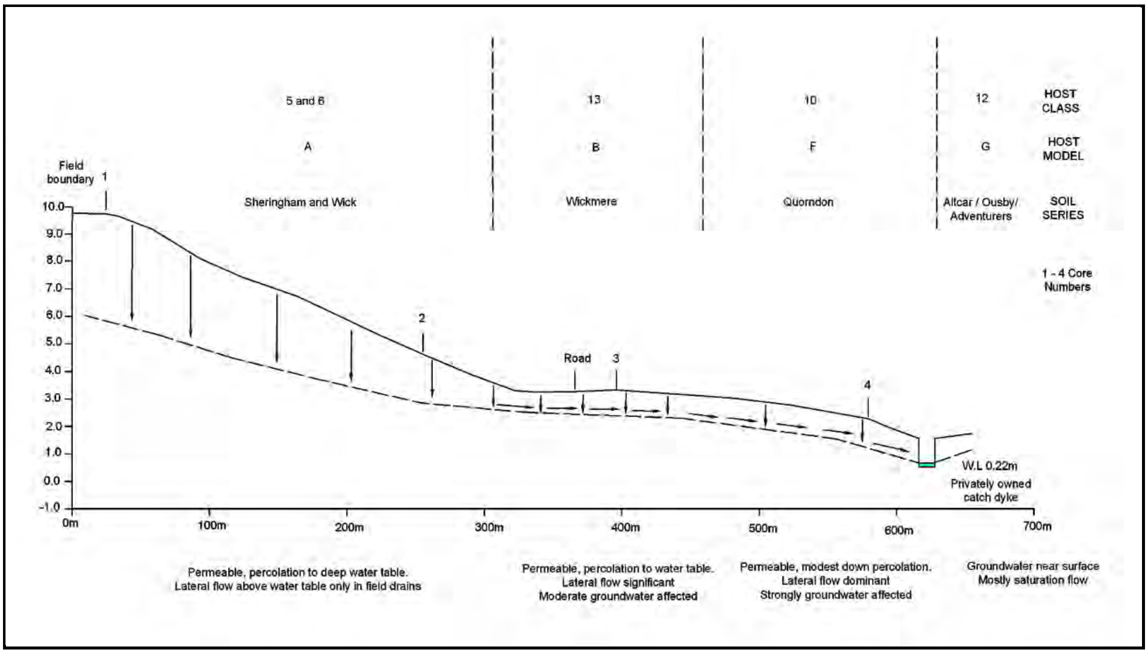
Site Name	Upton Fen
River System	Bure
Manager	Norfolk Wildlife Trust
Designations	SSSI, SAC, SPA, Ramsar
Landscape Context	A valley margin wetland along the south edge of the Bure. To the north are pump drained alluvial marshes, to the south rises the Bure valley slope to the undulating plateau at around 15m, c.1km distant.
Plant Communities (OHES 2011)	 Mostly communities typical of base-rich, low nutrient calcareous conditions, often as hover, mostly species-rich and of exceptional value for nature conservation. Some oligotrophic, base poor and acid communities to the west. A range of Habitats Directive communities.
Catch Dyke Characteristics	**Main Catch dyke**: Dyke Type 1, High Risk. Freeboard maintained by sluices, but in places these are too low causing some drainage of the Fen. From a point 350m west of Cargate Farm, it is IDB main drain, part of the pumped system. This is connected to a substantial private field ditch which starts about 100m east of Holly Farm. The Private ditch and the IDB dyke together make the Main Catch Dyke. It was created mainly by expanding pre-existing small catch dykes. The first section was dug in 1962, from Cargate Farm west for 200m and discharging to Great Broad, to enable a vegetable growing scheme on what was then pasture on peat. The scheme never took off, and could not even grow grass, apparently because of dilapidation of the drainage ditches and "..the rise of the level of the Broad" (Crane 1989). The eastern section of the IDB dyke was dug in 1983 to pick up outfalls of new under-drainage in the fields east of Cargate Farm. This was extended west about 50m that year, to divert polluted water from the piggeries at Cargate Farm which was then routing directly into Great Broad.

	In 1989, the arable fields east if Holly Farm were under-drained, which overwhelmed the small dyke between Holly and Cargate Farms, discharging into the fen. Crane (1989) proposed connecting the whole length together and blocking off the new integrated catch dyke from the Broad. This was completed in 1995, making a substantial catch water drain from Holly farm to the Upton Marshes, discharging to the Bure via the Doles IDB pump. The drain has a steep fall and there are insufficient sluices to maintain a constant level. Harding (2002) reported a 20cm difference in water level between Great Broad and the ditch, a significant hydraulic gradient, and water movement out of the site had been directly observed. Water exiting the site into the catch dyke via a board sluice was also observed during this study. In addition, the drain excludes from the fen an area of intense spring activity. There is a strong draw of water from west to east, and the ditch is maintained annually. The IDB dyke is broad and deep. At the head of the IDB section, the dyke is 3m wide at water level, 5.5m at top of bank, 0.6m depth of water plus 1.1m freeboard. Near to the water control structures, dimensions are the same but freeboard is 50cm. Sluice by-passes installed in 2008 prevent over-topping of the ditch but also prevent raising levels further. Between Ivy Farm and the head of the IDB dyke, the ditch has a steep fall and is privately maintained. It is smaller (3.8m top of bank, 1.8m at water level) with shallower water (0.2m at time of survey) and a freeboard of 1.1m. A board sluice connects the Broad to this ditch. The board is set 6cm above ditch water level. There was a small flow of water from the Fen to the ditch during the survey. In times of peak flows water could flow into the Fen from the catch dyke. The water level of the Broad in winter 1989 was at 0.085m AOD (Crane 1989), while and the water level flowing into the upper catch dyke from the Broad ditch during this survey was around 0.289m AOD, perhaps a high winter level. The bed of the IDB drain at its head is -0.508m AOD, the water level at 0.091m AOD. The bed of the minor catch dyke was -0.076m AOD and the water level 0.224m AOD. Bed levels are both well below fen water level, and the dyke water levels were also below, and thus at the time and point of survey the Fen and Broad were losing water to the catch dykes. Whether this persists throughout the length of the dyke, and whether this prevails in summer, is unsure. The dyke is dug into the margins of the peat. Fieldwork showed the beds of both ditches near where they meet to be on hard, orangey-yellow coarse sand which could be the Crag. In other places, the IDB ditch runs through the peat fen margin and can be boggy. A small area of woodland contains spring and seepage discharge and is excluded from the fen by the dyke. Clearly the ditch has been dug through the valley marginal seepage/spring line. Ditch boundaries have variable porosity but there

	may be hydraulic connection to the sub-surface watery mud layer in places. There are some connections to the internal fen dykes, while other stops are leaky. Connection could also occur when floods overtop the dyke, but these are likely to be rare. The Upland arable land is under-drained which generates run-off and nutrients, which are likely to be especially problematic in high flows. **Minor Catch Dyke:** Marginal Type 1/Type 2. Borderline Moderate/High Risk. This flows west around the fen margin from Holly Farm, discharging to the South Walsham marshes pumped system via a sluice. This is a much smaller watercourse with low flows, less intensive upland but still intercepting shallow groundwater. Boundary between moderate and high risk.
Hill slope and floodplain soils including hydrology	See hillsope cross-section and catena, and plan. The soil cores are in Appendix 6. Soil cores largely confirm mapping in Tatler and Corbett (1977), although the landowners suggests there is some artistic license in the published map. From the top of the hillslope at 10m AOD to the toe slope, the catena is dominated by brown earths mostly developed over Happisburgh Formation with varying amounts of overlying Cover Loam, an aeolian silty sand loess. Both are non-calcareous parent materials. They give rise to permeable, free draining soils, principally the stony Wick Series together with stoneless Sheringham soils on the deeper aeolian loess. On coarser materials on the margins of the plateau, sandier Newport Series brown earths can replace Wick soils. Burlingham Series brown earths occur rarely on the highest ground where chalky boulder clay underlies the glaciofluvial drift. Newport and Burlingham Series were not contacted during fieldwork. On the lower slopes or in small flats and hollows, the brown earths show evidence of groundwater gleying – typically Aylsham and Wickmere soils. The soils are permeable and lateral movement can be significant, made very rapid with under-drainage. Between the brown earths and floodplain peat is a narrow band of Quorndon Series, a ground-water gley soil, typical of the toe slope. Here the groundwater table is more elevated in the profile, such that lateral flow dominates over downward percolation. This general sequence down the hillslope was confirmed by coring and illustrated by the cross section. The Quorndon Series passes to the peats of the Altcar, Ousby and Adventurers Series on the floodplain. Much of the fen is fresh peat of Altcar and Ousby profiles, but areas of older, uncut and humified peat could be the much less permeable Adventurers Series. Although the peat appears to thin along the valley margin, the mineral gradient may be steeper here than in other places in the Broads. Abruptly, north of the Upton Wall, the Bure floodplain is covered by Newchurch Series on marine alluvium.

Soil and Topographical Transect and Cross Section





Upland Soil characteristics (NSRI 2014a)	Upland soils are developed from glaciofluvial and aeolian drift and till. They are free draining soils in unconsolidated sands or gravels with high permeability and high storage capacity (overall Host Class 5). They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology (Wheeler et al 2009, Harding 2002, Harding and Smith 2005)	Deeper groundwater enters the site most likely from the Crag which is partially confined by clay layers. The peizometric head of the crag is above c. 0mAOD, and is consequently above Broad bed level. Crag water is strongly calcareous and ferruginous. The spring in the carr woodland to the south of the IDB catch dyke, referred to above, is also marked on the hydrogeology map. Further springs within dykes or other locations within the Fen are possible. South and west, the Crag is overlain by 20-30m of slowly permeable boulder clay which reduces recharge, but on the Bure slopes above the Broad, the drift is permeable Happisburgh Formation and aeolian sands providing localised recharge. The Broads (mostly Little Broad) are thought to be major sources of input as they have been dug to the Crag, although the volume of discharge may be reduced by siltation of the Broad beds. The chalk at depth is presumably blocked by 10m of London Clay, although this thins to the west where there may be contact between Crag and chalk. Drift groundwater may also enter the site from the southern slopes, passing into the watery mud which underlies the vegetation mat of much of the site. The catch dyke may intercept a good proportion of this marginal groundwater.
Surface Water Drainage (Crane 1989, Harding 2002)	The principal flood defence concern is Upton village. The main Spine Drain that runs from east to west through the centre of the Upton Marshes is the key watercourse for flood protection for the village and the properties on the margin of the Fen. Water exits the Fen by a number of routes. Water from the west area discharges to the South Walsham Marshes. There is a very small, old catchwater drain running west from Holly Farm to discharge to the South Walsham Marshes. This small feature is not thought to have a significant impact on the Fen. The South Walsham Level is pumped to the Bure. The central parts of the fen drain north to Upton Fen Wall and discharge to the soke dyke, entering the Upton Marshes Level where it is discharges to the Bure (the Doles Pump). The Upton Wall is leaky, water from which drains to the pumped Levels. The major surface water drain is the main catch dyke running west from Holly Farm to discharge to the Upton Marshes. This has been described above.
Eco-Hydrological Summary for the Fen	WetMec Types: 8b Groundwater Fed Bottoms with Aquitard – Distributed Bottom 13b Seepage Percolation Quag 13c: Seepage Percolation Water Fringe

(Wheeler et al 2009, Harding 2002, Harding and Smith 2005)	13d Distributed Seepage Percolation Surface Some evidence of WetMec 3 Bouyant, Weakly Minerotrophic Surfaces (transition bogs). Large areas of the site are former turbaries, now terrestrialised with a vegetation mat overlying watery mud. Surface peats originating from terrestrialisation of turbaries are often loose and highly conductive, but uncut peats are much less permeable and may be a barrier to lateral flow. Because of the complex pattern of turf ponding, the surface hydrology of the site is similarly complex. Two main wetland mechanisms are thought to operate, both groundwater driven. The first, and possibly most significant, supplies the loose vegetation infill of the old peat diggings. This system is driven by the upsurge in groundwater from the Crag aquifer which wells up into Little Broad and possible Great Broad). This directly permeates the floating fen that fringes the Broads (WetMec 13c). Groundwater then spreads laterally away from the Broad fringes through conductive shallow peats and underlying watery muds to supply further areas of hover over liquid mud. These areas are WetMec 13b, which includes the *Sphagnum*-rich Flight Pond area to the west. The second main mechanism is by distribution of groundwater rising from the Broads around the site by the dyke network (WetMec 13d). Sub-surface water could pass from dykes into the fen via underlying watery mud if they cut into re-vegetated turbaries, or if the peat is transmissive, by transmission through the peat. Dyke distribution may also benefit the solid, uncut peat areas which are not underlain by watery mud and which would otherwise have no access to groundwater. WetMec 8b is similar to this distribution mechanism, except that the groundwater originates from the margins, rather than deep Crag groundwater. It would operate between the fen margin and the Broad, but would be severely compromised by the catch dyke which would intercept groundwater flow from the upland. The significance of both distributed WetMecs is that they can carry groundwater around the site to locations which are distant from groundwater sources. However, any humified or uncut fen peat will have limited hydraulic conductivity, and the dykes are rarely brim full, so the significance of this mechanism is difficult to determine. Water distributed by dykes may not penetrate far into the fen compartments. Some areas at distance from ditches and groundwater may be mainly rain fed (with presence of *Sphagna*) and therefore have affinities to ombrotrophic WetMecs. Clearly, despite the great deal of research undertaken at Upton Fen, and despite relatively robust conceptual understanding of the fen, precise flow mechanisms in specific areas of the site remain difficult to pin down.

Main Issues	* Delivery to the site of agrochemicals, including nutrients, transmitted by permeable soils and by field under-drainage. The shallow groundwater arising from the immediate slopes will be most affected but deeper Crag groundwater supplied from a wider catchment could also be affected. Currently, the main catch dyke reduces this risk by diverting agrochemicals from throughflow and surface run-off. However the dyke still has muted connections to the internal fen dykes and a potentially semi-permeable boundary. * Changes to water quality by the capture and diversion of groundwater, both calcareous Crag and base-poor Happisburgh Formation. This affects mostly the area between the catch dyke and the Broads where the Crag discharges in volume. Where the upland groundwater has been lost, the water balance will be more dominated by rainfall. * Depletion of the water balance through diversion of contributing groundwater. The volumetric significance of this is not known. * Drawdown of the fen water table near to the dyke (around 20cm) and further depletion of the water balance of the areas affected. * Direct physical impact on potential groundwater seepages and their specific habitats, arising from dyke excavation and deposition of spoil. * Disruption of wetland to dry land end of the hydrosere.
Nature Conservation Constraints	* Water voles and otters may use the dyke corridor. * Intrinsic value of the ditch for aquatic plant and animal communities is not known in detail. * All of the site is of the highest grade for nature conservation. Engineering works within the site could have significant direct impact on designated habitats and features. * The eco-hydrology of the site is complex. Although it is understood conceptually, it is often with weak direct evidence. Interventions in sub-surface hydrological mechanisms are therefore high risk. Note that the catch dyke itself represents a significant intervention.
Physical Constraints	* Most of the dyke is IDB adopted Main Drain and therefore any works have to meet their requirement for integrated water management and take account of drainage needs for adjacent land managers. * Raising water levels in the catch dyke may (a) impact on adjacent landowners and particularly those with land drains (b) increase risk, frequency and severity of overbank flooding into the fen. * Significant assets are unlikely to be affected as the main flood defence is the Spine Drain in Upton Marshes. Local assets may be affected, however, and would need to be considered on a case by case basis. Cargate Farm buildings, and the AW sewage pumping infrastructure, would need further consideration.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.1.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered. Because the only issue not raised is ochre, nearly all of the potential solutions could apply. Many depend on cooperation or full partnership with adjacent landowners. Consequently options need to be considered in parallel as they cannot be dismissed at the desk stage. Note also that many solutions have a role in resolving more than one issue.

Generation of Nutrients

- Seal off wetland
- Reroute main drain
- Create Buffer/stripping zone
- Soil Management
- Nutrient Stripping Management
- Reduce run-off
- Improve Farm practices
- Change Upland Land use

Change of Groundwater Quality

- Comprehensive in-fill
- Raise Water levels
- Raise Bed by Partial infill
- Perforate perimeter – increase permeability

Depletion of Water Balance/Direct Drawdown of the Water Table

- Neutralise Under drainage
- Pre-Treatment through wet fen
- Weeping Boundary
- Pumped double ditch

8.1.3 Options Appraisal

Red tint – not taken forward. Yellow tint – only useful in combination with other measures. Green tint – core solution with or without other measures.

Option	Positives	Negatives	Outcome
Seal off wetland	Prevents ingress of nutrients. Prevents direct drainage.	Eliminates groundwater feed to both margins and potentially Broads. Technically difficult, may require impact on fen or significant land take upslope. Expensive.	Does not resolve issues. Not taken forward.
Reroute main drain	Removes drain from direct contact with Fen. Maintains current land use upslope. Reduces impact of run-off discharge to the fen. Restores significant part of groundwater flows and eliminates impact of drainage.	Can only be moved upslope. Requires change of land use between it and the Fen. Does not eliminate in-situ generation of nutrients or eutrophication of deeper groundwaters, although would significantly reduce both.	Possible solution in combination with others.
Create buffer/stripping zone	Reduces ingress of nutrients to the fen. Could create additional wildlife habitat such as toe slope wetland.	Does not address generation of nutrients or eutrophication of deeper groundwaters. Can be overwhelmed in storm flows. Does not address groundwater or water balance issues.	Possible part solution in combination with others.
Soil management	Would remove accumulated nutrients stored in topsoil of either upland or fen.	Regular cropping and permeable soils means arable topsoil not hugely enriched. Would be damaging to agricultural value of land. No evidence of accumulation of nutrients in main fen areas. Disposal of arisings very expensive with high carbon footprint. Does not address many of the key issues.	Not taken forward. May be helpful if the scrub were removed between the catch dyke and the Broad where some nutrient may have accumulated and the surface peat degraded.
Nutrient stripping management	Would deplete nutrients in fen surface peats or in topsoil of arable land.	Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues. Hydrological mechanisms	Not taken forward. Only useful as part of other measures which deal with

		suggests distribution of waters means nutrient accumulation is probably not concentrated in certain areas (other than the Broads). The most likely area to be cropped – between the catch dyke and the Broad – is currently scrub not fen. Annual cropping is expensive.	core issues, for instance could assist establishment of grassland/heath on ex-arable if land use change achieved.
Reduce run-off	Reduces nutrient and silt movement to the fen. Reduces incidence where catch dyke overwhelmed during floods. Low costs.	Requires cooperation and potentially compromise from managers of the upland. Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues.	Useful as part of other measures which deal with core issues.
Improve farm practices	Reduces nutrient and silt movement to the fen. Reduces incidence where catch dyke overwhelmed during floods. Low capital cost.	Requires cooperation and potentially compromise from managers of the upland. Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues.	Useful as part of other measures which deal with core issues.
Change Upland Land use	Could potentially remove significant inputs of nutrients. Removes need for a significant (or any) catchwater drain. Removes principle constraints on most effective solutions which would address all of the major issues. Allows restoration of the full hydrosere.	Requires comprehensive change in land management by all stakeholders, or large scale acquisition by conservation organisations.	Core solution for comprehensive remediation. Taken forward.
Comprehensive in-fill	Deals with all of the hydrological issues.	Does not prevent leaching of nutrients. Cannot be contemplated while adjacent land management requires significant freeboard. Requires extensive stakeholder agreement. Negative impact on intrinsic value of dyke.	Core solution for comprehensive remediation. Taken forward. Needs some degree of land use change.
Raise Water levels	Additional sluices and balancing of dyke and broad water level would prevent leakage of water from the wetland and depletion of the water balance.	Does not address nutrients. Increases risk of flooding of catch dyke. Does not restore water quality or groundwater flows.	Partial solution but with stand-alone benefits which should be taken forward.

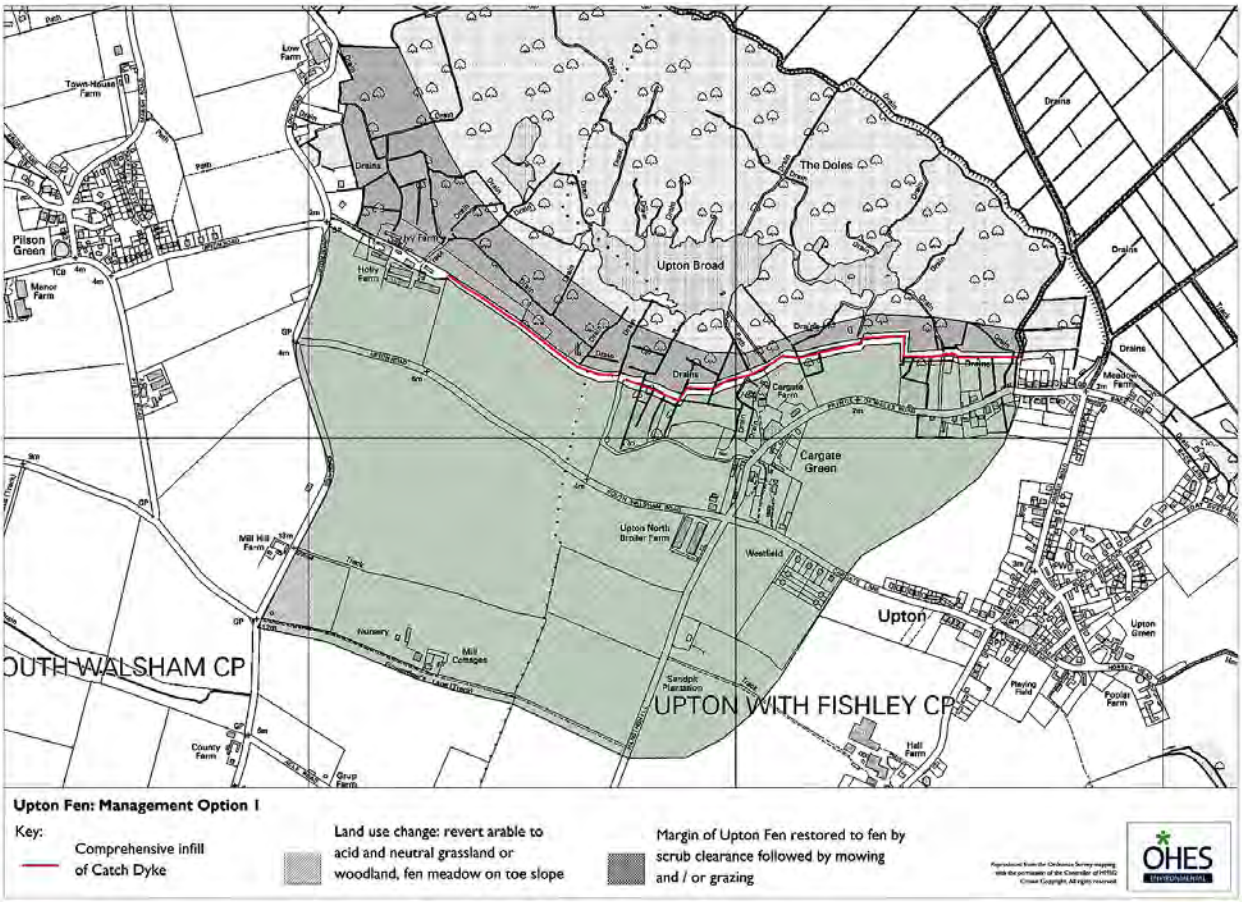
Raise Bed by Partial infill	Would help restore groundwater flow at dyke depth.	Does not deal with nutrients issue or with drainage issue. Expensive and requiring significant engineering. Excessive infill will cause reduction in dyke capacity and increase risk of flooding over.	Partial solution but with stand-alone benefits which should be taken forward if comprehensive infill is not feasible.
Perforate perimeter – increase permeability	Would help to restore groundwater input and assist with wetland water balance.	Water quality too poor unless land use change assured. May worsen drawdown of the fen water table if dyke water level not balanced with Broad throughout its length. Does not deal with nutrient issue or many hydrological issues.	Not taken forward.
Neutralise Under drainage	Reduces peak flows to dyke, therefore reduces sediment and nutrient delivery. Reduces likelihood of dyke overflow. Reduces requirement for such a large dyke and could enable other measures.	Significantly impacts on arable drainage and therefore on stakeholders. May require land use change or other financial measures. Does not reduce nutrient input or remediate other hydrological issues.	Only useful as part of other measures which deal with core issues.
Pre-Treatment through wet fen	Provides a buffer area to absorb ditch overflow before it enters the fen. Reduces impact of nutrients.	Does not address hydrological issues, reduce the application of nutrients or reduce eutrophication of groundwater. Significant impact on the fen as it would require clearance of woodland between dyke and Broad. The wet fen is likely to be eutrophic.	Minor solution only useful in combination with other measures.
Weeping Boundary	Promotes ingress of water from pre-treatment options, boosting water balance of the fen.	Does not address hydrological issues, reduce the application of nutrients or reduce eutrophication of groundwater. Significant impact on the fen as it would require clearance of woodland between dyke and Broad. May be unnecessary as the surface peat at Upton is often permeable.	Not taken forward.
Pumped double ditch	Allows maintenance of a ditch at fen ground level throughout the site. There would be no draw down of the fen water table.	Does not address nutrient issues or any of the groundwater hydrological issues. High impact on the fen because of cutting a new dyke. High capital and management cost, and high carbon footprint. Dubious effectiveness. Any impermeable barrier may further interrupt groundwater flow.	Not taken forward.

8.1.4 Conclusions and Recommendations

Because of the complexity of the site and because of the implications for stakeholders and agencies, it is not possible at this scoping stage to present one solution. Instead we present three options with increasing levels of constraints. Option 2 in particular would need considerable further development work.

Option 1: No Constraints On Upland

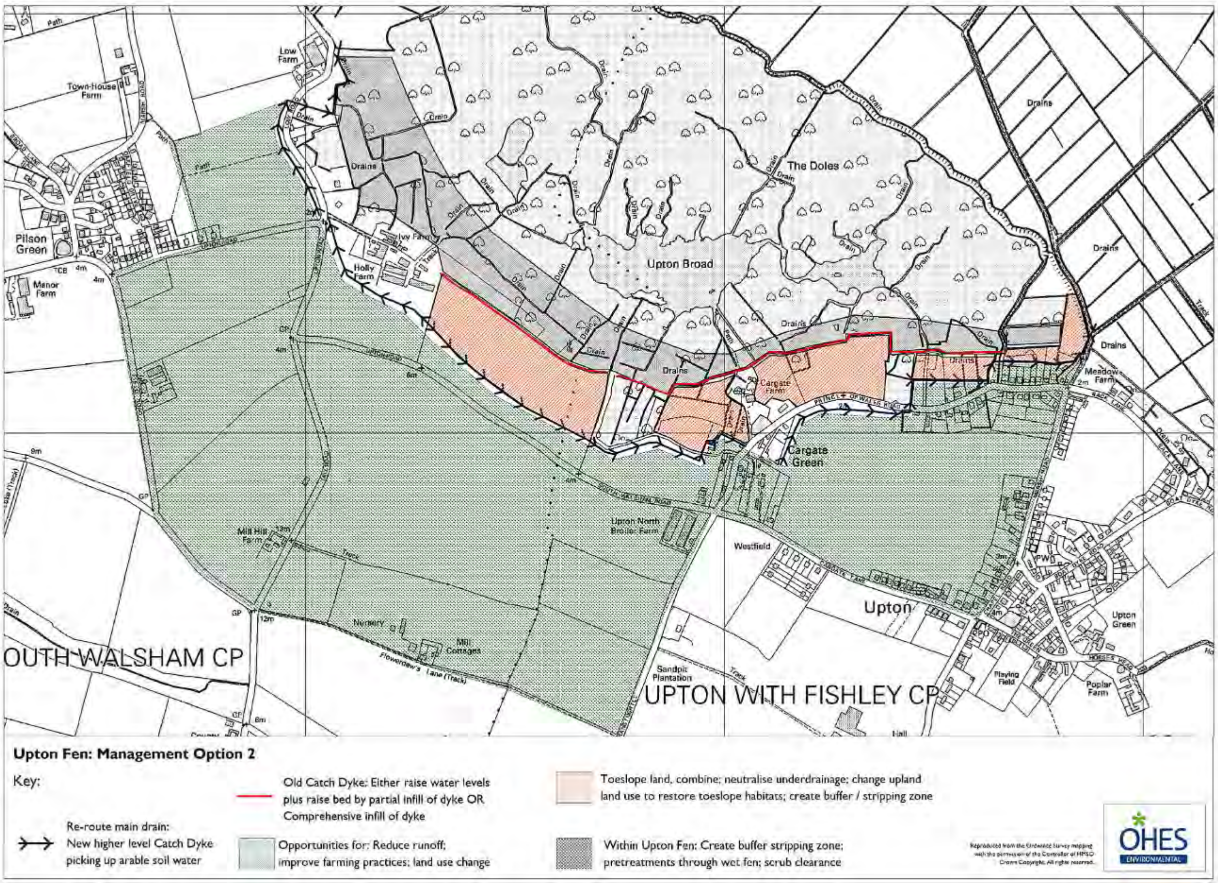
This presents the ideal solution which maximises benefits for the Fen and addresses all of the issues identified. It would fully restore the dry land to wetland hydrosere. It is the most sustainable option, with potentially the lowest cost and least engineering, but cost would radically alter if the shaded upland needed to be purchased. Houses and other assets south of Upton Road and Cargate Green would need careful evaluation for impacts.



Option 2: Moderate Constraints on Upland

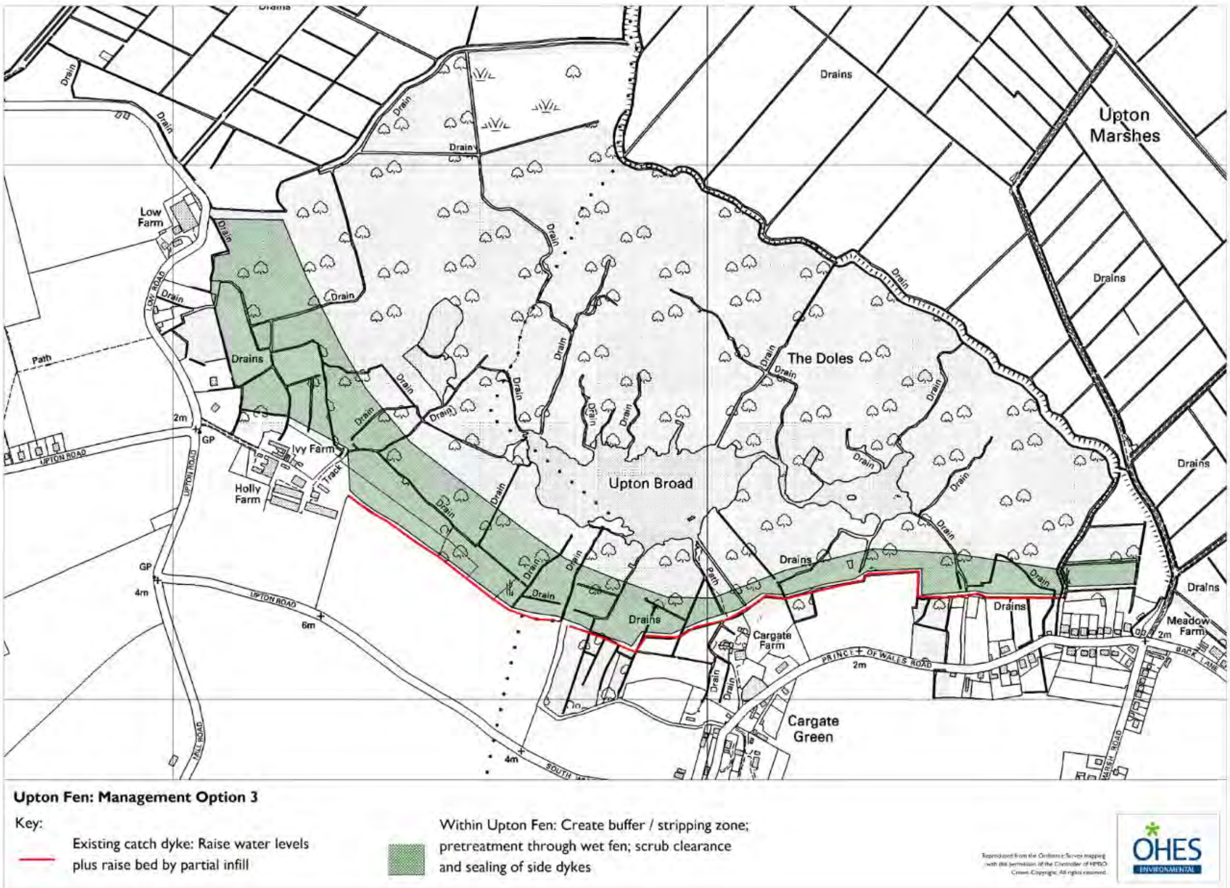
Here, most of the upland would remain managed as at present (although there would still be opportunities for catchment sensitive farming), but the first 150m of the toe slope could be acquired or otherwise brought out of intensive production. Then, the catch dyke could be re-routed upslope so it still picks up all of the shallow run-off and discharge from under drainage from the arable land, and discharge it away from the Fen. However, because it is more elevated it is less likely to cut deeply into the spring line and seepage which the fen benefits most from. The current catch dyke would be reduced or infilled entirely. Because this solution does not eliminate application of nutrients on upslope permeable soils, Option 2 still requires buffer land and nutrient stripping treatments on both toe slope and Fen margin. The Option allows partial restoration of the hydrosere.

The exact route of the moved catch dyke would need significant additional work, with the route on the plan currently indicative. It would need to rise far enough up the slope so that the bed would be at or above fen level and thus not interfere with groundwater flow. The route through Cargate Green is problematic because of buildings.



Option 3: Complete Constraints on Upland, Works only Possible Within Site

Here, no changes would be possible on the upland. The catch dyke water level is balanced with Great Broad with extra sluices so that it is drainage-neutral. However, because it does not change the upland nutrient and drainage regime, all the buffer strip, nutrient stripping zone and wet fen has to be created through clearing a belt of fen scrub flanking the catch dyke. The option stops direct drainage of the site and moderates the influence of nutrients but is not a full solution to any of the issues.

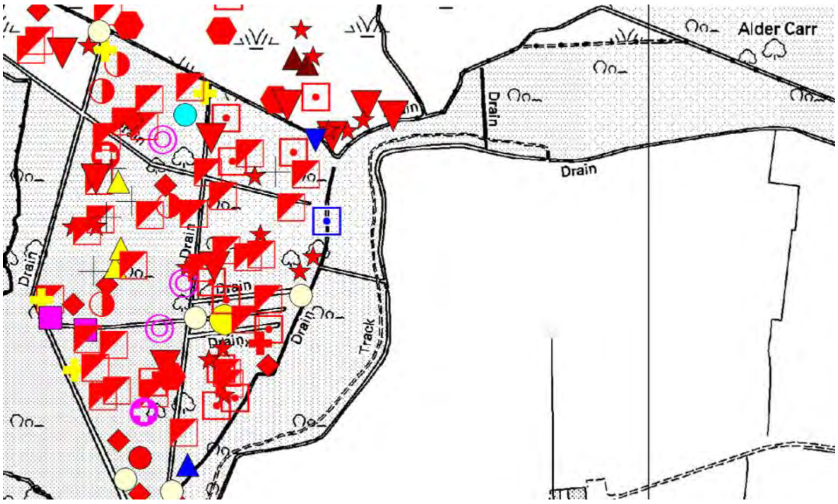


8.2 Catfield North and Sutton High Fen

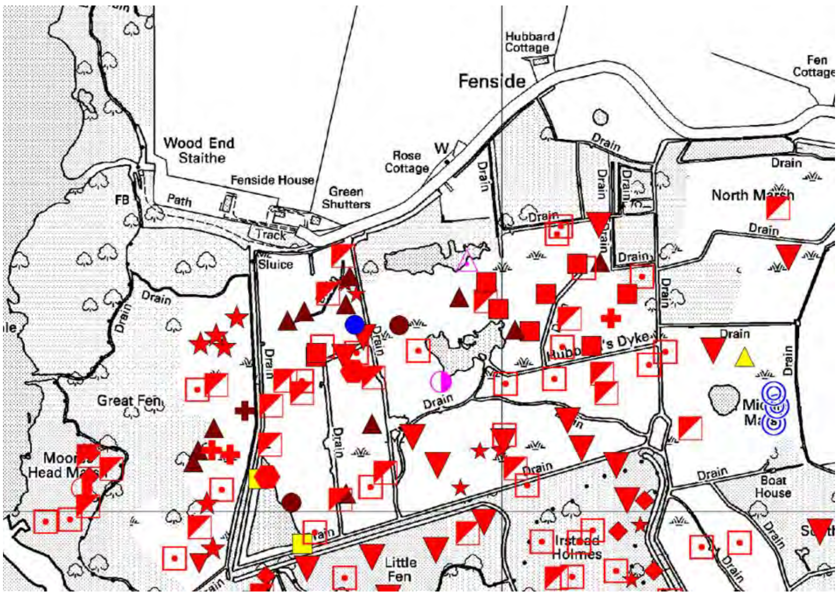
8.2.1 Defining the Nature of the Problem

<table>
<tr><td>Site Name</td><td>Catfield North and Sutton High Fen</td></tr>
<tr><td>River System</td><td>Ant</td></tr>
<tr><td>Manager</td><td>RSPB, Butterfly Conservation, Private Owners</td></tr>
<tr><td>Designations</td><td>SSSI, SAC, SPA, Ramsar</td></tr>
<tr><td>Landscape Context</td><td>Floodplain fen along the east (left) bank of the River Ant. The two Fen areas are split by a broad spur of low-lying agricultural land, edged in catch dykes. The floodplain fen extends from the river margin to the upland.</td></tr>
<tr><td>Plant Communities (OHES 2011)</td><td>

<u>Sutton High Fen</u>



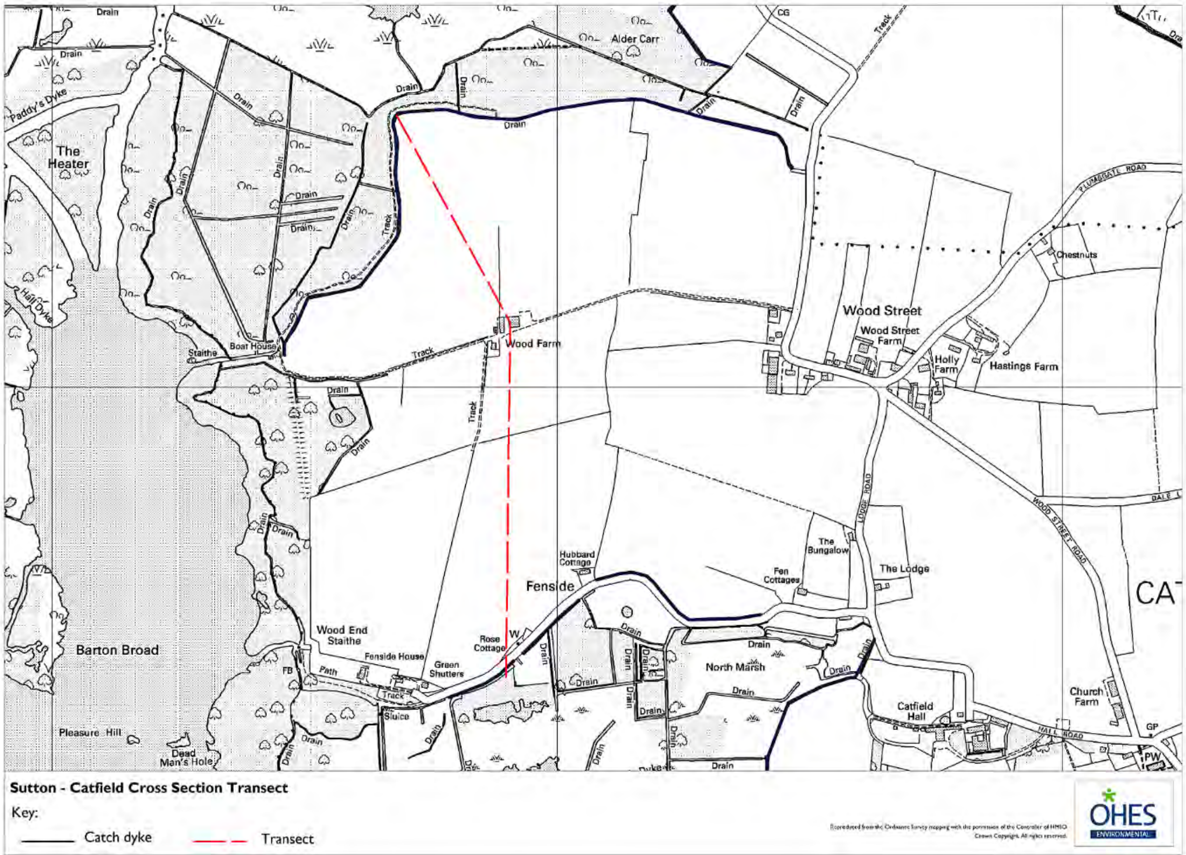
<u>Catfield Fen North</u>

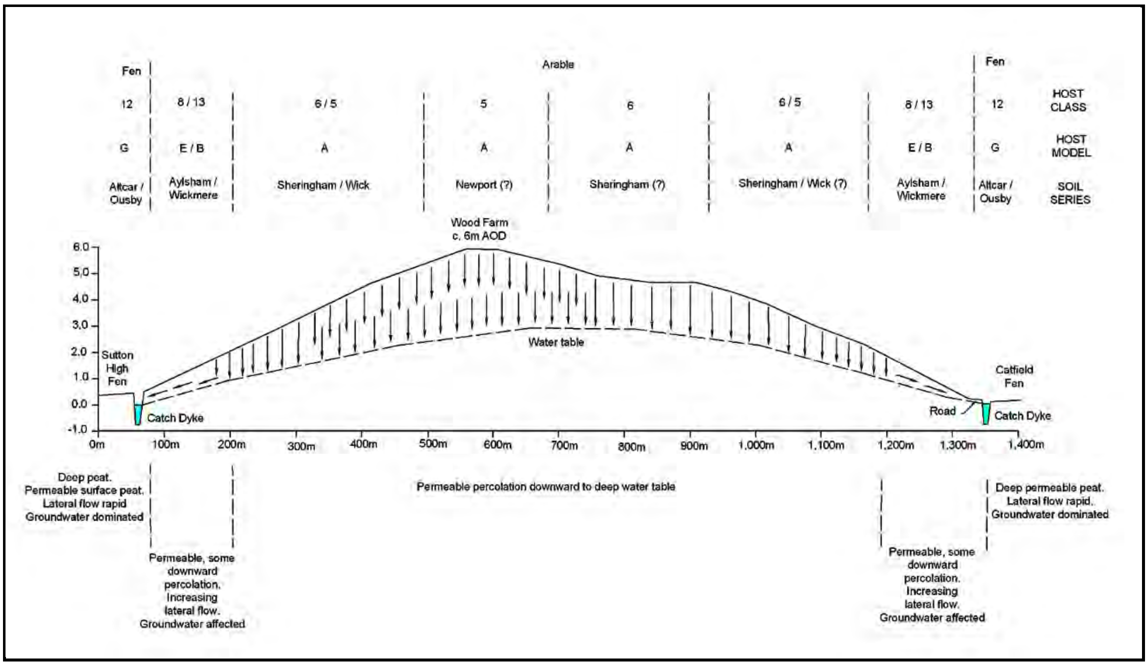


Mostly communities typical of base-rich, low nutrient calcareous conditions. At Catfield Fen, they are often in former terrestrialised turbaries, on Sutton Fen on loose floodplain peat. They range from very</td></tr>
</table>

	species-rich through to relatively species poor tall herb and swamp communities. Collectively they are of exceptional value for nature conservation and include Habitats Directive features. Along the margin of Sutton Fen is a zone of base-poor fen with *Molinia* and a few plants of *Calluna*.
Catch Dyke Characteristics	**Dyke Type 1/2**. This runs around Sutton Fen and along the north margin of the western (private) part of Catfield. They are significant dykes about 3.5m wide at the top, around 1m deep with significant but variable freeboard – from 20-70cm - and variable depth of water. The ditch around Sutton Fen abuts arable with a significant grass margin, and is thought to receive under-drainage. The catch-dyke discharges to a boat dyke to Barton Broad. When tides are high flow can reverse into the catch dyke. There are also connections to the internal ditches of Sutton Fen but they are infilled and of unknown hydraulic connection. Catfield Fen is separated from the arable land by a road. There is a dyke upslope of the road along the arable margin but this is thought to connect into the fen. Sutton and Catfield are therefore receptor sites for agricultural runoff. None of the ditches are part of a pumped level. Topographically, all catch dykes appear to be positioned slightly above the fen level, especially at Sutton, but when water levels are low it is possible there may be a gradient toward them from the fen – levels information is not available. In any case, the height difference is likely to be low and the gradient modest such that a drainage function would be very localised, unless the catch dykes were significantly enlarged. The main threats from the dykes are nutrient enrichment of the adjacent fen and cut-off of shallow groundwater from the hillslope. The latter is especially so at Sutton because the dyke by-passes the fen. At Catfield, where the dyke discharges through the fen, this is not likely to be significant. The dykes are dug into the margins of the peat and probably penetrate the mineral bottom. The Catfield dyke is significantly silted. Risk category: Moderate to high. They would shift to high were they better maintained or enlarged. **Dyke Type Intermediate 2 and 7**: The catch dyke along the eastern section of Catfield (Butterfly Conservation) is silted and carries water only in winter. The silt is mostly organic infill such as leaf litter so will be comparatively permeable. Although of the same dimensions as the more open dyke to the east, there is now very little freeboard, although it still may receive discharge from the arable land adjacent. It is not part of pumped drainage level. Risk Category: Moderate to low. Note however that having only intermittent flow, the dykes do not intercept and remove eutrophic agricultural runoff. **Note**: All dykes skirt a free-draining upland margin. All could be Type 1 High Risk dykes if fully maintained.

Transect and Cross Section Across Upland to Sutton High Fen and Catfield Fen. No access permissions were obtained so the following is illustrative and not based on fieldwork.





Hill slope and floodplain soils including hydrology	There was no access for fieldwork to the upland, hence no soil cores were possible to confirm soil conditions. The soils are mapped by Hodge et al (1984) as Wick 3 Association, a small group of brown earths mostly freely draining, with soils on the toe slope affected by groundwater and gleyed in the lower horizon. The cross-section provided here is rather speculative in the absence of fieldwork, but is a reasonable representation of the hill slope hydrology. On the crest of the spur there are likely to be freer draining Newport Series soils with coarse sand subsoils and little silt or clay in the profile. The main slopes carry a complex of Wick and Sheringham Series, also free draining sandy profiles but with more silty and clay material. Where the aeolian loess deposits are thickest, the Sheringham Series provides deeper soils, with siltier and more water retentive profiles. However, most of the top and slopes all conform to Model A, HOST Class 5 and 6, permeable profiles percolating downwards to a water table below the soil profile. The slope profile is comparatively steep towards the margins with little land which flattens out (c.f. Mrs Myhill's or Upton), and therefore groundwater gleyed soils are not typically part of this soil Association. However, experience on other sites, and the requirement to under-drain soils here, suggest that some gleyed profiles such as Wickmere or Aylsham Series will be present, demonstrating the influence of a rising water table in close proximity to the catch dyke. This are still characterised by downward percolation in permeable profiles but the groundwater table is within the profile. Saturated lateral flow is then characteristic. There is a transitionary margin to the true floodplain peats, which would include strongly gleyed sandy soils, possibly with sandy-clay alluvium at depth near to the floodplain edge and also humose or humified peaty cap to the still sandy profiles. All floodplain soils are peats, deep on the central floodplain but thinning towards margins. The basal peat is humified, often brushwood peat and not transmissive. Mid and upper peat is often humified but very variable and includes layers of fresh or partly humified sedge, reed and brown moss peat with greater hydraulic conductivity. Surface peats on both sites are usually recent, developing from turbary infill or re-flooding, and often loose and highly transmissive. They do not fit soil series very well, but are probably closest to Altcar or Ousby Series with humified profiles fitting with Adventurers Series.
Upland Soil characteristics (NSRI 2014c)	Upland soils are developed from glaciofluvial and aeolian drift and till. They are free draining soils in unconsolidated sands or gravels with high permeability and high storage capacity. They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology	The hydrogeology of the site is the subject of much debate and

	conjecture, mostly around the role that groundwater plays in the water balance and hydrochemistry of the fens. Aquacludes in the form of clay layers and impermeable peats are thought to constrain the main chalk and Crag aquifers, although gaps in the material or higher permeability pathways through these layers allow upward groundwater movement into the dykes or the peat mass. Groundwater contributions are most likely where the aquitards are at their thinnest or absent, and this could include the margins, where they may contribute directly to the wetland.
WetMecs and Ecohydrology (Wheeler et al 2009)	WetMec 5: Summer-Dry Floodplains 5c Winter Flooded Surface 5d Floodplain Sump WetMec 6: Surface Water Percolation Floodplains 6a Solid Surface Water Percolation Floodplains 6b Grounded Surface Water Percolation Quag 6c Surface Water Percolation "Boils". (WetMec 3 Bouyant, Weakly Minerotrophic Surfaces (transition bogs)) (WetMec 8b Groundwater Fed Bottoms with Aquitard) (WetMec 13d Distributed Seepage Percolation Surface) WetMec 6 is usually associated with old turbaries, with loose hydroseral surface peats fed by dykes or adjacent watercourses, supplying water laterally to the surface peat or to sub-surface layers of watery mud. In winter, shallow surface flooding may supply the peat. Features can be small or very extensive. There are three sub-types of WetMec 6, separated according to the age of infill and the buoyancy of the vegetation mat. Two are especially characteristic of Catfield Fen. Type 6b Grounded Surface Water Quag occurs in old turbaries where the vegetation mat does not float in summer (it is "grounded") and may feel solid. Type 6c, Surface Water Percolation Boils, occurs where the vegetation mat overlies watery mud and is bouyant all year. Thin mats largely immersed in minerotrophic waters, perhaps maintained by mowing, can be calcareous rich-fen communities. Thicker (perhaps older) mats can be consistently raised above the mineral water table, generally drier and perhaps dominated by rainfall. They often carry acid or mixed communities, with a surface layer of *Sphagna* and shallow rooted herbs responding to surface ombrotrophic conditions intermixed with deeper rooted fen species responding to underlying base-rich and circum-neutral hydrochemistry. Particularly Sphagnacious communities are transitional to WetMec 3 Bouyant, Weakly Minerotrophic Surfaces (transition bogs). Sutton High Fen may have components of WetMec 6. Wheeler records the surface as spongy peat typical of in-filled turbaries, although there is little evidence of historic peat excavation. Either they are very old, or the peat surface has developed following a period of rapid peat accumulation, perhaps associated with enhanced water levels (re-flooding). Regardless of origins, the eco-hydrological function is the same and is classified as WetMec 6a Solid Surface Water Percolation Floodplains. WetMec 6a lacks a wholly buoyant surface. The loose surface peats transmit water from marginal rivers and dykes deep into fen compartments, keeping them wet

	and buffering summer evapotranspiration. The noticeable, open dyke grid on Sutton High Fen may be a critical mechanism for maintaining the wet fen system. WetMec 6a probably also occurs on Catfield on uncut peat areas, but is much less extensive than 6b and 6c. Significant parts of the uncut peat of Sutton High Fen, and some uncut areas of Catfield, are likely to be WetMec 5, Summery Dry Floodplains. Here the peat is fed by surface water sources (river and upland run-off) and rainfall, but the peats are not transmissive and cannot be recharged laterally, so that evapotranspiration draws down summer water tables causing varying degrees of late summer dryness. The degree of drying depends on the tension between the early spring water level (starting conditions), rainfall and flooding events and the strength of evapotranspiration, all of which are affected by management and by annual rainfall and temperature. Water levels within plant communities are therefore characterised by variability and are not buffered by bouyant vegetation mats or re-supply by sub-surface flow. Two sub-categories are likely to be present. WetMec 5c Winter Flooded Surface, occurs across the main floodplain areas in the absence of other WetMec types. WetMec 5d Floodplain Sump, may occur along the floodplain margin near the upland, where field and road runoff can collect in low lying areas in hollows and derelict dykes. WetMecs 5 and 6 are differentiated by near-surface peat permeability. As this can vary greatly over short distances, especially in fens with a dynamic history of peat digging, the arrangement of these WetMec types across the fen surface may be very complex. This, among other factors, contributes to the spatial variation in fen communities at these sites. Although WetMecs 5 and 6 are essentially topogenous, driven by the hydrological regimes of water courses, topographic variation and rainfall, it becomes more complex where groundwater may supplement or even dominate water balances of the ditch network or peats. Groundwater may become significant if water courses cut into groundwater tables (especially if they cut through confining aquitard layers and release upwelling groundwater), or are fed by lateral groundwater movement from a permeable highland margin. There may also be circumstances whereby bulk groundwater can move up from deeper sources under artesian pressure, but such movement requires gaps in aquitard peat and clay layers. The likely presence of such deeper groundwater pathways at Catfield has caused much debate in recent times and is not resolved at the time of writing. The volumetric contribution of groundwaters from the various sources to fen water balances has not been evaluated. At Sutton and Catfield, it may play a direct role at the location of groundwater discharge or an indirect role through redistribution in dykes. Regardless of the significance of deep aquifer groundwater paths, the

	likelihood of shallow groundwater inputs at the margins or through dyke beds remains significant and is of key relevance to this study. It is likely that WetMecs driven by dyke distribution of groundwater occur on both Sutton High Fen and Catfield. Where groundwater arises from the margins of a permeable upland, this is likely to be WetMec 8b Groundwater Fed Bottoms with Aquitard – Distributed Bottom. Where dykes cut into the Crag aquifer and tap deeper groundwater, the mechanism is closer to WetMec 13d Distributed Seepage Percolation Surface.
Main Issues	* Delivery to the site of agrochemicals, including nutrients, transmitted by permeable soils. Both the shallow groundwater on the immediate slopes and potentially the deeper groundwater supplied from a wider catchment are at risk. Many of the most important ecological features are dependent on low nutrient groundwater. * Disruption of the shallow groundwater discharge to the fen margin. What may have been a seepage discharge zone somewhere between the toe slope and the flat floodplain has been disrupted by the creation of the catch dyke. The margin of Sutton Fen is the prime location. Most is lost to the system as the catch dykes discharge to the Broad, not the fen dykes. At Catfield, because the catch dykes are not drawn and drained, it is not lost to the fen system, but redistributed to the floodplain. Consequently, a potential seepage margin has been replaced by a strengthened floodplain distribution system. It is difficult to evaluate the loss against the benefit without a quantitative assessment of the contribution of the marginal groundwater to the floodplain water balance. However, it is likely to be a proportionately small, and at the expense of what could have been a rare conservation feature at the valley margins. This is consequently judged to be a negative change which would be beneficial to reverse, if feasible. * Disruption of wetland to dry land end of the hydrosere.
Nature Conservation Constraints	* Intrinsic value of the catch dykes for aquatic plant and animal communities is not known in detail but site inspection shows this is likely to be modest. * Both component sites are of the highest grade for nature conservation, across the spectrum of plant and animal taxa. Engineering works within the site could have significant direct impact on designated habitats and features. Many features of importance, or areas that could be restored to features of importance, lie close to the floodplain margins.
Physical Constraints	* There are relatively few physical constraints. All of the land at Catfield and Sutton High Fen is in conservation management and works which benefitted the sites could be implemented. * There are no statutory drainage interests involved, no Main Drains or Main River. * There are houses along Fenside north of Catfield, and the minor road itself, would all need to be considered including any soakaways associated with them.

Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.2.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered. It is assumed that here, because of land ownership on the upland, this will be a highly constrained situation and that no land would be yielded and arable management would continue. This necessarily means that options are limited, although modifying farm practises may be possible. Restoring the wet to dry land hydrosere will not be possible.

Generation of Nutrients

Seal off wetland
Reroute main catch dyke
Create buffer/stripping zone
Soil management
Nutrient stripping management
Reduce run-off
Improve farm practices

Change of Groundwater Quality

Raise Water levels
Raise bed by partial infill
Perforate perimeter – increase permeability

Depletion of Water Balance

Pre-Treatment through wet fen
Improve farm practises
Weeping boundary

(**NB**: Distributor ditches, an option to address “Depletion of water balance” area already present on both sites)

8.2.3 Options Appraisal

Red tint – not taken forward. Yellow tint – useful in combination with other measures. Green tint – core solution with or without other measures.

Option	Positives	Negatives	Outcome
Seal off wetland	Prevents ingress of nutrients, especially for Catfield.	Eliminates groundwater feed to both margins and potentially the distributor dykes. Technically difficult, may require impact on fen or significant land take upslope. Expensive.	Does not resolve issues. Not taken forward.
Reroute main catch dyke.	Reduces seepage of nutrients to fens. Maintains current land use upslope.	Can only be moved upslope. Requires change of land use between it and the sites which is currently not feasible. Does not address in-situ generation of nutrients or eutrophication of deeper groundwaters.	Possible solution in combination with others (see Option 2 in Upton Fen as an example), but not feasible with current land ownership. Not taken forward.
Create buffer/stripping zone	Reduces ingress of nutrients to the fen. Partly in place with wide margins on arable fields adjacent to Sutton Fen. Could create additional wildlife habitat such as toe slope wetland.	Does not address in-situ generation of nutrients or eutrophication of deeper groundwaters. Can be overwhelmed in storm flows. Does not address groundwater or water balance issues.	Possible part solution in combination with others.
Soil management	Would remove accumulated nutrients stored in topsoil of either upland or fen.	Regular cropping and permeable soils means arable topsoil not hugely enriched. No evidence of accumulation of nutrients in main fen areas. Process would be damaging in fen areas. Does not address many of the key issues.	Not taken forward. May be helpful if the scrub were removed between the catch dyke and the open fen, especially along the margin of Sutton Fen, although the remnant *Molinia* habitat would need to be protected.
Nutrient stripping management	Would deplete nutrients in fen surface peats. It may be especially effective	Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the	Only useful as part of other measures which deal

	along Sutton Fen margin where the catch dyke is not connected to the fen dykes, but at Catfield the margin is probably by-passed by the distributor dykes.	hydrological issues. Requires scrub clearance along Sutton Fen margin at least. Annual cropping is expensive.	with core issues. Useful for Sutton Fen margin (if scrub cleared), not taken forward for Catfield Fen.
Reduce run-off	Reduces nutrient and silt movement to the fen sites, especially on steeper slopes. Low costs.	Requires cooperation and potentially compromise from managers of the upland. Wide margins present along Sutton Fen catch dyke suggests the owners may be amenable to further suggestions. Does not address in-situ generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues.	Only useful as part of other measures which deal with core issues.
Improve farm practices	Reduces nutrient and silt movement to the fen. Low capital cost.	Requires cooperation and potentially compromise from managers of the upland. Wide margins present along Sutton Fen catch dyke suggests the owners may be amenable to further suggestions. Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues.	Only useful as part of other measures which deal with core issues.
Raise water levels	Raising water levels to promote leakage into the wetland would improve water balance. This is especially so for the Sutton Fen site where freeboard is very high and water in the catch dyke discharges to the River Ant. Less beneficial at Catfield where freeboards are already high and marginal water is discharged to wetland distributor dykes.	Does not address in-situ generation of nutrients, and could increase diffusion of nutrients into the wetland at Sutton Fen where agricultural water was previously diverted. May be severely limited at Sutton Fen by the requirement to maintain freeboard below the invert under-drainage discharges.	Partial solution for Sutton Fen that may be possible following further discussions with landowners and detailed technical work.
Raise Bed by Partial infill	Would help restore shallow groundwater flow at dyke depth, boosting water quality and water balance at least at Sutton Fen. No benefit for Catfield as the water is not lost to the fen system.	Does not deal with in-situ generation of nutrients. Expensive and requiring significant engineering. May be severely limited at Sutton Fen by requirement to maintain freeboard below under-drainage.	Partial solution for Sutton Fen. May be possible with further discussions with landowners and detailed technical work.

Perforate perimeter – increase permeability	Would help to restore groundwater input and assist with wetland water balance.	Would promote ingress of water of poor and unreliable quality, unless land use could be changed. Does not deal with nutrient issue or many hydrological issues.	Not taken forward.
Pre-Treatment through wet fen	Provides a buffer area to absorb poor quality water before it enters fen. Reduces impact of nutrients.	Does not address hydrological issues, reduce the application of nutrients at source, or reduce potential eutrophication of groundwater. It would require clearance of scrub and subsequent development of wet fen with high nutrient loadings, and/or use of existing fen areas. As the fen margins would naturally support low nutrient transitional communities, the option may be of limited value.	Not taken forward because of potentially negative impacts and limited benefits.
Weeping Boundary	Promotes ingress of water from pre-treatment options, boosting water balance of the fen.	Does not address hydrological issues, reduce the application of nutrients or reduce eutrophication of groundwater. Significant impact on fen as it would require clearance of woodland between the dyke and the Broad. May be unnecessary as the surface peat at both sites is mostly permeable.	Not taken forward.

8.2.4 Conclusions and Recommendations

The review of options, predicated on land use on the arable remaining as it is currently, makes clear that there are few individual options that will address the catch dyke issues at Sutton and Catfield Fens. Indeed all of the partial solutions still require a high degree of co-operation from the managers of the upland. Because of the intrinsic value of the floodplain marginal habitat of both sites, within-fen solutions are rarely appropriate and in any case do not significantly address the core issues.

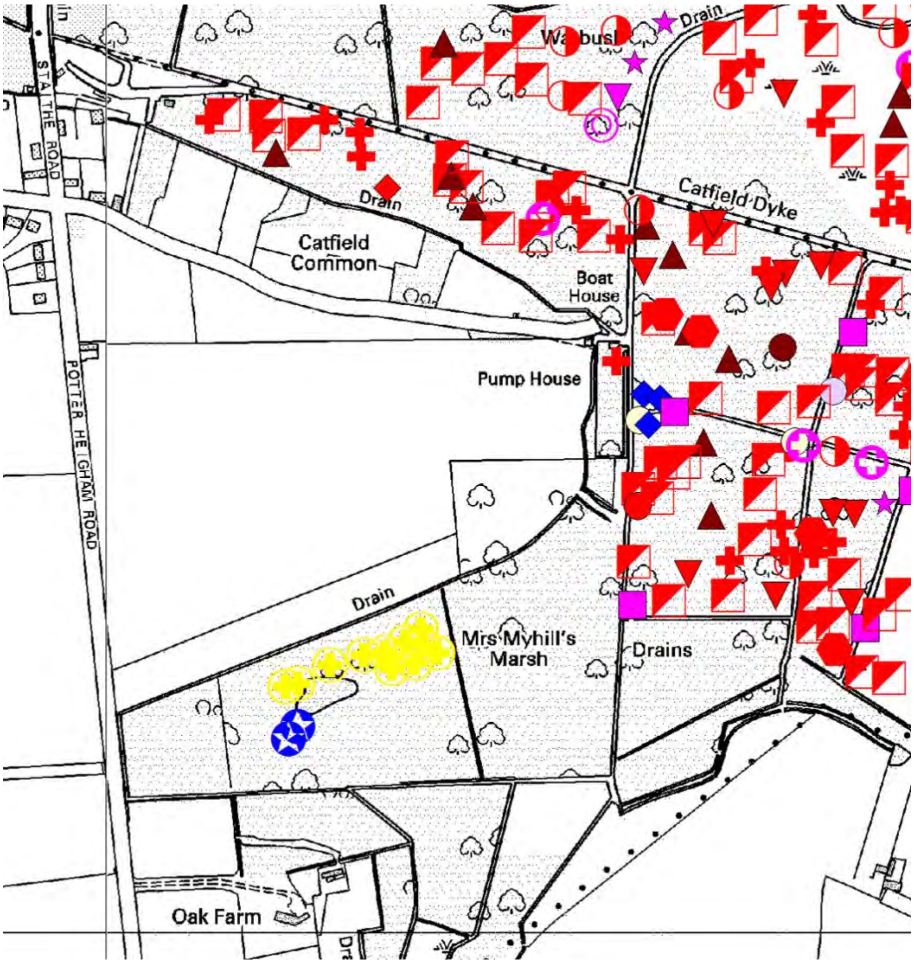
Even so, it would be worth pursuing some of the identified options. The presence of wide margins on the arable fields next to Sutton High Fen suggests a landowner sympathetic to the needs of the fen and to environmentally sensitive farm practises. They may be willing to take the approach further.

There appears no prospect of resolving core issues, or of restoring the full wet to dry land hydrosere, without land use change on the upland.

The case study illustrates once more the difficulty of managing the floodplain habitats when they sit cheek by jowl with top grade arable land.

8.3 Mrs Myhill's Marsh and Catfield Common

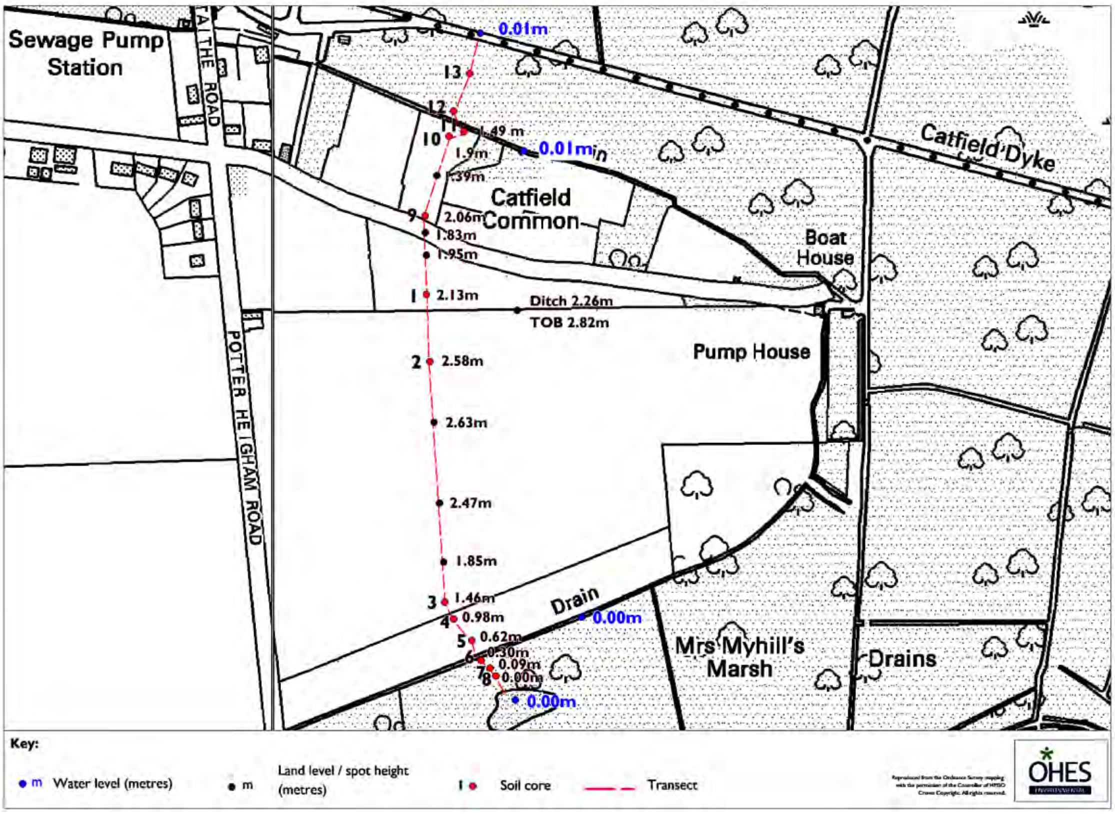
8.3.1 Defining the Nature of the Problem

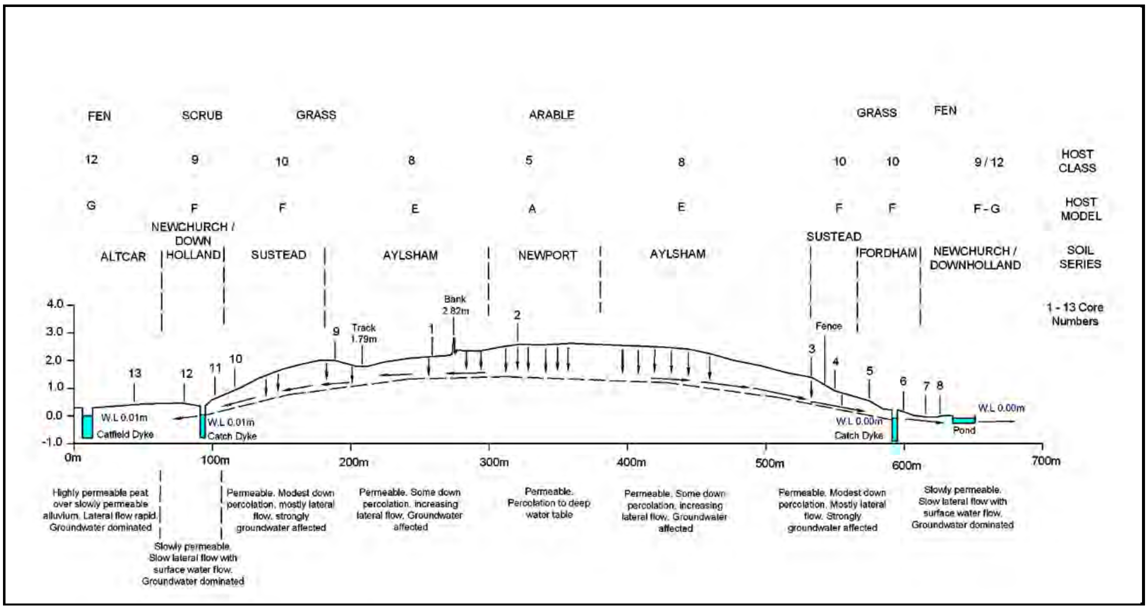
Site Name	Mrs Myhill's Marsh and Catfield Common
River System	Thurne
Manager	Norfolk Wildlife Trust
Designations	SSSI, SAC, SPA, Ramsar
Landscape Context	An area of fen along the margin of the western peat floodplain surrounding Hickling Broad. The two areas are split by a low spur of agricultural land. Around the perimeter of the upland is a catch dyke separating the upland from the floodplain.
Plant Communities (OHES 2011)	 The vegetation around Catfield Common is typical calcareous, base rich Broads fen with *Cladium* swamps and S24 mixed tall herb fen. The fens in the west part of Hickling are the most species-riches in the Thurne catchment. The vegetation of Mrs Myhill's Marsh is distinctly acid, intermediate between S27*Carex rostrata-Potentilla palustris* fen and M5 *Carex rostrata-Sphagnum squarrosum* mire. There are also some stands of base poor M25 *Molinia caerulea-Potentilla erecta* mire. Such acid communities are uncommon in Broadland. Much of the site qualifies as Habitats Directive fen.
Catch Dyke	**Mrs Myhills Catch dyke**: Intermediate Dyke Type 1/2. Trapezoidal section,

Characteristics	hard bottom, 1.1m deep, 0.3m freeboard in wet winter, probably increasing in summer, clear water with good aquatic flora. Reasonable maintenance. Permeable upslope soils. Negligible flow, not connected to regional pumped drainage. Dyke water level the same as the pond in Mrs Myhill's. Receives under-drainage from the arable land to the north. A narrow strip of pasture and rush pasture flanks the dyke. This dyke is on the margin of High and Moderate Risk. **Catfield Common Catch Dyke:** Dyke Type 2, but potential for dyke Type 1 with management. Not regularly maintained. 1m deep to hard bottom, 3m wide top width. Scrub covered for much of its length. Freeboard 10-20cm in wet winter, probably increasing in summer. Connected to Catfield Dyke, gravity drained, no sluices. No significant aquatic vegetation. Traverses between fen and permanent pasture with patches of woodland.
Hill slope and floodplain soils including hydrology	See cross section and the core logs in Appendix 6. In summary it is a sandy, permeable spur developed in aeolian fine sand and Happisburgh Formation, a decalcified drift. The slopes lead on both sides to peat over sandy clay alluvium in the valley, with a narrow but complex transition between. Most of the soils are affected by groundwater, resolved in the arable fields through under-drainage. At the highest point of the spur there is a deep free draining **Newport Series** soil which is sandy throughout and very sandy in the subsoil. It is flanked on both sides by the **Aylsham Series** which is siltier in the upper horizon and gleyed in the lower, showing the influence of groundwater. Deeper parts of the soil are coarse-sandy with fine gravel. Further downslope groundwater becomes more significant again with the **Sustead Series** with increasing fractions of silt and, further downslope, clay in the lowest horizons although sand still dominates the profile. Gleying is stronger and higher in the profile. Sustead soils grade into **Fordham Series** straddling the catch dyke, a profile with the same hydrological characteristics as Sustead soils. On the fen side of the dyke, the topsoil is peaty loam over a quite complex series of essentially sandy-clayey horizons of marine alluvium. The slope-floodplain transition areas are complex on both margins of the spur, as the slope grades into the depositional environments of the floodplain. The cores in the Mrs Myhill's fen area show shallow (c.10) loamy peat top layer over stiff sandy silty clay alluvium. An uneven marsh surface and the water tables being above marsh levels made accurate coring of the peat layer difficult, but even so much shallower peat was recorded in this survey than by Wheeler and Shaw (2006). These profiles have been referred to **Newchurch Series** but are possibly transitional to **Downholland Series**. On the toe of the north spur slope, above the catch dyke, there was an unusual, unclassified soil with groundwater gleying within 25cm of the surface and a strongly layered and complex lower horizon of coarse sand and coarse sand with clay. This presumably arose as a localised depositional sequence. Close to the catch dyke on the fen side is another profile difficult to classify but closest to **Newchurch Series,** with a thin layer of surface humified peat, again possibly transitional to **Downholland Series**. The

	Cladium beds of the fen compartment had around 50cm of loose, conductive fresh peat over the sandy clay marine alluvium, much as Wheeler and Shaw (2006) found for peat fens elsewhere around Hickling. It is probably closest to the **Altcar Series**. Hydrologically the profiles progress from freely draining soil characterised by downward percolation on the spur crest (Host Model A), to increasing influence of groundwater and lateral movement down slope (Host Models E and F) to a hydrology where groundwater dominates and is close to the surface for much of the year and water moves across the surface and through the surface peat, with relatively little downward percolation (Models F and G). It is a classic permeable hillslope sequence. The impact of the catch dykes in intercepting shallow groundwater can be readily seen from the cross section.

Transect and Cross Section of Hill slope Soils. Levels use a local datum (water level in Mrs Myhill's catch dyke) not Ordnance Datum.





Upland Soil characteristics (NSRI 2014b)	**Note**: Although mapped as Gresham Association, fieldwork suggests they are closer to Wick 2. Soils are developed from glaciofluvial and aeolian drift and till. They are free draining, in unconsolidated sands or gravels with high permeability and high storage capacity. Water expressed from such soils would be non-calcareous, neutral to mildly acid. They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology (Wheeler and Shaw 2006, OHES 2011)	The Thurne overlies Crag then Chalk. The peizometric head of the Crag is above 0m OD, although may have been reduced by regional groundwater pumping. Crag water is calcareous. Although the Broad has apparently been dug down to the mineral bottom, the margins appear to have clay underlying the peat. This is borne out by hydrogeological maps and by coring in this study and in Wheeler and Shaw 2006. The hydraulic contact between the Crag water table and the fens is therefore uncertain – Wheeler and Shaw even cite evidence that the surface water may recharge the Crag. Above the Crag on the highland are drift deposits of Happisburgh Formation and aeolian fine sands (cover loam), both permeable and decalcified. The flora of the catch dyke at Mrs Myhill's is distinctly neutral to base-rich. Set within decalcified drift and adjacent to acid fen vegetation, this is curious. It suggests at least some contact with calcareous Crag water, although whether the connection is direct (the base of the ditch cutting the crag surface) or whether Crag water moves through drift, is not certain.

	The Broad is tidal and also subject to high water levels, which will drive water laterally through the marginal peat. It is subject to surface flooding which can also recharge the peat. Wheeler and Shaw (2006) also suggest the possibility of groundwater seepage at the margins where the clay thins (their core showed only 20cm). OHES report that groundwater boreholes 120m from fen dipwells show levels on average 60-70cm higher than the fen dipwells, suggesting significant ground water head above the fen. The strata the boreholes monitor is not recorded. Water tables recorded during fieldwork indicate a likely gradient of shallow drift water into the sites. It is therefore possible that Crag water may enter the site laterally, through the permeable margins. Marginal dykes, whose beds could penetrate the thinning alluvial clay, could also contact the Crag aquifer. The marginal drift also forms its own shallow aquifer which is likely to contribute to the water balance through lateral flow to the wetland. This may be intercepted by catch dykes. The volume of groundwater significant to the site is difficult to estimate, but is likely to be small.
Surface Water Drainage	Catfield Common lies between the catch dyke and the Catfield Dyke, the latter being a major water course receiving upland drainage water. The Broad is an important part of the regional surface water system whose water level is driven by tides and by fluvial flooding. Mrs Myhill's Marsh may be more isolated from this regime than the Catfield Dyke fens, being some distance from a major dyke and less frequently inundated. It is drained by the catch dykes and the marsh drains nearby.
Eco-Hydrological Summary for the Fen (Wheeler et al 2009, OHES 2011)	WetMec Types: 6a: Solid surface water percolation surface (Catfield Common) 13a: Seepage Percolation Surface (Mrs Myhill's Marsh) 13c: Seepage Percolation Water Fringe (Mrs Myhill's Marsh) Mrs Myhill's has some characteristics of WetMec 4b Drained Ombrotrophic Fen At Mrs Myhill's Marsh, water levels fluctuate significantly between years and seasons (OHES 2011), with levels dropping by c.30cm in the summer. OHES could not accurately relate this to below ground level. They also note that fluctuations in ditch water levels do not always correlate with in-field dipwell levels, suggesting peat water tables are not always reactive to surface water courses. Perhaps this reflects distance from the Broad. OHES (2011) used the indirect Ellenberg Indicator Values (interpolated from vegetation data) to suggest that nutrients (or at least nitrogen) did not penetrate the fen compartments from dykes, including the catch dykes. Similar analysis for salt indicated Mrs Myhill's was beyond brackish water influence. It is likely that this isolated arm of the valley is fed more by rainwater and shallow groundwater seepage (as indicated by fieldwork) rather than from Broad water. The potentially important role of lateral groundwater described in the hydrogeology section above led OHES to suggest WetMec 13a and c. WetMec 13c Seepage Percolation Water Fringe occupies a small area around the pond where it is assumed that groundwater discharges to the

	adjacent peat. Field inspection suggests that this zone would be narrow. In addition, the peat here is very shallow (around 10cm or so) and underlain by sandy clay alluvium with low lateral hydraulic conductivity. The pond water level would have to be at bank-full to supply the fen. It is likely therefore to be a partial mechanism at best. The remaining area was classed by OHES as 13b, Seepage Percolation Quag, although 13b typically forms as a mat over watery mud (Wheeler et al 2009), which does not occur at Mrs Myhills. It is most likely to be WetMec 13a Seepage Percolation Surface, which is grounded rather than floating. They are also characteristically thin peats, although can be spongy. WetMec 13a would encompass most of the open fen. Wheeler et al (2009) note the close relationship of WetMec 13a to seepage types such as WetMec 10, Permanent Seepage Slopes. It is unlikely that the small hill slope aquifer is large enough to sustain this kind of seepage, but it could be supplemented by regional Crag groundwater. An alternative perhaps more likely "natural" precursor here is WetMec 11 Intermittent or Part-drained Seepage, reflecting the likely weakness of the seepage. Whatever the strength of natural groundwater flow, it is likely that the excavation of the catch dyke will have caused significant depletion of shallow groundwater and affected the eco-hydrology of the fen. Rainwater may now dominate the site and the fen be less buffered against droughts. The dominance of rainwater gives rise to a character much like WetMec 4b Drained Ombrotrophic Fen. Catfield Common, with shallow loose peat, is likely to experience similar hydrological regimes to all the fens surrounding the Broad. Water from the Broad (and the watercourses tributary to it) permeates the Fens with a hydraulic gradient driven by high Broad levels. OHES (2011) show that levels in the Broad and ditches are similar to levels in fen dipwells to the east, nearer to the Broad. There is additional recharge of the fen peat by rainfall and surface flooding which can occasionally occur in summer. OHES classify Catfield Common as WetMec 6 Surface Water Percolation Floodplain. The sub-type is not altogether clear, with Wheeler et al and OHES suggesting different alternatives. It certainly appears to be a more solid, dryer fen surface than compartments closer to the Broad (e.g. Lings Hill). Coring indicates the peat is north floating or buoyant. Hence we suggest WetMec 6a Solid Surface Water Percolation Surface. Being fed by the Broad and by surface water explains the calcareous nature of the vegetation. It is likely that in former times there would have been a contribution to Catfield Common from the permeable slopes above, yielding essentially base poor low nutrient water. OHES refer to Catfield Common having "a heathy edge where the fen meets the upland..". The historic existence of base-poor wet fen along the margins is quite possible, a transition habitat that would have been affected by the catch dyke.

Main Issues	* Delivery to the site of agrochemicals, including nutrients, transmitted by permeable soils. This is relatively minor for the Catfield Common side where most of the land is pasture and not under-drained. Transmission of nutrients to Mrs Myhill's, aided by efficient under-drainage, may be more significant. The shallow groundwater may also be affected. The degree to which nutrients cross the dyke into the fen is uncertain. Note however that dyke aquatic flora appears to be good, suggesting nutrient enrichment is somehow being moderated. * Potential changes to water quality arising from capture of original good quality shallow groundwater destined for both wetland areas. The Happisburgh Formation from which shallow groundwater arises is likely to be base-poor, while the Crag is base rich and hence the net impact of change on the fen communities is complex and difficult to predict. * Modest drawdown of the water table in Mrs Myhill's Marsh (10-20cm based on winter level, perhaps more in summer depending on sluice management). * Direct physical impact on potential groundwater seepages and their specific habitats, arising from dyke excavation and deposition of spoil. * Disruption of wetland to dry land end of the hydrosere. The catch dykes both overlie the transition zone which have complex soils.
Nature Conservation Constraints	* Water voles and otters may use the dyke corridor. * Intrinsic value of the ditch for aquatic plant and animal communities is not known in detail. The Myhill's catch dyke had clear interest, the Catfield Common catch dyke little obvious interest. * All of the site is of the highest grade for nature conservation. Engineering works within the site could have significant direct impact on designated habitats and features. The sites are small with high value plant communities in close proximity to the catch dykes. Consequently land available for engineered solutions is very modest within the fen.
Physical Constraints	* Any changes to the catch dyke on Mrs Myhill's could impact the land drains discharging into it. * No other assets are likely to be affected as the houses in the north-west corner are influenced by Catfield Dyke, not the catch dyke.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.3.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered. Note that issues relating to Catfield Common are much more modest than Mrs Myhills Marsh and in most cases do not warrant significant action.

Generation of Nutrients (Mostly Mrs Myhill's Marsh)

Seal off wetland
Reroute Main Drain (catch dyke)
Create Buffer/stripping zone
Soil Management
Nutrient Stripping Management
Reduce run-off
Improve Farm practices
Change Upland Land use

Change of Groundwater Quality

Comprehensive in-fill
Raise Water levels
Raise Bed by Partial infill
Perforate perimeter – increase permeability

Depletion of Water Balance/Direct Drawdown of the Water Table (mostly Mrs Myhills Marsh).

Neutralise Under drainage
Pre-Treatment through wet fen
Weeping Boundary
Pumped double ditch

8.3.3 Options Appraisal

Red tint – not taken forward. Yellow tint – only useful in combination with other measures. Green tint – core solution with or without other measures.

Option	Positives	Negatives	Outcome
Seal off wetland	Prevents ingress of nutrients. Prevents direct drainage.	Eliminates groundwater feed to both margins. Technically difficult, may require impact on fen or significant land take upslope. Expensive.	Does not resolve issues. Not taken forward.
Reroute main drain (catch dykes)	Removes dykes from direct contact with fen areas. Maintains current land use upslope. Reduces impact of run-off discharge to the fen. Reduce depletion of groundwater flows and would eliminate impact of drainage.	Can only be moved upslope. Requires change of land use between it and the Fen. To be effective the drain would need to be 1.5m above the current position. Because of the modest topography this requires a significant shift upslope, removing much of the available agricultural land. Bed and banks would need to be lined to prevent downward percolation and passage to the fen.	Insufficient gains. Not taken forward.
Create buffer/stripping zone	Reduces ingress of nutrients to the fen. Could create additional wildlife habitat such as toe slope wetland.	Does not address generation of nutrients or eutrophication of deeper groundwaters. Can be overwhelmed in storm flows. Does not address groundwater or water balance issues. The toe slopes on both sides of the spur are already in low intensity grassland, while the fen adjacent to the catch dykes are already being cropped.	Already largely in place. Not taken forward.
Soil management	Would remove accumulated nutrients stored in topsoil of either upland or fen.	Regular cropping and permeable soils means arable topsoil not hugely enriched. Action on upland not beneficial. Soil stripping would be damaging in fen areas and would not be justified by current evidence of surface eutrophication in the fens. Does not address many of the key issues.	Not taken forward.
Nutrient stripping	Would deplete nutrients in fen surface	Does not address generation of nutrients,	Little opportunity to

management	peats and prevent ongoing accumulation. Would deplete nutrients in arable soils.	eutrophication of deeper groundwaters or any of the hydrological issues. Annual mowing (optimal for nutrient reduction) is expensive and not appropriate for *Cladium* habitats. Both fen areas being managed optimally for the habitat with little flexibility.	amend management. Not taken forward. May be appropriate for arable in combination with land use change.
Reduce run-off	Reduces nutrient and silt movement to the wetland. Low costs.	Requires cooperation and potentially compromise from managers of the upland. Does not address generation of nutrients, eutrophication of deeper groundwaters or any of the hydrological issues.	Only useful as part of other measures which deal with core issues.
Improve farm practices	Reduces nutrient and silt movement to the fen. Low capital cost.	Requires cooperation and potentially compromise from managers of the upland. Does not address hydrological issues.	Only useful as part of other measures which deal with core issues.
Change upland land use	Would remove significant inputs of nutrients. Removes need for a significant (or any) catchwater drain. Removes principle constraints on most effective solutions which would address all of the major issues. Allows restoration of the full hydrosere.	Requires comprehensive change in land management by all stakeholders or large scale acquisition by conservation organisations.	Core solution for comprehensive remediation. Taken forward.
Comprehensive in-fill	Deals with all of the hydrological issues.	Does not prevent leaching of nutrients. Cannot be contemplated while adjacent land management requires under-drainage or significant freeboard. Requires extensive stakeholder agreement. Negative impact on intrinsic value of dyke.	Core solution for comprehensive remediation. Taken forward. Requires land use change.
Raise Water levels	Raising water levels in the Myhill's catch dyke in the summer would neutralise any direct drainage effect and would improve water balance.	Does not address nutrients. Does not restore water quality or groundwater flows.	Partial solution but with stand-alone benefits which should be taken forward.
Raise Bed by Partial infill	Would help restore groundwater flow at dyke depth.	Does not deal with nutrients issue or with drainage issue. Expensive and requiring significant engineering. Could impact intrinsic value.	Partial solution but with stand-alone benefits which should be taken forward if

			partial infill not feasible.
Perforate perimeter – increase permeability	Would help to restore groundwater input and assist with wetland water balance.	Could encourage ingress of poor water quality. May worsen drawdown of the fen water table if the summer dyke water level is not at marsh level. Does not deal with nutrient issue.	Not taken forward.
Neutralise Under drainage	Reduces peak flows to dyke, therefore reduces sediment and nutrient delivery. Reduces likelihood of dyke overflow. Important in enabling other measures.	Significantly impacts on arable drainage and therefore on stakeholders. May require land use change or other financial measures. Does not reduce nutrient input or remediate other hydrological issues.	Only useful as part of other measures which deal with core issues.
Pre-Treatment through wet fen	Provides a buffer area to absorb ditch overflow before it enters fen. Reduces impact of nutrients.	Does not address hydrological issues, reduce the application of nutrients or reduce eutrophication of groundwater. Significant impact on fen as it would require significant sacrificial area. The fen at Catfield Dyke is already narrow, the key plant communities at Mrs Myhill's are very close to the dyke and would be impacted by the scheme.	The impacts on fen communities would greatly outweigh benefits. Not taken forward.
Weeping Boundary	Promotes ingress of water from pre-treatment options, boosting water balance of the fen.	Does not address hydrological issues, reduce the application of nutrients or reduce eutrophication of groundwater. Significant impact on fen because of lack of space for engineered solutions. Not necessary on Catfield Common side as the peat is highly transmissive.	Not taken forward.
Pumped double ditch	Allows maintenance of a ditch at fen ground level throughout the site. There would be no draw down of the fen water table.	Significant impact on fen because of lack of space for engineered solutions. Benefit uncertain if summer freeboard relatively high.	Not taken forward.

8.3.4 Conclusions and Recommendations

The catch dykes around the spur perimeter are undoubtedly having a negative impact on both fens, most especially Mrs Myhill's Marsh. The most significant impact is interception of shallow drift groundwater and possibly some Crag groundwater, and in the truncation of the wetland to dryland hydrosere. The arable upland may also cause some eutrophication of the wetland although at least some of this will be intercepted by the catch dykes. There is little direct evidence of eutrophication of the fens, although no-one has specifically been looking for it. Depending on the summer level, there may also be a direct drainage effect at Mrs Myhill's Marsh.

Impacts of the catch dyke along the upland margin of the Catfield Dyke fens are very modest and do not warrant significant intervention. No action is required except continued lack of maintenance of the catch dyke. If the dyke is substantially cleaned, it would be moved to Type 1, High Risk, and would be subject to review.

A combination of constraints and prevailing site management on both upland and fens mean that relatively few measures emerge from the Options Appraisal. The review suggests a short and long term approach should be considered.

Long Term – ideal, comprehensive solution

Land use change is the key to a comprehensive solution. If the land were taken out of arable, and put into low intensity management (ideally habitat restoration), the land drains could be stopped up, applications of nutrients cease and downslope movement of sediment and agrochemicals stop. The catch dykes themselves would be unnecessary and could be filled in allowing the restoration and proper hydrological functioning of the transitional habitats.

Short term measures to moderate impacts

If land use change cannot be effected the current drainage infrastructure must remain. All that can be achieved is further moderation of the effects of commercial arable management.

- Firstly, the summer water level in the ditches should be reviewed to ensure that the maximum height is attained without unduly affecting land drains.
- Secondly, a range of catchment sensitive farming methods to reduce runoff, application of fertilisers and generation of sediment could be applied if it were compatible with arable farming.

8.4 Limpenhoe Meadows

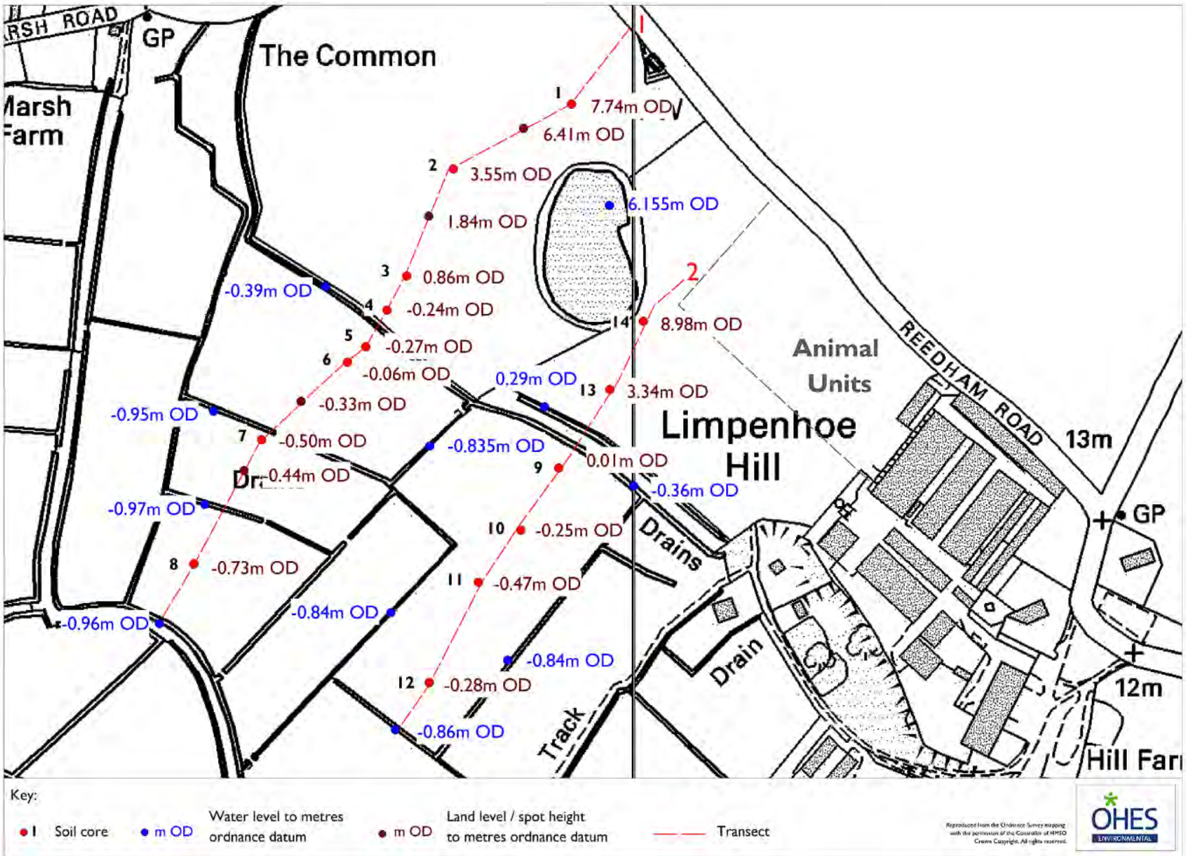
8.4.1 Defining the Nature of the Problem

<table>
<tr><td>Site Name</td><td>Limpenhoe Meadows</td></tr>
<tr><td>River System</td><td>Yare</td></tr>
<tr><td>Manager</td><td>Private Landowner</td></tr>
<tr><td>Designations</td><td>SSSI</td></tr>
<tr><td>Landscape Context</td><td>A valley margin wetland along the northern edge of the lower Yare valley, between the highland and extensive alluvial floodplain grazing marshes. The upland behind is exceptionally steep, rising to Limpenhoe Hill which forms an abrupt edge to the gently undulating plateau behind.</td></tr>
<tr><td>Plant Communities
(Map from RMA 2013)</td><td>

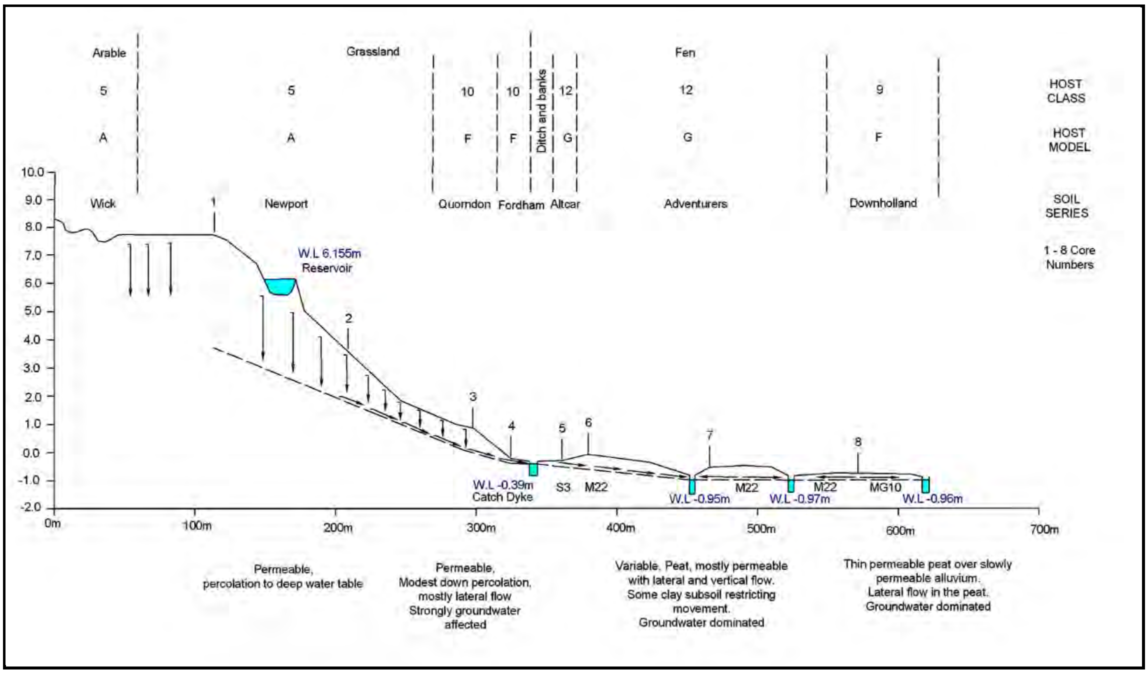
The site is a complex of mire, fen meadow and alluvial wet grassland. The extensive areas of peat supports M22 *Juncus subnodulosus-Cirsium palustre* fen meadow of great species richness. A trench of deep peat, possibly an old dyke, has dense sedge tussocks of S3 *Carex paniculata* swamp, is not recorded on the above map. There are areas of groundwater discharge, and there are areas of wet acid seepage fen with *Sphagnum* and *Drosera*. Wheeler and Shaw (2006) refer to this as M24 *Molinia caerulea-Cirsium dissectum* fen meadow, but RMA (2013, map above) have split this</td></tr>
</table>

	between M24 (orange on the map) and M13a *Schoenus nigricans-Juncus subnodulosus* mire, based on MATCH coefficients. However, inspection of the data suggests the link between the vegetation samples and M13 is tenuous. The pink area on the map is described by RMA as a mosaic of M25 *Molinia caerulea-Potentilla erecta* mire and M26 *Molinia caerulea- Crepis paludosa* mire. Both are associated with base-poor conditions, the latter being a western and northern community. Again there are rather few samples and the classification is a little tenuous. Lower down the slope profile to the south, the peat thins and the wet grassland is semi-improved and typical of the alluvial soils of the lower Yare, dominated by marsh grasses and species typical of standing waters.
Catch Dyke Characteristics	**West side: Catch Dyke Type 1/2** There is a significant catch dyke along the highland margin. It is 5m wide at bank, 1.1m deep with small freeboard and with dense vegetation, clearly being maintained rarely. The dyke, although silty, is cut into the sandy material of the slope behind. The water level is at -0.39m AOD, around 60cm above the marsh dykes and about 15cm above marsh surface in March 2014. There appears to be no direct connection to the floodplain dykes but there is clearly a strong hydraulic gradient. The landowner did not appear to know how or if it was connected to the floodplain dykes, and if it is, then it must be silted up. The upslope soils are sands and gravel and highly permeable. They are pasture, seeded from arable eight years ago, and are in Higher Level Stewardship. There are no land drains discharging to the catch dyke. Arable is extensive on the plateau behind the pasture slope. **East side: Catch Dyke Type 1**. This ditch is 6.5m wide, between 1.0 and 1.5m deep, and apparently better maintained with open water. Water level is -0.36m AOD, again around 50-60cm above marsh dykes and 15-20cm above a more variable marsh level. There is a clear hydraulic gradient. The bed is hard, not on peat. Above the catch dyke is a dyke-like trench scooped out of the toe slope with a water level of 0.29m AOD, 65cm above the catch dyke. The trench was intended to intercept run-off before it enters the main catch dyke, dug when the farm kept pigs on the slopes and the top, 20 years or more ago (source: the landowner). The cattle sheds built recently are on concrete. Assuming their storm water drainage is not a soakaway to the ground, they should restrict leakage of nutrients. The farmer does not apply fertiliser to the grassland. There are no land drains discharging to the east catch dyke. Although connection to floodplain dykes are not working, the catch dykes are technically part of the pumped floodplain level which discharges to the Yare at the Reedham Pump. The catch dykes intercept drift groundwater and may tap into the Crag. They will also intercept and then pass through high nutrient loadings from the ground above. Neither catch dykes appear to have a healthy aquatic flora. There was a clear improvement in the dyke flora with distance from the highland margin, with dense beds of charophytes in the more distant dykes.

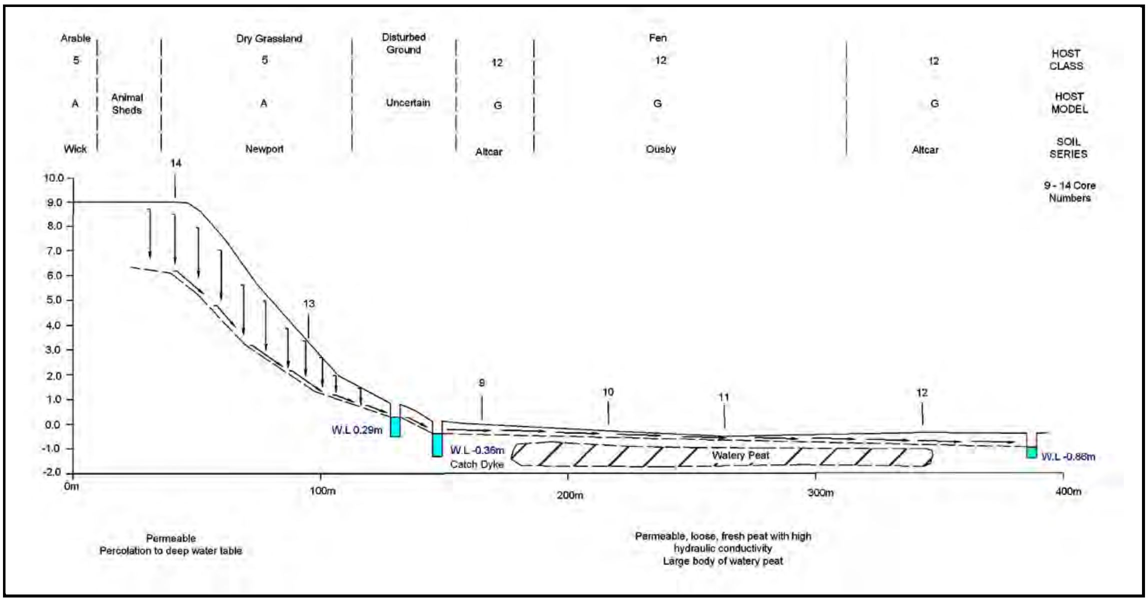
Transects and Hill Slope Catenas at Limpenhoe Meadows



Transect 1



Transect 2



Upland and Floodplain Soil Catena including hydrology	See hillslope cross-sections above. Soil cores are described in Appendix 6. Part of the site falls on the margins of the area surveyed by Hazelden (1990), with coring here confirming broadly his mapping. Hazelden maps the plateau of the upland to the north (not sampled) as Wick Series. In the western Transect 1, the slope soils are stony, sandy Newport Series with some sandy-clay inclusions. Towards the toeslope, the groundwater starts to influence the soils with gleyed profiles of Quorndon then Fordham Series at the toe slope. The saturated water table level was around 0m AOD and -0.40m AOD respectively, suggesting a steep gradient on the water table down to the marsh. The water table in the Fordham soil is the same as the catch dyke water level. There is a narrow trench of very wet peat (Altcar Series) parallel to the west catch dyke, under *Carex paniculata* swamp. From 20-190cm this is fibrous, fresh, very wet peat, with humified peat below. The bottom of the peat was not contacted by the end of the core at 235cm. Thereafter the profiles under fen meadow are variable Adventurers peat, in more fibrous and less humified profiles verging on Altcar Series. Core 6, in M22, is shallow (55cm) peat over wet, soft, presumably alluvial clay, then Core 7 is a very deep (>235cm) peat with a 5cm layer of clay within, and finally under the MG10 at the end of the transect is a thin (25cm) layer of humified peat over a soft wet alluvial silty clay (Downholland Series). Marsh levels are relatively even. Cores and dyke water levels show that the fen water table was about the same as the water level in the dykes. In the eastern Transect 2, the sequence has been truncated with animal housing being built on what may have been the gravelly Newport soils shown in Core 1 of Transect 1. The toe slope was disturbed by the excavation of the send dyke. The slope between was again the permeable, sandy Newport Series.

	The floodplain cores are more consistent on the east side of the marsh, and mostly rather different to the west, with deep peat in all cores, from the surface to below coring depth at 235cm. They include mostly fresh peat. Where there is a loamy humified surface peat they are Altcar Series. Profiles with fresh fibrous peat more or less to the surface are Ousby Series, with transitional areas between the two. Much of the peat examined seemed to be "brown moss" peat usually associated with very wet, base rich conditions. There was a crust of firm peat across the marsh (the surface did not wobble like a true hover), around 60-70cm thick in the central marsh areas under which was a very watery, soft unconsolidated peat, almost semi-liquid and difficult to pick up with the corer. The base of this watery peat was not contacted. The crust of firm peat thickened at both the catch-dyke and south ends of the marsh. Marine alluvium clays were not contacted (although the southern grass marsh could not be accessed). The east side of the site carried the fen mapped as M13, M24 and the sphagnacious fen, and had a higher groundwater table, +/- at the surface in all floodplain cores. There appears to be a broad correlation between plant communities and floodplain peats and water table. The marsh surface was much more uneven than on the west side with a hollow of c. 10-20cm around core 11. Surprisingly, levelling did not show a classic raised dome or "boil" in the sphagnacious fen, although the density of levels may not have been sufficient to be definitive. The water table was at surface or within 10cm in the fen of the east side, whereas the dykes were c.50cm below. It suggests the fen water table was, in contrast to the west side, being maintained above marsh dyke level.
Upland Soil characteristics (NSRI 2014d, e)	Upland soils are developed from glaciofluvial and aeolian drift and till. They are free draining soils in unconsolidated sands or gravels with high permeability and high storage capacity (overall Host Class 5). They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology (Wheeler and Shaw 2006)	The deep chalk is sealed from the site by London Clay. The slope to the north is Crag, overlain by decalcified till (Happisburgh Formation) on the slopes and by marine alluvium and peat on the floodplain. The Crag is described as confined to unconfined and where the latter conditions persists, provides calcareous groundwater to the site. The degree to which the Happisburgh Formation provides shallow groundwater (base poor in composition) is not indicated by Wheeler and Shaw. They note "Springs emerge within the meadows close to the base of the valley slope, but wet conditions are very localised". It is quite possible that groundwater feeds, and is responsible for, the large body of saturated semi-liquid peat that underlies much of the east marshes. The evolution of the marsh appears very different on the east and west

	sides. The east side has deep peat without contact with the marine alluvial base, whereas the west side only has one profile with this character. It is possible that peat infill of an old floodplain feature such as a former cut off river meander has created this pattern. A water body that was progressively terrestrialised could produce a crust of denser peat over loose peat. The old peat crust is now mature, thick (c.70cm) and very firm. The watery peat underneath the crust may act as a reservoir of groundwater – and any pollutants which seep in from the highland – and may buffer the fen from gross changes in water levels. It is curious that in the M22 fen meadows of the west side, the water table was consistent with dyke water levels and 50cm below marsh level, whereas in the M24/M13 and other communities, the water table was at or close to ground surface and 40-50cm above dyke water level. The soils here are Ousby peat, more or less fresh peat to the surface, suggesting the water table is at or near ground level throughout the year. Areas not underlain by the watery peat have at least a crust of surface humified peat (Altcar or Adventurers Series). It is tempting to conclude rising groundwater accounts for these water level and peat differences. However, more comprehensive data, including summer water level recording, would assist this interpretation. Note that the reservoir is lined and is filled by winter pumping from a borehole.
Surface Water Drainage	The site is surrounded, and dissected, by dykes. These are connected to the wider floodplain dyke system which is pumped to the river Yare. Note the catch dykes seem to be blind and sit above the floodplain dykes. If the catch dykes were originally connected, occlusion by silt and vegetation has rendered them ineffective. If the connections were opened, the catch dykes would drop significantly and would directly drain the upper marsh. According to the land owner, there is no site-specific management of water controls. Floodplain dyke water levels were below fen surface level in March 2014. Their summer level is not known. Groundwater may buffer summer declines, but the landowner indicates that water is pumped into the wider floodplain dykes from the Yare by the pump at Reedham Ferry. This is undertaken approximately from April to September to maintain high water levels in the dykes, so cattle can be pulled out if needed. The quality of such water is not known but the Yare is unlikely to supply water suitable for SAC fen habitats. This needs to be investigated. In the winter, dykes are drawn down by the pump. The landowner notes that when the Reedham Ferry pump kicks in, the dykes are drawn down noticeably, so the site should clearly be considered part of a pumped level. Dykes are only likely to be effective sub-irrigators of the fen on the east side where fresh peat extends nearly to the surface. The dykes are likely to be in hydraulic contact with the watery peat under the solid peat crust. Flooding by River Yare water is thought to be insignificant on this site – although note this may not always have been so, as there is evidence of

	silt in the shallow peat deposits.
Eco-Hydrological Summary for the Fen (Wheeler et al 2009)	WetMec 8 : Groundwater Fed Bottoms with Aquitards 8b Distributed Bottom WetMec 9 : Groundwater Fed Bottoms 9a Wet Groundwater Bottom 9b Part Drained Groundwater Bottom There is a clear eco-hydrological gradient from the margin to alluvium floodplain, represented by sequences of WetMec types. WetMec 9, Groundwater Fed Bottoms, are sites where the water table is mostly sub-surface all year round, in essentially topogenous sites, but where the main catchment water input is groundwater, supplemented by rainfall which may feed the surface in dryer periods. Groundwater, derived from the Crag, passes upward and laterally from the highland, with no intervening aquitard. These conditions appear to persist along the upland margin where groundwater influence is strongest. The transects suggest that the water table surface is likely to have a steep gradient, with the catch dyke sitting significantly above the marsh, creating hydraulic gradients in both permeable upland soils and the largely permeable peats. Limpenhoe Meadows appear to host the wetter variant WetMec 9a, at least along the margin and in the centre of the eastern area. Wheeler et al (2009) suggest that closest to the upland margin where groundwater influence is strongest, it is even transitional to a seepage system of WetMecs 10 and 11, supported by the NVC survey which indicates seepage-related plant communities. Wheeler et al note that groundwater seepage WetMecs may be pushed to WetMec 9 by drainage. They cite abstraction and valley drainage as main factors in the conversion. Abstraction is not known to be affecting this site, but it is part of the pumped Yare surface water system and clearly the influence of floodplain dykes could be an important factor. Currently the catch dykes appear not to be connected to drainage and therefore may not be depleting groundwater. Note that Poplar Farm Meadows, nearby in the Yare, is also accorded WetMec 9a, and it seems likely that much of the northern margin of the valley may have had significant groundwater influence at one time. In the area surrounding WetMec9a, where the influence of groundwater declines and the influence of the pumped floodplain dykes increases, the dryer WetMec 9b is likely to be characteristic. Away from the deep peat profiles where the clay alluvium is closer to the marsh surface, the site is underlain by a clayey aquitard (marine alluvium) which dominates the soil hydrology. Although such areas still benefits from groundwater input, such groundwater is circulated by the dykes. This then becomes WetMec 8 Groundwater Fed Bottoms with Aquitards, which carry a different, perhaps drier vegetation (M22 and MG10) to the more

	directly groundwater supported areas. Because of the presence of dykes, this is almost certainly 8b, a Distributed Bottom. The end point of the sequence is given by the alluvial wet grasslands without fen interest, solely driven by dyke water level management and rainfall. There is a distinctive base-poor element, as well as the more obvious base-rich fen meadow. M25 and M26 were both recorded around the upslope areas of the east marshes, above the M13 and M24. The area of *Sphagnum* within rich fen communities appeared to be extensive at the time of the current survey. As the shallow drift on the upland is decalcified Happisburgh Formation sands, it could be the source of base-poor seepage, or the base poor fen could be nourished by rainwater over a calcareous groundwater. Unlike the *Sphagnum* dominated raised domes recorded in many places in the Broads, the base poor fen element at Limpenhoe was not clearly associated with raised ground. The situation is curious and further work on this aspect is needed. It remains possible that prior to the excavation of the catch dykes this site may have had an overlay of poor-fen at the floodplain margin, fed by decalcified shallow groundwater emitted by upland sands and gravels.
Main Issues	* Delivery to the site of high nutrient loadings from stock operations on the upland, transmitted by permeable soils and steep groundwater gradients. Since the change-over from pigs to cattle in concrete floored housings, and since the reversion of the slope to grassland, nutrient flow to the site is likely to be very much reduced. The shallow groundwater arising from the immediate slopes will be most affected by historic eutrophication or any modern low level impacts. The deeper groundwater supplied from the Crag may also be affected. Retention of historic eutrophication of the watery peat mass beneath much of the fen could also be a concern. The residence time of historic eutrophication is not known. The interceptor drain on the east side is only of limited effectiveness; the bund has been placed on the north (upslope) side so any runoff must run around the bund and possibly miss the interceptor. Unless it is pumped out the intercepted nutrient would leach down and into the wetland. * Yare river water, imported into the site in summer, may be of poor quality and may adversely affect low-nutrient fen communities. It may permeate the water peat mass of could directly irrigate fen communities. * As the catch dykes sit above the floodplain, and seem not to be directly connected to the floodplain dykes, direct drainage is not likely to be an issue. Neither is diversion of groundwater or the depletion of the water balance. This would change enormously were the catch dykes to be reconnected to the floodplain. * Although the catch dykes will intercept groundwater and mix it with rainwater, modifying the hydrochemistry that passes to the wetland, this is likely to be volumetrically very minor.

	Groundwater may also flow under the catch dyke, avoiding interception and mixing. * Direct physical impact on potential groundwater seepages and their specific habitats, arising from dyke excavation and deposition of spoil. * Disruption of wetland to dry land end of the hydrosere. * The small size of the site makes it especially vulnerable to change and to edge effects (which in a dyke network are significant).
Nature Conservation Constraints	* Water voles and otters may use the dyke corridor. * Intrinsic value of the ditch for aquatic plant and animal communities is not known in detail. The ditch flora as a whole is recognised as an important part of the SSSI designation. Inspection during this survey suggests the catch dykes have a poor aquatic flora but may have better invertebrate interest. * The site is comparatively small and all is of national significance for nature conservation. There is little or no area which could be considered sacrificial. Some of the most important areas, such as the seepage communities, are likely to be close to the catch dyke. Engineering works within the site could have significant direct impact on designated habitats and features.
Physical Constraints	* As the catch dykes receive no land drains and the upland slopes are in grassland in HLS, there are no land use constraints on works to the dykes. * Significant assets are unlikely to be affected as there are none within the site or within direct hydrological influence of the dykes.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.4.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered.

The site presents an unusual opportunity as the catch dykes do not receive under-drainage, do not have arable land upslope (the grassland is in HLS) and is not required for drainage of assets. There is therefore considerable potential flexibility in applying comprehensive solutions, and in the restoration of the full floodplain to dry land sequence.

As long as the ditch is not reconnected to the floodplain dykes, direct drawdown of the water table and depletion of the water balance are not issues and do not need to be addressed. If the dykes are cleaned out and reconnected however, they would be significant issues. The potential impact therefore remains.

The nutrient issue here may be largely historic. With conversion to low intensity grassland, removal of pigs on the fields and the housing of cattle on concrete-based housing units, the two aspects that could cause concern are over-stocking of the field combined with intense rains and run off, and possible run-off from the concrete areas during storms, or discharge of concrete washings to ground.

Generation of Nutrients

Reduce run-off
Improve Farm practices
Comprehensive in-fill

A number of the measures in Figure 11 were not considered because upland land use is not arable or because the nutrient issues are not acute enough to warrant them.

Change of Groundwater Quality

Raise Water levels
Raise Bed by Partial infill

Depletion of Water Balance/Direct Drawdown of the Water Table

This issue only requires remedial treatment if the catch dykes are dredged out and reconnected to the floodplain. The key action is therefore **not to reconnect them**.

A complete, long term solution would be comprehensive in-fill. Other options under this issue are considered excessive or damaging to the site and are not considered further.

8.4.3 Options Appraisal

Red tint – not taken forward. Yellow tint – only useful in combination with other measures. Green tint – core solution with or without other measures.

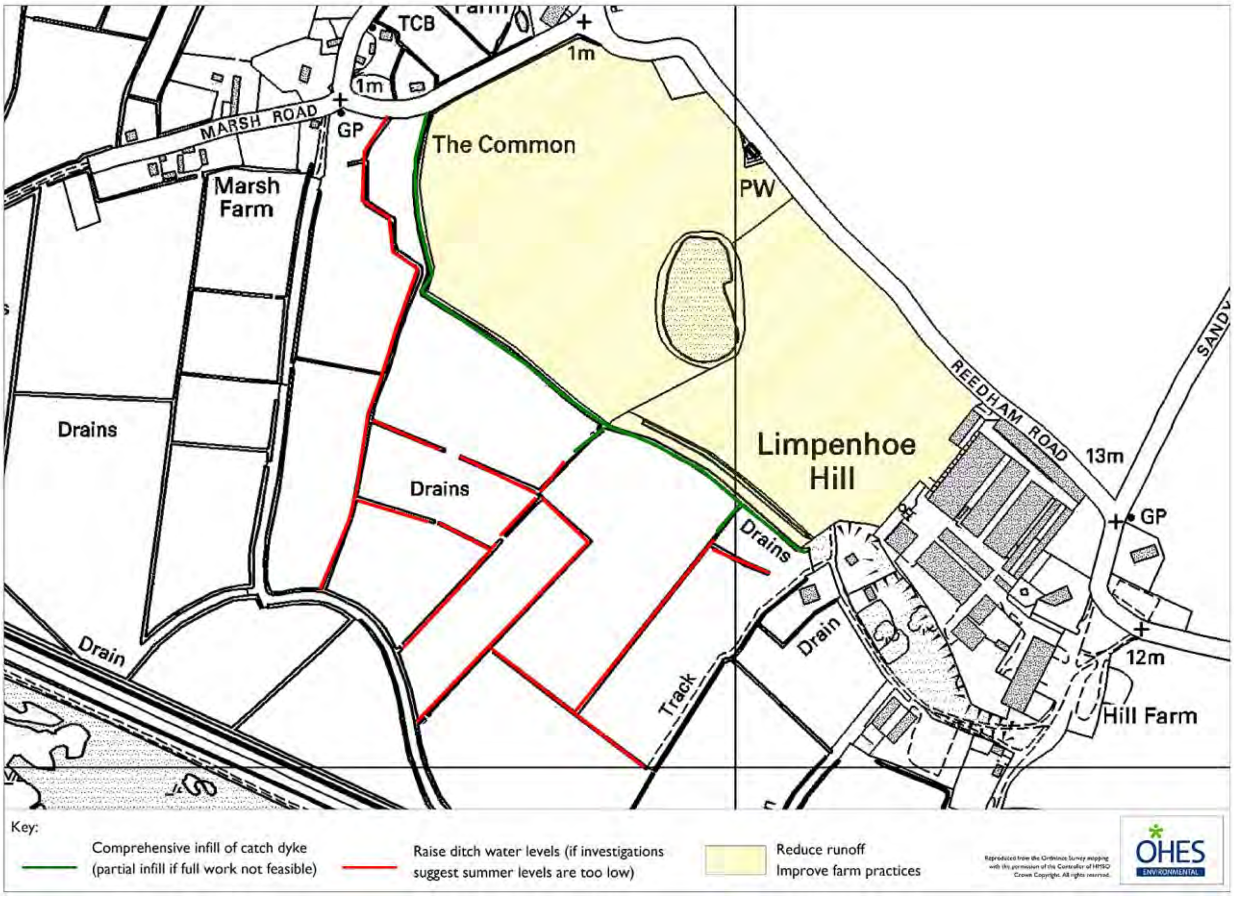
Option	Positives	Negatives	Outcome
Reduce run-off	Reduces nutrient and silt movement to the site. The steep slopes of the upland are especially prone to run-off during intense rainfall. As the land is already grassland, it requires only the relaxation of grazing to develop a denser sward to reduce incidence of overland flow.	Reduces numbers of stock the farm can graze here.	Taken forward as part of range of farm management measures.
Improve farm practices. As the upland is already grass, this relates mainly to control of washings from the concrete cattle housing.	Reduces nutrient and silt movement to the fen.	Depending on current arrangements, may require investment in management and disposal of washing from the housing units.	Taken forward as part of range of farm management measures.
Comprehensive in-fill	Deals with all of the hydrological issues. Allows the restoration of the wetland to dryland sequence and repair of impacted seepage slope. Permanently prevents any connection to the floodplain dyke system.	Does not prevent leaching of nutrients.	Core solution for comprehensive remediation. Taken forward.
Raise Water levels	This option would maintain disconnection of the catch dykes from the floodplain dykes. It would also prevent impacts on water quality and on	Does not address nutrients. Only needed if summer water levels provides too much freeboard.	Water level management including import of Yare water, is an important component of the project

	water balance should water levels in the catch dyke drop during summer. There may be more benefit from examining water controls on the floodplain dykes, and from assessing water quality of Yare water brought into the site.		and should be taken forward regardless of catch dyke issues.
Raise Bed by Partial infill	Would help restore groundwater flow at dyke depth.	Does not deal with nutrients issue. Does not allow restoration of the floodplain to dryland sequence and does not allow full restoration of the seepage area. Expensive and requiring significant engineering, especially for the level of benefit offered.	Partial solution. Only considered if comprehensive infill not possible.

8.4.4 Conclusions and Recommendations

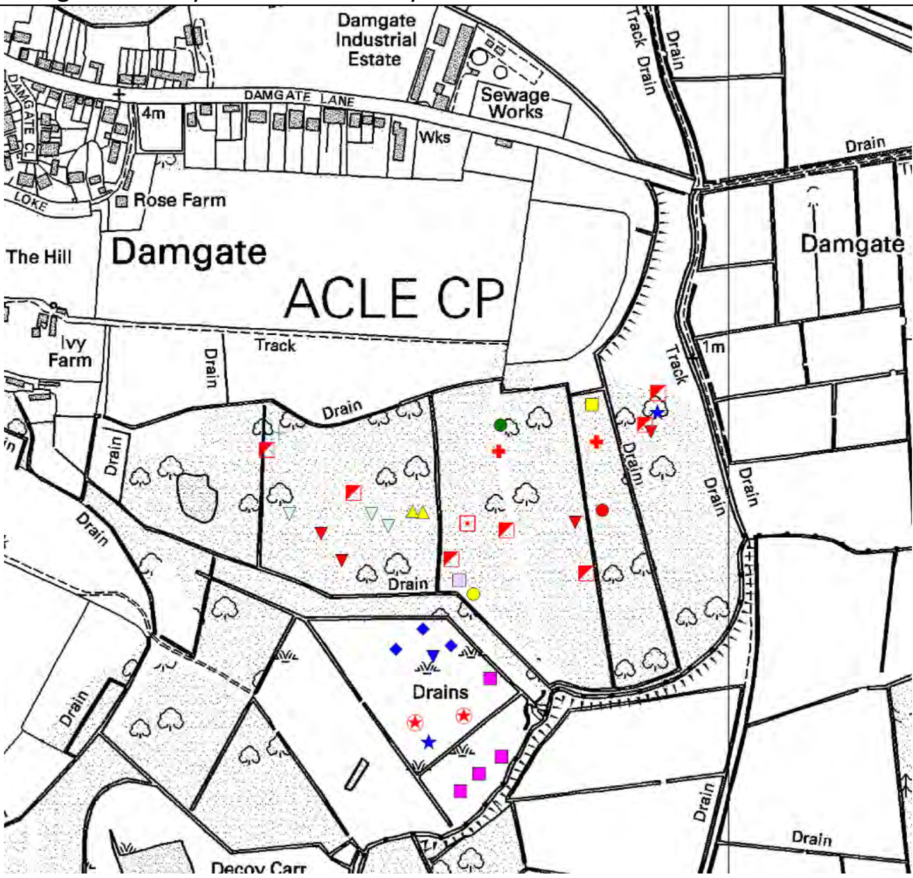
This site presents a relatively straightforward opportunity to restore the floodplain margin through comprehensive in-fill of the catch dykes. The upland is already in sympathetic management, there are no under-drains and there are no assets dependent upon it for drainage. Nutrient issues are likely to be largely historic. However, some modest improvements to farm practise could improve this further.

Proposed Plan Of Improvement Works Is Attached.



8.5 Decoy Marshes, Acle

8.5.1 Defining the Nature of the Problem

<table>
<tr><td>Site Name</td><td>Decoy Marshes Acle</td></tr>
<tr><td>River System</td><td>Bure</td></tr>
<tr><td>Manager</td><td>Private Landowners</td></tr>
<tr><td>Designations</td><td>SSSI, SAC, SPA, Ramsar</td></tr>
<tr><td>Landscape Context</td><td>Decoy Marshes lie on the floor of a small tributary valley of the Bure floodplain, just west of the Halvergate Marshes. The valley trends directly north-south and has steep slopes especially on the west and east flanks. At the north end of the valley, where the remaining open fen lies, the slope is shorter and more gentle. The small valley opens out to the Halvergate Marshes on the east side of the north end, the eastern margin of the site being marked by the Weavers Way track.</td></tr>
<tr><td>Plant Communities</td><td>


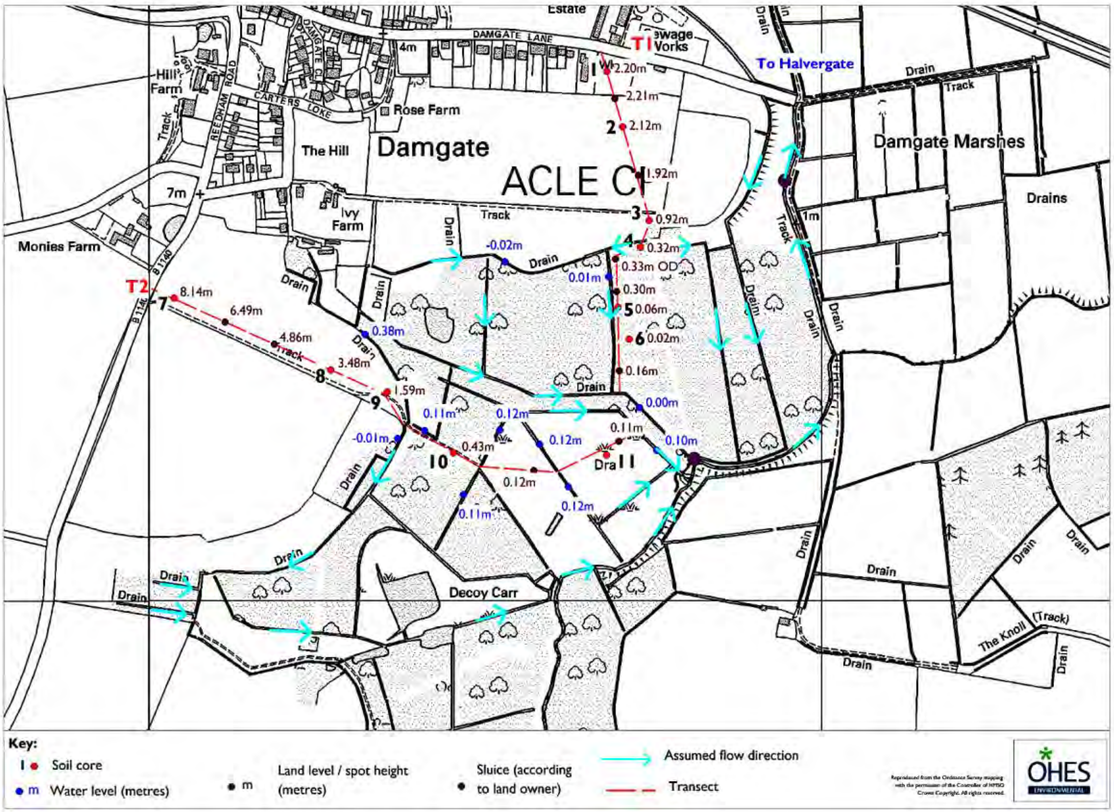
Most of the site is scrub and carr woodland. All of the open fen is in the north of the site. There are areas of young fen recolonizing from scrub and woodland clearance. The communities are very mixed but are all base-rich and calcareous tall-herb fens with some stands of M22 Juncus subnodulosus-Cirsium palustre fen meadow. Since the survey was undertaken, further areas of scrub have been cleared. The main fen areas are a wide range of sub-communities of S24 Phragmites australis-Peucedanum palustre fen, including species-rich and very wet communities, and some extensive areas of Cladium. There are stands of S1 Carex elata swamp, now rare in the Broads, and Phragmites, Typha and Glyceria swamp.</td></tr>
</table>

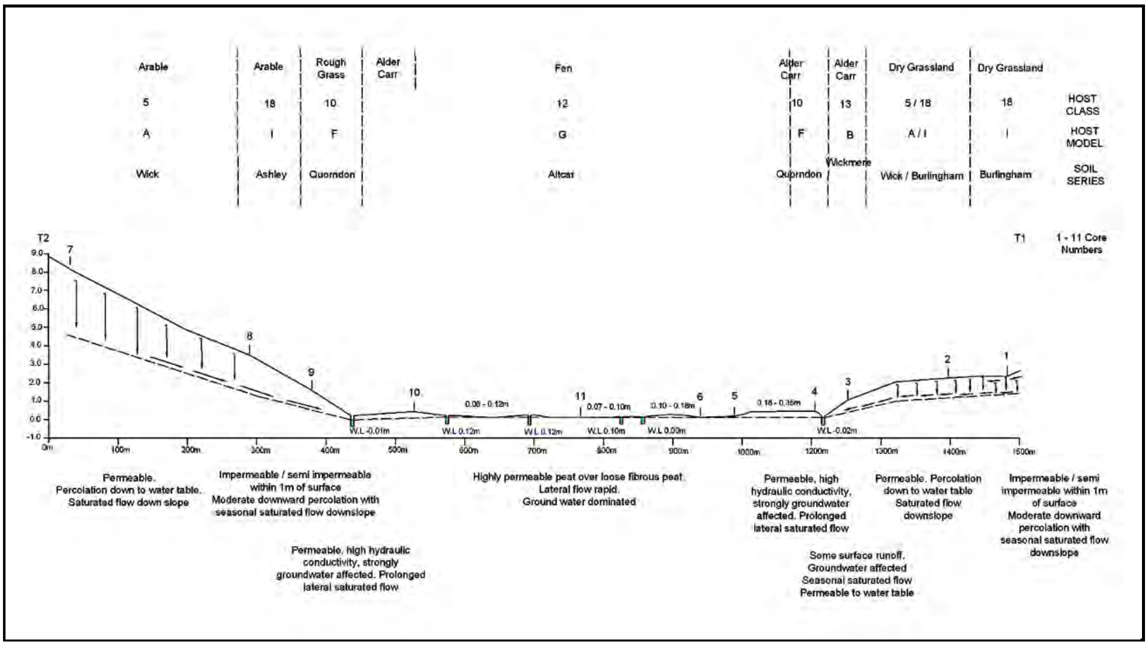
	Wheeler et al (2009) note that there are records for communities approaching M9 *Carex rostrata-Calliergon cuspidatum* mire, with Wheeler and Shaw (2006) recording this as a semi-floating mat of vegetation close to the west margin probably over the former Decoy.
Catch Dyke Characteristics	There are catch dykes along all of the margins of the site. Those of most significance to the fen interest are along the north margin and the northern part of the western margin. Levels described below and on the accompanying Plan and cross section are nominal, not to OD (no local benchmarks were available) and take their datum of 0.00m from the water level in the dyke at the end of Transect 1. Note that levels given were recorded on 17/03/14, at the end of a wet winter. Summer levels are not known. **Northern Catch Dyke: Transect 1: Type 1**. High Risk. The water level (-0.02m) is about the same as the adjacent floodplain dykes to which it is connected. The dyke is 2.4m wide with 0.7m depth plus a freeboard of around 50cm. The dyke is scrubbed over, silted and not obviously maintained. Bottom was hard and the dyke course was along the peat/mineral soil boundary. The dyke does not receive under-drainage and upslope land use is either semi-natural habitat or low-input grassland. The ground surface slopes gently from the edge of the dyke to the flat valley bottom through alder carr. The ground surface of the carr is at around 0.40m above catch dyke water level, grading down to about 0.18m at the edge of the open fen. Thereafter the fen is relatively flat varying between 0.10 and 0.18m above dyke water level. The carr woodland has overgrown part of the gentle toeslope. This slope is directly drained by the catch dyke and by the connecting floodplain dykes. **Western Catch Dyke: Transect 2: Type 1 or 2**. High or Moderate Risk. The dyke is split by a crossing through which Transect 2 passes. Both of the western catch dykes are 3m wide and 1m deep. The much higher bank on the upslope side suggests the catch dyke has been cut along the edge of break of slope, above the level of the peat margin. Ditch bottom was hard. Upslope land use is arable with small parcels of rough grassland adjacent to the dyke. There is no discharge from under-drainage. The short, blind northern section has a high water level at 0.38m, around 25cm above the floodplain dykes and is not connected to the main drainage network. This is Type 2, moderate risk. It would be Type 1 if it were connected to the network. The southern section is at more or less the same level as the northern catch dyke, -0.01m, with freeboard of around 0.9m on the fen side. Although this seems very high it is reflecting a localised area of high ground flanking the crossing. According to the landowner, it flows to the south to join the main site outflow drain. It is Type 1, High Risk. It is not directly connected to the dykes in the open fen. The open fen ditches have a water level of around +0.11m, 10cm or so above the level of the catch dyke, further evidence they are not connected. There is again a gentle toeslope overgrown by carr woodland, which starts at around 40-50cm

	above catch dyke water level, grading down to the start of the valley bottom fen at about 0.15m. Thereafter the fen varies between 0.07 and 0.10m. Overall, it is a very similar pattern to the northern margin, the alder carr being a little wider on the western transect, and with a slightly greater fall from catch dyke edge to valley bottom. This section of toe slope is also directly drained by the catch dyke and to a slightly lesser extent, by the floodplain dykes. In summary the main catch dykes and the floodplain dykes in the north section are all at around 0m and probably controlled by the same sluice retentions. The floodplain dykes in the southern section are at around 0.11m, perched above the others, and presumably retained by a blockage or separate sluice. Although the catch dykes are controlled by sluices, the retention level means they still drain the toe slope and are connected to the pumped drainage of the Halvergate Level. The catch dykes will be intercepting groundwater derived from the soil, shallow Cover Loam and Brick Earth drift. They may also intercept Crag water rising upward or flowing laterally from the highland. Because of retained dyke water levels much of this water is kept within the wetland so impacts on the water balance will be modest. However, the gentle upper fen/carr slope will be directly affected by drainage and depletion of water balance by the catch dykes and the marsh dykes.
Upland and Floodplain Soil Catena including hydrology	The site falls within the area surveyed by Hazelden (1990). He maps the most of the upland as Wick Series. The toe slope along the west and north margins are mapped as a complex of Arrow and Quorndon Series. The floodplain is mapped as Adventurers Series, a humified peat. The eastern half of the open fen area (which was not cored in this survey) is mapped as a complex of Adventurers and Prickwillow Series, the latter being a peat soil with inter-bedded marine alluvium. Hazelden indicates that Prickwillow can be very acid when drained. Just to the east of the site, on the edge of the Halvergate Marshes, a complex of Wallasea (calcareous and acidic phases) and Downholland Series are mapped, a typical arrangement for the marine alluvium floodplain. Coring of two transects (see maps and cross section below, and soil cores in Appendix 6) suggests Hazelden is only partially applicable, with upland soils more clayey than he suggests. Some of the upland profiles contacted were difficult to assign to soil series. To the north (Transect 1), the top of the slope has a stiff clayey subsoil under a sandy loam topsoil, closest to Burlingham Series. Down the slope, the soil progresses towards a sandier but still clayey soil between Burlingham and Wick. Thus far land use is grassland reverted from arable. In young alder scrub on the toe slope, the groundwater becomes significant, with mottling appearing in a profile which is clayey at the surface but sandy in the sub-soil. On the margin of the floodplain, where groundwater rises higher up the profile, a rather clayey Quorndon Series abuts the peats of the flat floodplain. On the west hill

	slope (Transect 2), the highest ground is a rather clayey Wick Series, again possibly transitional to Burlingham. Down the slope towards the toe, the clayey Ashley series occurs where the first effects of groundwater are being shown by mottling in the lower profile. The slope to this point is under crop. Near the catch dyke, within an area of rough grassland, the belt of Quorndon Series is contacted again with groundwater affecting much of the profile. The presence of much clay – sometimes quite stiff - in the soil profiles suggests that permeability should be lower than that typical for the series they have been ascribed to. However, the landowner on western slope reports that, unusually, none of the fields on these slopes are under-drained, and that lack of underdrainage does not in their opinion affect yields. This indicates that permeability may be higher than coring would suggest. Both transects unite on the valley floor where deep peats of the Altcar Series are found. This is a variable peat profile, although most cores share a humified surface horizon over a deep, largely fibrous peat below the water table. This is often brown moss peat or moss/sedge peat. This often rapidly becomes very loose, saturated and fragmented peat, feeling sloppy and very difficult to pick up with the corer. It is mostly sedge and grass peat, and is suggestive of the infill of turbaries but Wheeler and Shaw (2006) note there are no records of significant peat diggings. There are some differences in the peat between the west and north transects which may account for some of the differences in vegetation. The two peat profiles of the western transect (T2) had clay within the peat, either dispersed to create a silty/clayey peat (both cores), or with a thin (5cm) layer of soft buttery clay within the peat body (core 11). Core 11, in the fen meadow, had a deeper (60cm) humified peat layer which was rather silty. The marine alluvium, here a soft grey silty clay, was contacted at the base of coring at about the same topographic level (-1.70m below the local datum) in both. The northern peat profiles generally had less humified peat at the surface (especially under open fen, core 6), no clay or silt in the profile and the marine alluvium base was not contacted (coring ceased at around -2.25m below local datum). Core 6 had abundant snail shells in the upper fibrous peat. The western fen compartments with more silty/clayey, humified peat and the base alluvium within 2m had M22 fen meadow rich in *C. acutiformis* whereas the northern fen areas with deeper, more fibrous shelly peat had mixed S24 and S25 fen. Note that these observations are supported by a small number of soil cores, and may also be coincident with a higher water table in the M22 meadows (although this may be a recent increase in water levels). True Prickwillow profiles described by Hazelden, with a significant clay layer within the peat, were not encountered, although the very thin clay layer in Core 11 may indicate the last remnants of this profile.

Topographical Transects and Soil Catena





Upland Soil characteristics (NSRI 2014f)	Upland soils are developed from glaciofluvial and aeolian drift and till. They are mapped as free draining soils in unconsolidated sands or gravels with high permeability and high storage capacity (overall Host Class 5). However, coring in this survey has shown a higher clay content than implied by NSRI (2014f), which is likely to reduce permeability. They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low, but where clay is significant in the upper profile, it may be higher. Note that despite the heavy rains over the winter there was no evidence of surface erosion from concentrated runoff. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology (Wheeler and Shaw 2006)	The fen is underlain by Crag, separated from the Chalk by London Clay. The Crag is overlain by Drift sands and gravels, the Happisburgh Formation, and is thought to be in hydraulic continuity with these, but layers of clay both within the Crag and Drift may create semi-confined conditions. Wheeler and Shaw note that the water table at the western margin is thought to be close to or at the fen surface for all of the year. The piezometers located on the eastern margin are not representative of the fen areas. They suggest the Crag and superficial drift is the main contributor to the water table, but acknowledge the undetermined role of rain and surface run-off. They further suggest that lateral flow could be via preferential flow paths in loose peats associated with the old Decoy and other possible peat diggings, although there is no direct evidence, and that there may also be upward flow into the peat within the fen – some ponds are thought to be spring fed and presumably, then, also some dykes – but this is also not evidenced. The current survey has shown extensive depths of very loose peats which would facilitate movement of groundwater around the site. The extent and depth of the marine alluvium which underlies the peat is not certain.
Surface Water Drainage	The site is surrounded by and dissected by dykes. These are connected to the wider floodplain dyke system of the Halvergate Marshes. The main drainage channel flows west to east along the southern margin of the open fen, then flows north around the eastern margin of the fen and into the Halvergate system. Although it is part of the pumped system there is a sluice as the dyke leaves the site at the north end of the east margin. The west catch dyke (from the track crossing southwards) connects to this main drain and its level is presumably controlled by the sluice. This survey suggests the internal fen dykes operate on two slightly different levels, split by the east-west trending droveway. To the north, the Old Decoy section of marsh has lower dyke levels, this survey suggesting all at the same level (c. 0.0m in winter) and all floodplain dykes are cut into peat. They must all penetrate the wettest, lower peat layers. The fen surface is 10-18cm above this level, providing a low winter freeboard but a dryer fen surface than the compartments to the south.

	The transect compartment was dry underfoot. The alder carr slopes gently another 30cm up to the edge of the catch dyke. The bottom feeder dyke discharges into the main arterial drain via a sluice. In the fen compartments to the south and west (Transect 2), the dykes also drain to the main drain but via the dyke parallel to the Old Decoy feeder drain. The water level in the marsh dykes is c.0.11m, perched a little above the area to the north and the catch dykes, with the marshes at 0.08-0.12m. The marshes have standing water in the grips and hollows and were very wet underfoot. Although the landowner did not describe a sluice in the southern marshes, something must be holding levels up above the neighbouring marshes and the main drain. Despite being dryer (in the winter survey), note that the Old Decoy marshes have a comparatively shallow depth of humified peat over fresh peat, suggesting the latter is somehow kept wetter, possibly by upward groundwater flow. Wheeler and Shaw (2006) refer to a central ditch with a water level control that had been "recently" (at the time of their writing) raised, making a significant part of the site wetter. This may refer to the western, wetter marshes. The exact workings of the ditches, especially sluice arrangements and summer retention levels, would benefit from further investigation. Note that "downstream" of the site, on the Halvergate Marshes, is the Damgate Marshes SSSI, an area of calcareous freshwater dykes. This area surrounds the "mouth" of the valley and will receive all waters from it, whatever its quality.
Eco-Hydrological Summary for the Fen (Wheeler et al 2009, Wheeler and Shaw 2006)	WetMec 9 : Groundwater Fed Bottoms 9a Wet Groundwater Bottom 9b Part Drained Groundwater Bottom WetMec 9 : Groundwater Fed Bottoms are sites where the water table is mostly sub-surface all year round, in essentially topogenous sites, but where the main catchment water input is groundwater, supplemented by rainfall which may feed the surface in dryer periods. The landscape context of the site, with a narrow valley bottom mostly surrounded by steep, permeable or semi-permeable slopes and unconfined or semi-confined shallow aquifers, would promote groundwater flows to the site. Because of the presence of the marine alluvium, this is likely to be marginal and lateral groundwater discharge, although pathways through the alluvium, which is likely to thin from east to west, are quite likely especially along the western half of the site. Under natural conditions, the site would have been fed by the shallow base-poor aquifer seeping from the Happisburgh Formation and overlying soils, and by calcareous groundwater coming from the Crag. From comments made in Wheeler and Shaw (2006), and from this author's memory of the site during summer vegetation surveying, the margins

	around the north and west where groundwater inputs are strongest, are much wetter suggesting WetMec 9a is predominant here. In the south and eastern section, where drainage and the influence of the Halvergate Marshes is more pronounced, there is likely to be a transition to WetMec 9b. The greater depth of humified peat to the south of the droveway suggests that draw down of the fen water table draw down is more marked here, perhaps because the northern areas are more strongly supported by groundwater. Without summer water level measurements this must remain speculative. On this site, dykes may have only a limited role in distributing groundwater and maintaining in-field wetness. The main fen communities appear to be underlain by a depth of saturated, loose peat which is highly conductive. The dykes may cut into this, and may distribute water rising into this water peat from groundwater. Groundwater, driven by west to east gradients, would probably penetrate all of the fen through this loose peat, with or without the dykes. Where the dykes have little or no freeboard, they may assist penetration of water into the upper peat, although for dykes to be effective sub-irrigators, a surface peat of loose hydroseral infill is required. This was not recorded at the surface anywhere, although was closer in the northern marshes. Lateral movement may be restricted in the more humified peats of the southern marshes. While the northern marshes may have peats more conducive to lateral transmission from the dykes, freeboard here is greater, reducing hydraulic gradients into that peat. More peat cores and summer dyke water levels are required to provide a deeper understanding. The hydrochemistry of groundwater that irrigates the fen under natural circumstances is difficult to determine. Base-poor Happisburgh Formation and rainfall derived supplies would have mixed with calcareous Crag water. The clayey nature of the Happisburgh Formation here and the potentially high volume of Crag water suggests the base-poor element would have been comparatively minor. There is little evidence for base-poor fens in the current vegetation, although most floodplain margin habitats have been lost to alder woodland. The catch dyke would almost certainly have intercepted the base poor water and increased mixing with and dilution by Crag water. Whether this has caused loss of marginal poor fen is more difficult to say. Levelling shows there is a gentle gradient from the flat herbaceous fen through a gradual rise through the alder carr to the catch dyke, and beyond where the slope steepens markedly. Under natural conditions, the toe slope and transition areas could provide some direct seepage areas, whatever its hydrochemistry. WetMec 9 can be derived from other WetMecs characterised by direct discharge of groundwater at the surface (such as seepages) by drainage (Wheeler et al 2009). It is possible that these hydrological processes have been disrupted by catch dykes. Even if there were not actual seepages, the catch dykes are providing significant drainage of the fen/carr slope.

	Hence a zonation in WetMecs is apparent; the fen/carr slope next to the catch drain is WetMec 9b, then there is a band of wetter groundwater fed 9a, then there is a second area of drainage affected and drier fen in the valley bottom, although the recent raising of sluice retentions may have pushed this last area back toward 9a. Wheeler et al (2009) note the presence of eutrophic fen communities along the margin of the site and suggest that ingress of poor quality agricultural water may be causal.
Main Issues	* Delivery to the site of agrochemicals, including nutrients, transmitted by permeable and semi-permeable soils. This factor may be relatively low significance here compared to other case studies, as the northern slope has no arable while the western slope is not under-drained and has a broad band of low-intensity grassland upslope of the catch dyke. In addition, there is a broad band of woodland between the catch dykes and the fen. The shallow groundwater arising from the western upland could be affected by downward percolation of nutrients, as could deeper groundwater supplied from the Crag which is likely to have a much wider catchment. Much of the field-derived water is likely to be captured by the western catch dyke which connects to the main arterial drain, by-passing the fen. It could then find its way into the Damgate Marshes SSSI with its sensitive low-nutrient dyke communities, although the pathways and the impact of progressive filtration are both unclear. For all of these reasons only the simplest measures are likely to be justified. * Change of water quality through removal of groundwater. Most if not all of the Happisburgh Formation-derived groundwater is likely to be intercepted by the catch dykes. Some Crag water may also be intercepted but flow pathways are likely to be deeper and much may pass under the catch dykes. The groundwater from the north slope will be distributed around the fen by the dyke network, some of which may penetrate back into fen peats while a proportion will exit the site via the main dyke. Groundwater intercepted by the western catch dyke will by-pass the fen and is lost to the system. On both slopes, groundwater feed to the shallow footslope (mostly carr) will be removed, significantly affecting this margin. An increasing proportion of the main fen water supply, and all of the marginal slope, is likely to be rainfall. The soil column is therefore increasingly characterised by infiltration. Water quality is pushed toward base poor. * Partial depletion of the water balance through capture and removal of groundwater by dykes toward the pumped drainage system. Some may be transmitted back to lower parts of the fen by dykes. Lateral penetration from dyke to fen is uncertain but likely to be low because of low conductivity peat and low hydraulic gradients. Summer sluice retention levels are an important element to this. The most severely affected areas are the slopes between the catch dykes and the flat floodplain.

	* Direct drainage of the gentle slope between the catch dyke and the floodplain. This is mostly now covered in alder scrub and woodland, but the value of this carr is itself affected by the drainage. Drainage by catch dykes will have drawn down the water table in this transitional area, formerly supported by groundwater. * Direct physical impact on potential groundwater seepages and their specific habitats, arising from dyke excavation and deposition of spoil. * Disruption of the wetland to dry land end of the hydrosere. * The small size of the site and the limited extent of open fen makes it especially vulnerable to change and to edge.
Nature Conservation Constraints	* The site is comparatively small and all is of national significance for nature conservation. There are no areas of open fen which could be considered sacrificial. The carr can either be restored back to fen or may be intrinsically valuable in places. Engineering works within the site could have significant direct impact on designated habitats and features.
Physical Constraints	* Significant assets are unlikely to be affected as there are none within the site or within direct hydrological influence of the dykes. * Management of the dykes are relatively unconstrained by neighbouring land use. No land drains discharge, and where arable continues it is on elevated land.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.5.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered. Note some (change upland land use, comprehensive infill, improve farm practises) address a broad range of issues.

Generation of Nutrients (only applies to the west catch dykes where arable remains above the catch dykes)

Reduce run-off
Improve Farm practices
Change Upland Land use

The following options were not considered either because they are in existence or are excessive responses to a minor issue:

Nutrient Stripping Management
Seal off wetland
Reroute main drain (already the existing situation)
Create Buffer/stripping zone (already existing on the western toe slope)
Soil Management

Change of Groundwater Quality

Comprehensive in-fill
Raise Water levels
Raise Bed by Partial infill
Perforate perimeter – increase permeability

Depletion of Water Balance and Direct Drawdown of the Water Table. These issues are also addressed by measures under *Change of Groundwater quality* Additional measures could include:

Weeping Boundary

8.5.3 Options Appraisal

Red tint – not taken forward. Yellow tint – only useful in combination with other measures. Green tint – core solution with or without other measures.

Option	Positives	Negatives	Outcome
Reduce run-off (west side)	Reduces nutrient and silt movement to the fen.	Requires contour ploughing which may be difficult in narrow fields. Also requires minimising bare land phase.	Useful as part of programme of other measures.
Improve farm practices (west side)	Reduces nutrient and silt movement to the fen. Reduces incidence where catch dyke overwhelmed during floods. Low capital cost.	As there are only two smallish arable fields the options for major change are limited but include reducing nutrient applications.	Useful as programme of other measures.
Change Upland Land use (west side)	Would deal entirely with nutrient issues. Requires the conversion of only two fields. Removes entirely the need for a significant (or any) catchwater drain. Allows restoration of the full hydrosere.	Requires comprehensive change in land management on the intensive arable.	Core solution for comprehensive remediation. Taken forward.
Comprehensive in-fill	Deals with all of the hydrological issues especially for the transition slopes, but also beneficial for the floodplain. Little impact on neighbouring land uses as catch dykes not critical.	Does not prevent leaching of nutrients. Negative impact on intrinsic value of dyke.	Core solution for comprehensive remediation. Taken forward.
Raise Water levels	Ensuring a high summer water level would prevent leakage of water from the wetland and address depletion of the water balance. It would also restore water quality as groundwater remains in situ. Beneficial in the floodplain even if	Does not address nutrients. Excessive water level increase could make the fens difficult to manage.	Partial solution but with stand-alone benefits which should be taken forward. Needs further investigation – current summer levels uncertain.

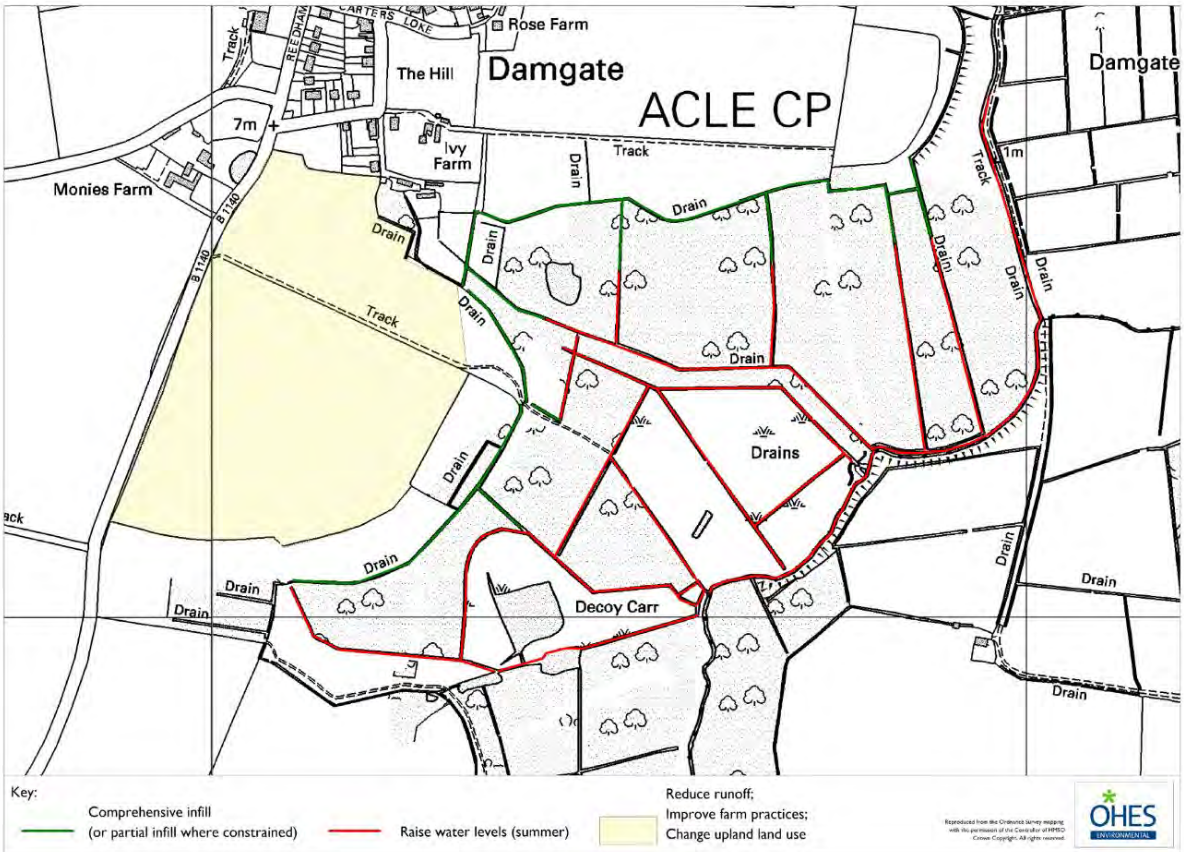
	catch dykes in-filled.		
Raise Bed by Partial infill	Would help to restore groundwater flow. It would also reduce direct drainage of the transitional slope. May be more acceptable to adjacent landowner.	Does not deal with nutrients issue. Expensive and requiring significant engineering.	Partial solution but with stand-alone benefits which should be taken forward if comprehensive infill is not feasible.
Perforate perimeter – increase permeability	Would help to restore groundwater input and assist with wetland water balance. It would only be effective if water levels were increased so that full dyke boundary was made permeable.	Would increase ingress of poor water quality along the western catch dyke. The downslope perimeter is wooded making operations difficult.	Not taken forward. Could be considered if land use change effected on the west side and water levels are raised in the catch dyke.

8.5.4 Conclusions and Recommendations

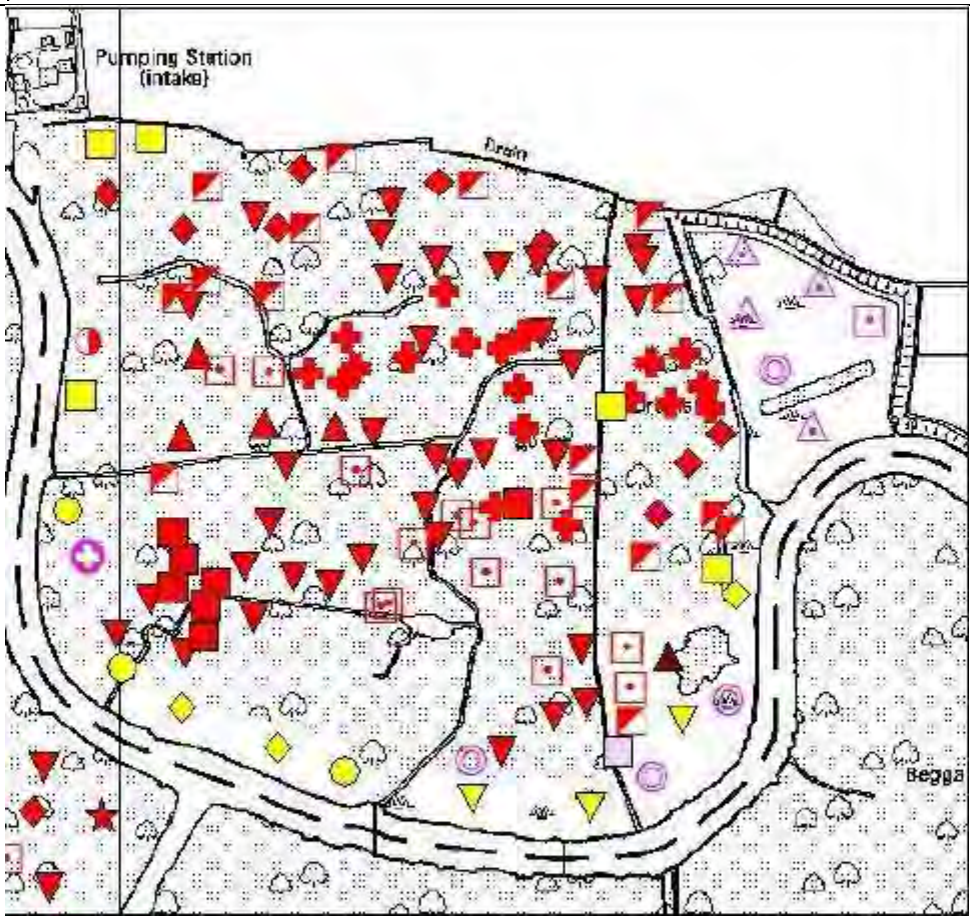
The almost unique benefit of this site is that the catch dykes are not required for adjacent land use. Comprehensive in-fill is a real possibility.

Similarly, other measures have a high chance of being implemented successfully. Changing land use on the west slope is perhaps more uncertain, but in this case, nutrients are not thought to be the most important issue.

The following plan summarises recommended measures for future development. The dyke infill should include dykes running down the marginal transitional slope to the floodplain. Raising water levels in the floodplain requires determination of the summer water level and matching this to the ideal level for the fen communities.



8.6 Ebb and Flow Marshes

Site Name	Ebb and Flow Marshes
River System	Bure
Manager	Norfolk Wildlife Trust
Designations	NNR, SSSI, Ramsar, SPA, SAC
Landscape Context	A valley margin wetland along the north edge of the Bure. To the south are Ranworth Marshes, to the north rises the Bure valley slope to the undulating plateau at around 11m.
Plant Communities (OHES 2011)	 The vegetation communities that are found here span a range of pH values. The wetness and nutrient status within the site is extremely variable. S26 *Phragmites australis-Urtica dioica* community, with S4 *Phragmites australis* swamp occurs close to the river and in compartment 9 (where commercial reed cutting used to take place and the area is known to be very wet). S24d *Phragmites australis-Peucedanum palustre,* the Typical sub-community was found throughout the whole site. However, more localised distributions included S24f, the *Cladium mariscus* sub-community (occurring mainly in the northern half of the site), while S24g *Myrica gale* sub-community occurred mainly in the south. A small stand of *Sphagnum-Dryopteris* fen (BS5) occurred in compartment 7. Some of the S24 stands can be very species rich.
Catch Dyke Characteristics	**Ebb and Flow Marshes Catch Dyke:** Dyke type 2, lower end of the range of Moderate Risk. It is not regularly maintained, heavily reeded with some scrub for most of its length. It is not part of a pumped system, and there are no land drains discharging to it. Depth is 0.75m to hard bed, 2.5m wide top width. 0.5m

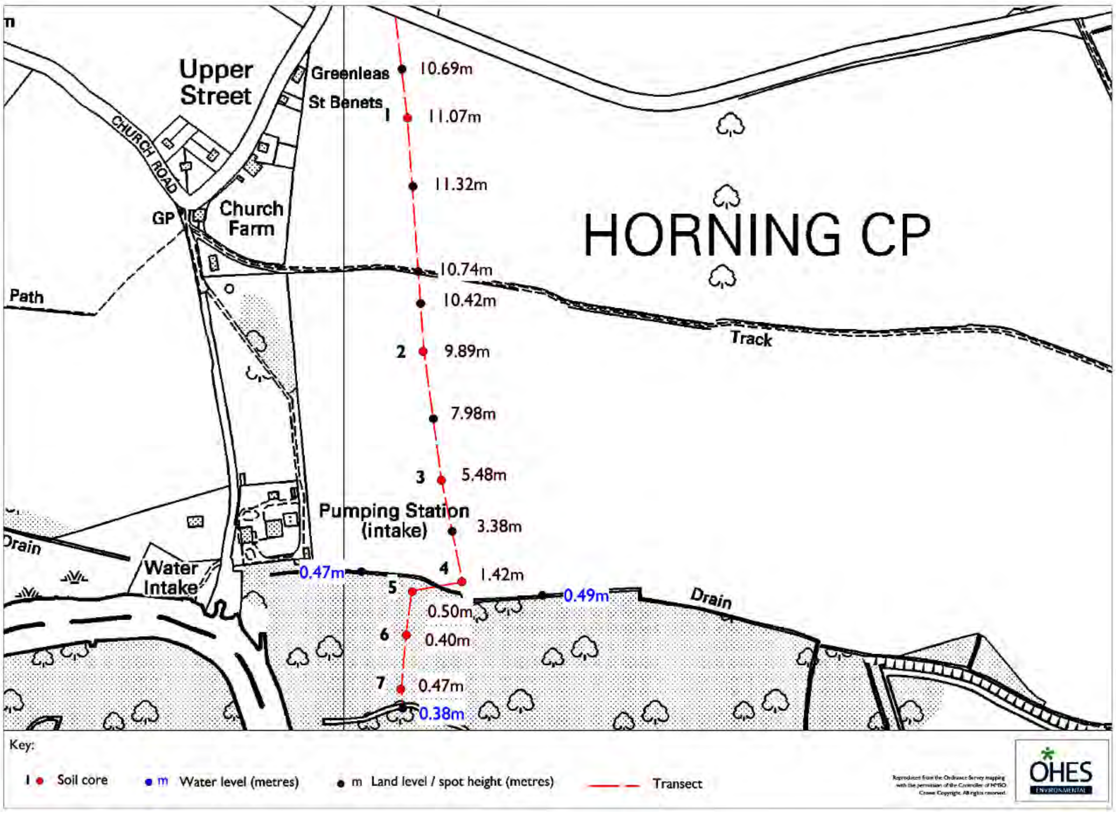
	freeboard, with the potential to increase during the summer due to a low summer water table. Connected to the eastern catch dyke (very similar water levels), assumed by a culvert but the pipe was not found during site visit. No significant aquatic vegetation. Sewage treatment pumping station located to the west.
Hill slope and floodplain soils including hydrology	See cross section below and the core logs in Appendix 6. The soil survey of England and Wales, Hodge et al (1984), identifies the site as Norwich Brickearth with Gravel Upland (both loamy and sandy) on the slope, with Bure floodplain underlying the fen. Site investigations revealed that this is not the case. The arable fields were identified as a mixture of **Wick** and **Newport**, which are freer draining with sandy loamy subsoils. In the plateau top Wick profile there is some sandy clay at around 0.7 metres, becoming stiffer with depth, but the Newport slopes are generally sandy with little clay. At the foot of the slope the soils changed to the **Aylsham** series which is siltier in the upper horizon and gleyed in the lower. Deeper parts of the soil are soft silty fine sand. The gleyed profile demonstrates the influence of a rising water table in close proximity to the catch dyke. On the fen side of the catch dyke there is peat referable to the **Altcar** series, followed by a band of **Ousby**, followed again by the **Altcar** series. These series have a shallow peat profile, which is underlain by a thick layer of 'buttery' grey clay, from approximately 0.4m near the fen edge to approximately 1.2m further into the fen. The clay material is probably underlying marine alluvium. These could be interpreted as 'turf ponds' as described in Wheeler et al (2009).
Upland Soil characteristics	**Note**: Fieldwork suggests the soils are **Wick** and **Newport**. Soils are developed from glaciofluvial and aeolian drift and till. They are free draining, in unconsolidated sands or gravels with high permeability and high storage capacity. Water expressed from such soils would be non-calcareous, neutral to mildly acid. They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. With modern methods, they provide very productive arable land. Under semi-natural conditions would sustain acid to neutral grassland and woodland.
Hydrogeology (Wheeler et al 2009, OHES 2013)	The role of groundwater, if any, in these systems is not well understood. The site is located over peat deposits, with intercalated layers of estuarine clay, and is likely to be separate from the deep chalk aquifer by basal clays. The upslope permeable soils derived from the Happisburgh Formation overlay the Norwich Crag deposit and Upper Chalk aquifer. It is likely groundwater moves from the highland towards the fen from at least the Happisburgh Formation and possibly the Crag. The catch dyke may be intercept this groundwater, although the quantities are not known. Dipwells on the fen reveal that water levels fluctuate seasonally by approximately 45cm, with mean levels as follows; - mean winter water levels of 0.50mAOD, - mean spring water levels of 0.43mAOD, - mean summer water levels of 0.36mAOD and - mean autumn water levels of 0.47mAOD.

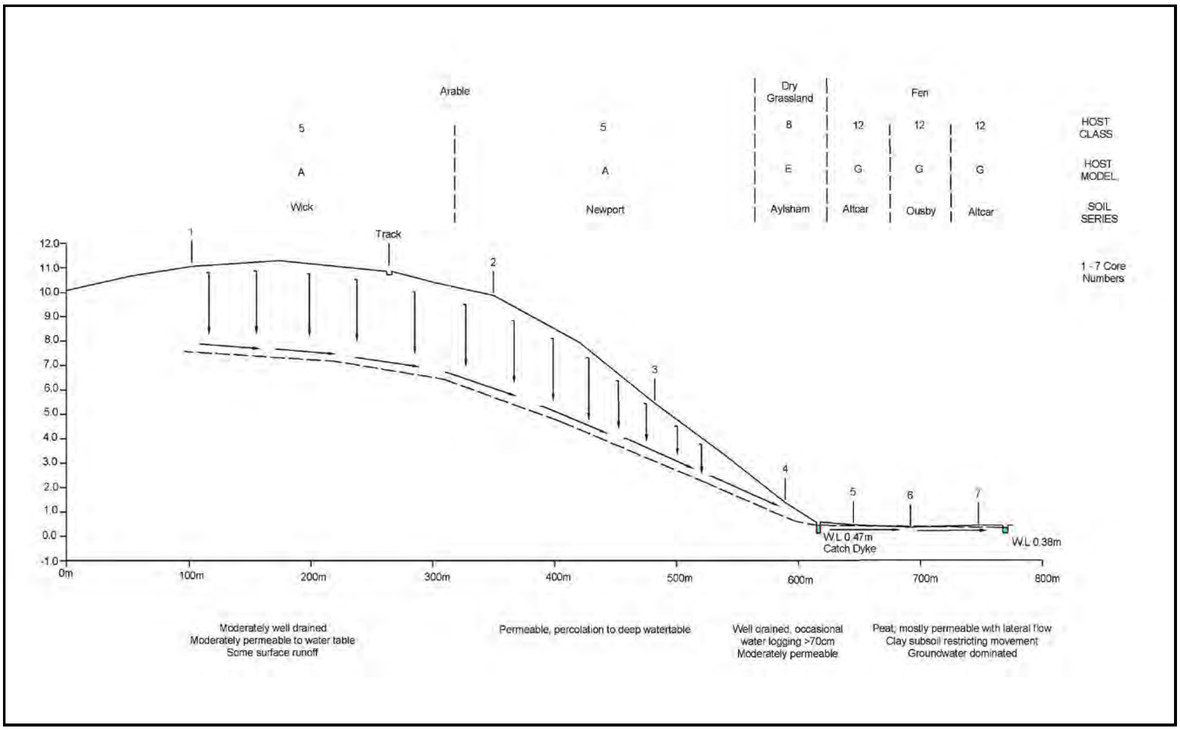
	Marsh height was not known for the sampling locations, therefore only a crude estimate of the depth of the water table below ground level can be made. It is estimated that the ground level is 1.1m AOD, making the mean water table between 60-75cm bgl.
Surface Water Drainage	There appears to be seepage through the Bure embankment. There is a zone of eutrophic fen all around the river margin of the site. This implies seepage of poor quality water from the river but could also be associated with disturbance or deposition of materials associated with the river wall and its soke dyke.
Eco-Hydrological Summary for the Fen (Wheeler et al 2009, Management plan, Norfolk Wildlife Services (2008), OHES 2013)	WetMec 5 : Summer-dry Floodplains WetMec 6: Surface Water Percolation Floodplain, four sub-types: 6c Surface water percolation 'boils' 6d Swamped surface water percolation surface 6e Wet surface water percolation quag 6f Surface water percolation water fringe On the floodplain of the River Bure successive sea level changes have resulted in the deposition of layers of peat and clay. The surface of the Upper Clay typically lies around 2–2.5m below the fen surface. Alongside the river channel, the clay layer is over 10m thick, but this decreases with distance from the river. Above this clay layer are peat beds, deposited following a change to a predominantly freshwater system following the partial closure of the mouth of the Bure estuary. Ebb and Flow is a floodplain fen and derives most of its irrigating water from a fluvial source, to a lesser extent from rainfall and a very small proportion from springs. Ebb and Flow receives a large nutrient input directly from the river Bure. Ebb and Flow is mostly WetMec 6: A Surface Water Percolation Floodplain. Here, surface water sources are largely responsible for recharging the peat, supplemented by rainfall. OHES (2013) had difficulty in mapping the four sub-types occurring on the site. They are broadly as follows. WetMec 6e, Wet surface water percolation quag, are usually summer-wet and have a buoyant mat of peat, where vegetation forms a raft over a loose mix of rhizomes, re-deposited peat and water. They can be associated with former turf ponds, where they form hydroseral succession infill. WetMec 6e has a mean summer water level 12.5cm above ground level and best matches the wettest parts of the site. This was not encountered during the site visit but previous work suggests that quag exists elsewhere on the site. Where the fen is not buoyant but grounded, in poorly drained parts of the site, the dominant mechanism is WetMec 6d, Swamped surface water percolation surface. These areas may remain wet throughout the year. These were not encountered during the site visit but previous work at the site suggests that they are present. They can be isolated from watercourses and dykes, and occur on spongy rather than buoyant peat. WetMec 6d has a mean summer water level of 4cm below ground level. This WetMec type may particularly apply to those parts of Ebb and Flow Marshes for which the internal ditch network has become overgrown and therefore swamp.

	Sub-unit 6c Surface Percolation Boil is typically associated with areas fed by precipitation (ombrotrophic) and have a mean summer water level of -16.6cm bgl. WetMec 6c is also typically dominated by *Sphagnum* sp. and occurs on acidic surfaces which can consolidate to permit colonisation of birch woodland. 6c is transitional to WETMEC 3 Buoyant Weakly Minerotrophic Surfaces ('transitional bogs'), and is the locus for the uncommon *Sphagnum-Dryopteris* fen. Finally, there are one or two areas which may fall into WetMec 6f Surface Water Percolation Fringe where very wet conditions were recorded around the perimeter of pools and perhaps the larger dykes. Once again 6f is linked to buoyant surfaces, which are encroaching directly upon open water bodies. Mean summer water levels for WetMec 6f are -1.8cm bgl and can be associated with S2 *Cladium mariscus* and S4 *Phragmites australis* swamps.The wetter fens associated with WetMec 6 occur almost always in association with WetMec 5, Summer-Dry Floodplains. In Broadland, WetMec 6 is often separated from rivers and land margins by these hydrological conditions. WetMec 5 occurs in areas which have much lower summer water tables either because of elevated topography or because of isolation from irrigating waters. This WetMec was not mapped by OHES 2013 for the site.
Main Issues	* Delivery to the site of agrochemicals, including nutrients, transmitted by permeable soils. There is little evidence of a eutrophic northern margin to the fen. There is no under-drainage discharging to the Catch Dyke. The entire eutrophic fen is associated with the River Bure margin. The importance of eutrophication from the highland is therefore difficult to assess but is likely to be low. * Potential changes to water quality arising from capture of original good quality shallow groundwater. The Happisburgh Formation from which shallow groundwater arises is likely to be base-poor, while the Crag is base rich and hence the net impact of change on the fen communities is complex and difficult to predict. However, because the groundwater is not drawn off, or is recirculated, the impact of this issue is likely to be small. * Because the water is not drawn off significantly, depletion of the water balance and direct draw down of the water table are not thought to be significant issues here. This could change were the management of the catch dyke changed. * Disruption of the wetland to dry land end of the hydrosere.
Nature Conservation Constraints	* Water voles may be present within the dyke system * The entire site is designated SSSI and SAC. Opportunities for placing major engineered solutions within the fen are therefore potentially limited.
Physical Constraints	* Possible impacts of the sewage treatment plant located to the west. * Possible impacts of drainage of arable land upslope of the catch dyke. * No other infrastructure will be impacted.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage, however it is noted that a commercial harvest on a rotational 3 year is undertaken on the site. This has socio-economic benefits providing a resource for local industry, thatchers, cutters, tourism and releasing NWT resources for other areas. It is proposed to increase the commercial harvest where possible.

8.6.1 Defining the Nature of the Problem

Topographical Transects and Hill slope Catena





8.6.2 Potential Remedial Measures

Running the various site issues through the decision trees in Figures 10 and 11 suggests the following remedial measures should be considered. Because of the relatively low impact of all of the issues identified, heavily engineered solutions (Seal off wetland, Reroute Main Drain (catch dyke), and Soil Management, Raise Bed by Partial Infill, Perforate Perimeter) are not warranted.

Generation of Nutrients

Create Buffer/stripping zone
Nutrient Stripping Management
Reduce run-off
Improve Farm practices
Change Upland Land use

Change of Water Quality

Comprehensive In-fill
Raise Water Levels

Red tint – not taken forward. Yellow tint – only useful in combination with other measures. Green tint – core solution with or without other measures.

Option	Positives	Negatives	Outcome
Create buffer/stripping zone	Reduces ingress of nutrients to the fen. Could create additional wildlife habitat such as toe slope wetland. Would work well with change in upland land use.	Does not address generation of nutrients or eutrophication of deeper groundwaters. Can be overwhelmed in storm flows. Does not address groundwater or water balance issues.	Useful as part of other measures which deal with core issues.
Nutrient stripping management	Depletes nutrients in fen surface peats and prevent ongoing accumulation. Extra management would have benefits for fen communities, fostering species-richness.	Does not address generation of nutrients at source or potential eutrophication of groundwater. Annual mowing (optimal for nutrient reduction) is expensive.	Useful as part of other measures which deal with core issues.
Reduce run-off	Reduces nutrient and silt movement to the wetland. Low costs.	Requires cooperation and potentially compromise from managers of the upland. Does not address in-situ generation of nutrients or eutrophication of deeper groundwaters.	Useful as part of other measures which deal with core issues.
Improve farm practices	Reduces nutrient and silt movement to the fen. Low capital cost.	Requires cooperation and potentially compromise from managers of the upland.	Useful as part of other measures which deal with core issues.
Change Upland Land use	Would remove significant inputs of nutrients. Removes need for a significant (or any) catchwater drain. Removes principle constraints on most effective solutions which would address all of the major issues. Allows restoration of the full hydrosere.	Requires comprehensive change in land management the owner or large scale acquisition by conservation organisations. Potentially expensive.	Core solution for comprehensive remediation. It is not necessary to convert all of the upland field to achieve good results – a portion of the slope would yield much of the benefit.
Comprehensive in-fill	Deals with all of the hydrological issues. Does not affect upland land management as the fields are not under-drained.	Negative impact on intrinsic value of dyke.	Core solution for comprehensive remediation. Taken forward.
Raise Water levels	Raising water levels would improve	Does not address nutrients.	Partial solution but with

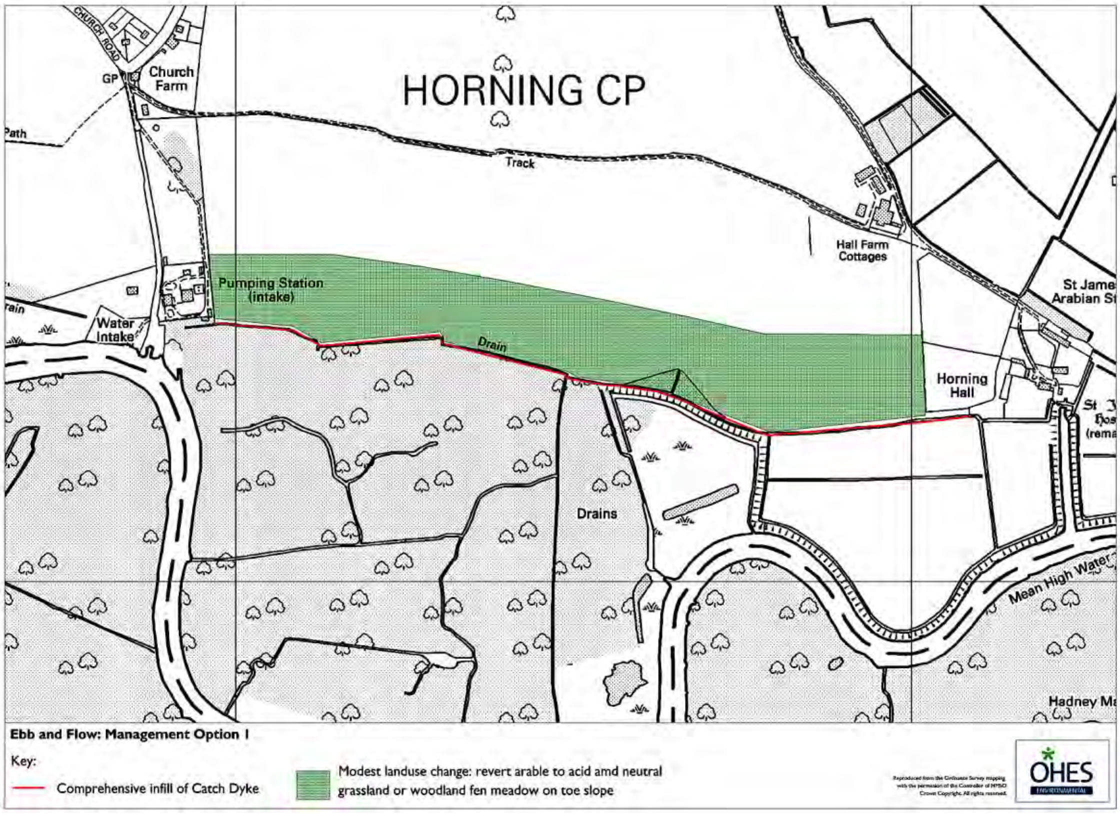
	water balance and flow of groundwater to the wetland.		stand-alone benefits which should be taken forward.

8.6.3 Conclusion

The issues created by the catch dyke are probably quite modest but significant conservation gains could be obtained from modest remedial measures. Two options present themselves, depending on whether or not comprehensive infill can be pursued:

Option 1: Comprehensive Infill

Here the dyke is fully infilled. Combined with only modest land use change on the upland (e.g. 100m), this could see the reinstatement of the full hydrosere succession. Greater land use change could have additional benefits in reducing nutrient benefits and creating additional dry land habitats. The fen grazing unit could then be incorporated. The Option could be combined with measures from Option 2 to provide added value.

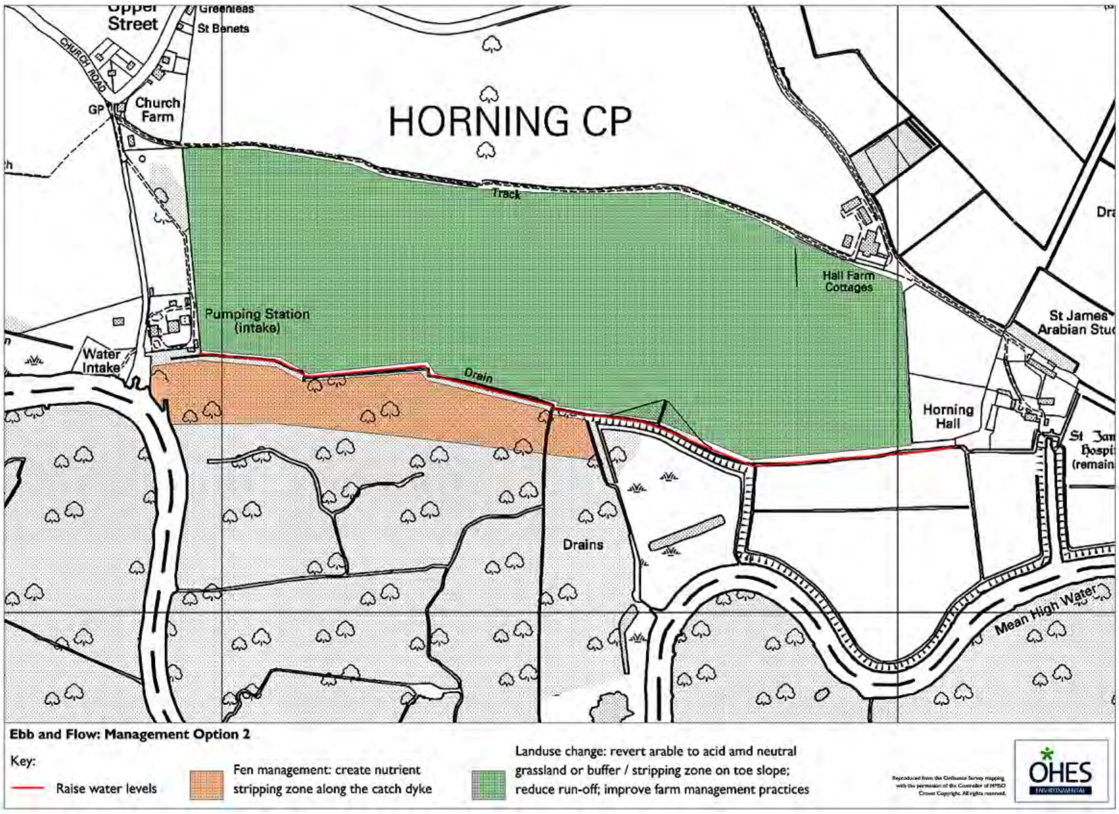


Option 2: Without Comprehensive Infill

If, for whatever reason, filling in the catch dyke is not taken forward, a suite of measures can be adopted to improve current conditions. These could include land use change on the upland, with the first 100m being the main priority. This would allow creation of toe-slope wetland, raising of the dyke water levels and creation of a buffer. Hence on the map this option includes:

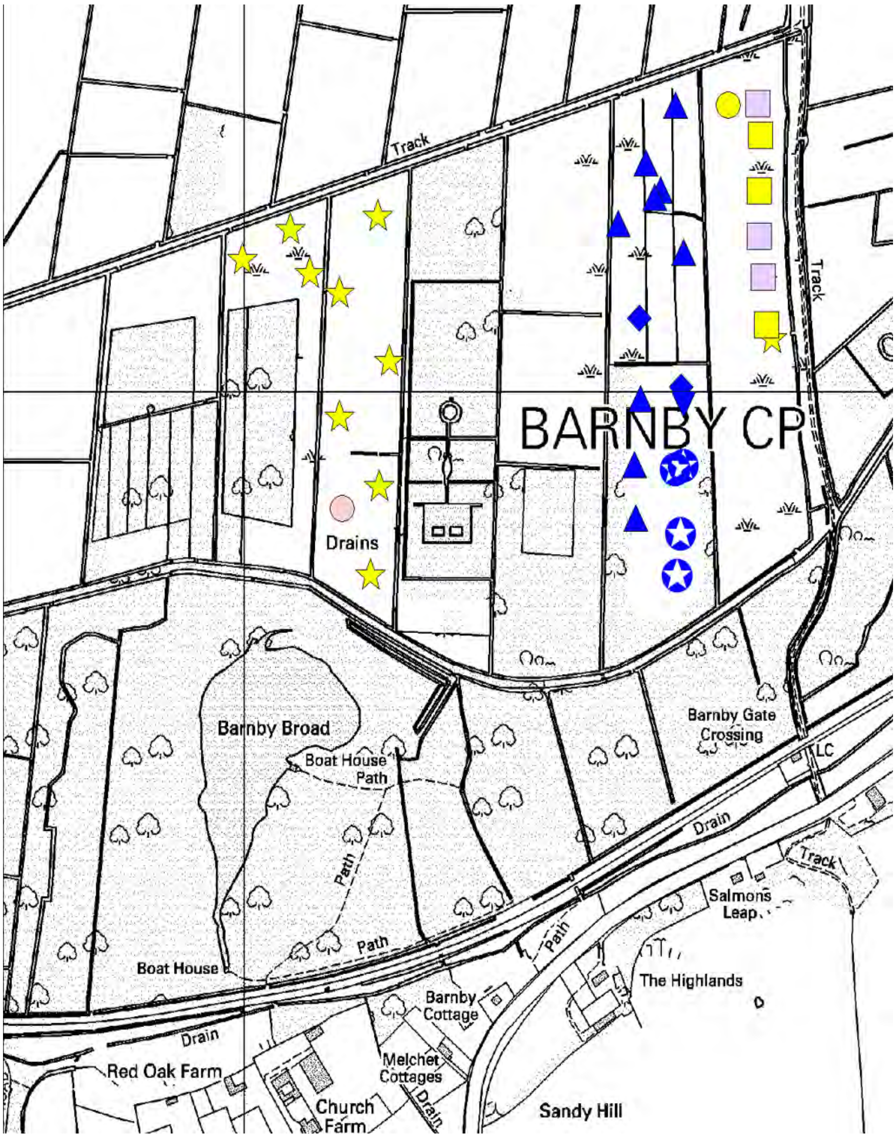
- Land use change (especially in the first 100m of the slope)
- Reduce Run-off (all of the arable)
- Improve Farm Management practises (all of the arable)

- Create buffer/stripping zone (toe slope zone)
- Nutrient stripping zone (fen management along the catch dyke)
- Raise water levels in the catch dyke.



8.7 Barnby Broad and Marshes

8.7.1 Defining the Nature of the Problem

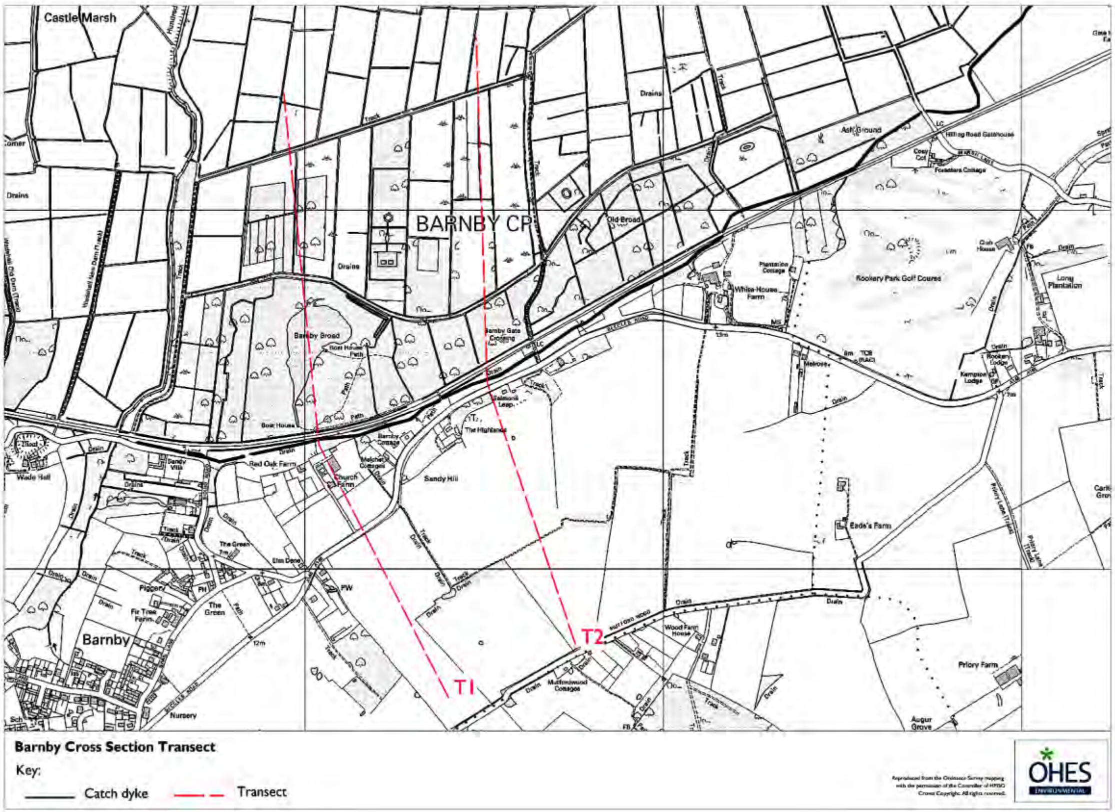
<table>
<tr><td>Site Name</td><td>Barnby Broad and Marshes</td></tr>
<tr><td>River System</td><td>Waveney</td></tr>
<tr><td>Manager</td><td>Private Landowners</td></tr>
<tr><td>Designations</td><td>SSSI, SAC, SPA, Ramsar</td></tr>
<tr><td>Landscape Context</td><td>Barnby Broad lies on the southern margin of the Waveney Valley, separated from the highland by a railway line and road. To the north, cross a double-ditched track there are a series of marshes which retain their semi natural vegetation. Further north lies the River Waveney.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Plant Communities</td><td>


The vegetation on the marshes (mapped above) is either species-poor reed vegetation often S26 Phragmites australis-Urtica dioica fen. More species rich M22 Juncus subnodulosus-Cirsium palustre fen meadow occupies the central marsh (blue triangles) while there is an extensive area of base-poor fen meadow attributable to M25b Molinia caerulea-</td></tr>
</table>

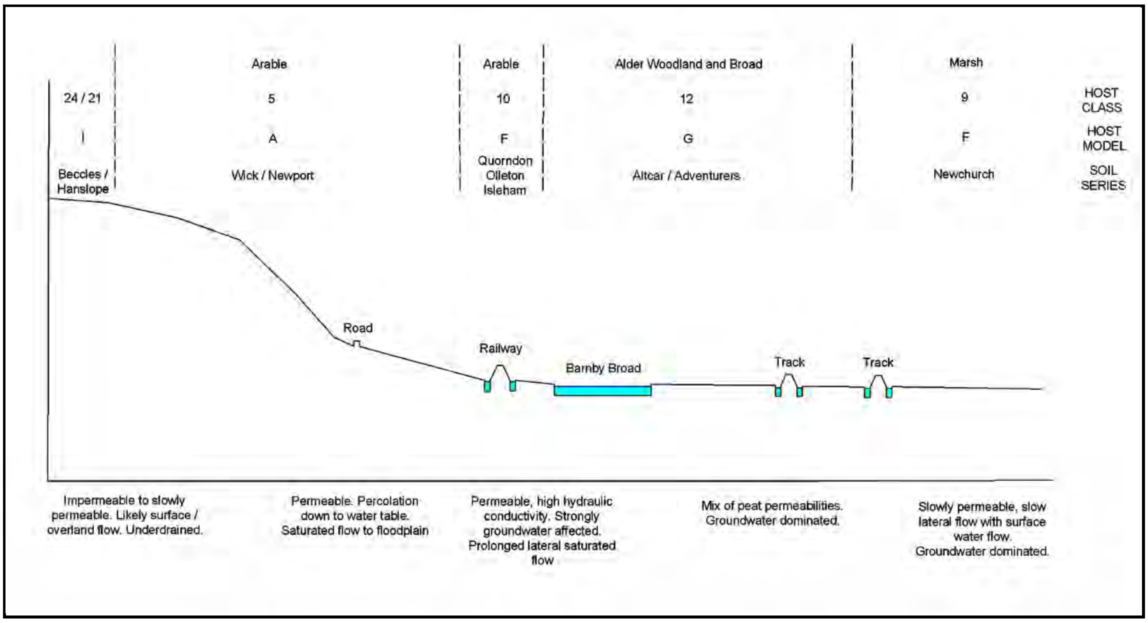
	Potentilla erecta mire, the *Anthoxanthum odoratum* sub-community. The fen meadows are reported to have extensive *Sphagnum* patches (wheeler and Shaw 2006) but a walkover for this report showed relatively small areas. There are areas of hover around the Broad and open areas in the woodland which area also thought to have a significant component of *Sphagnum (*Wheeler and Shaw 2006). These areas were not surveyed by OHES (2011). During this work, the fen fringe to the broad was reed and *Carex paniculata,* but little *Sphagnum* was found. It was somewhere between S3 *Carex paniculata* swamp and S24a *Phragmites australis-Peucedanum palustre* swamp the *C. paniculata* sub-community, the former being extremely uncommon in Broadland (OHES 2011). Scrub was invading this fringe. There are extensive areas of rich fen in the open areas west of the Broad and just north of the railway line. They include stands of *Cladium* and *Myrica gale*, and a series of M22 meadows which include wet patches with *Pedicularis palustris.* There are also footdrains with dense beds of *Chara* and tussocks of *Carex elata* and *Schoenus nigricans*. These were not surveyed by OHES but may be the vegetation which led Wheeler and Shaw (2006) to suggest the southern margin was groundwater seepage feed. The site is not well characterised by the map shown above and would benefit from a more comprehensive survey.
Catch Dyke Characteristics	Barnby Broad is separated from the highland by two, and in places, three dykes at the foot of the slope, associated with drainage of the railway line which runs along the valley margin. Collectively they are Type 1 High Risk dykes. The first catch dyke, next to the highland slope, is around 4.5m top width and 1.5m depth to a hard bottom with about 0.5m silt and with a 0.5m freeboard – a substantial dyke at the point of measurement near the east rail crossing, but it varies along the length. It is mostly cut into mineral substrate. It is relatively open and well maintained. There are no sluices but flow was very slow. There are culverts under the railway so water passes into the second catch dyke. The second catch dyke (on the Broad side of the railway line) was 4m top at the same location but narrows westwards to about 3m. It had about 1m freeboard and had recently been slubbed out. It is owned by the Estate. Grips in the eastern marsh were piped under the dyke side spoil and discharged to this drain. The low freeboard meant that the whole southern edge of the site would leak into this dyke, but we gather from the site manager sluices mean the level in this dyke are raised for the summer by sluices. Flow was very slow to nil. The dyke was cut into mineral soil at the crossing but descended rapidly into peat westwards. Both catch dykes are presumably linked in to the floodplain dyke system which is a pumped one discharging to the Waveney. The northern fen meadows are divided from the Broad by a pair of ditches either side of the track trending east west. These are c. 3.5m wide, 0.5m

	of water with 0.5m freeboard. They are entirely peat with a soft bottom. They are further isolated by dykes all around. Their distance from the highland and their isolation by series of dykes suggests that they may be cut off from groundwater and are mainly fed by winter flooding and rainfall. There is no doubt that the site is significantly drained by the dyke network and the highland margin particularly so.
Upland and Floodplain Soil Catena including hydrology	Access was not gained for the highland, so soil coring could not be undertaken. Fortunately it falls within the area mapped by Corbett and Tatler (1970), the cross sections being drawn from this. The upper slopes are a complex of Hanslope Series and Beccles Series. These are both developed in chalky boulder clay and are rather impermeable with gleying in much of the profile. East of Sandy Hill the complex reaches to the road. West of Sandy Hill, Wick Series and Newport Series lie directly behind the Broad. These are freely draining permeable brown earths, without gleying in the profile, and are non-calcareous. In low spots and at the exit of minor dry valleys there are groundwater gleys (Quorndon Series and in more permeable sands, Isleham and Ollerton) with Isleham series presenting a transition to valley peats with a peaty loam topsoil. These are generally very limited in extent. Note that wider soil mapping (Hodge et al 1984) shows the chalky boulder clay soils to be limited, an island surrounded by the sandier soils which extend to the south and east toward Lowestoft. Hence the chalky boulder clay may limit local recharge of groundwater, but the main groundwater body is likely to be recharged through the extensive light soils further to the south. North of the railway line and on the flat floodplain floor, the soils are mapped as complexes of Adventurers and Altcar Series (the latter described by Corbett and Tatler (1970) as Sedge-Carr Peat) differentiated according to degree of humification. They do not record the unhumified profiles of the Ousby Series, but it is most likely present around the Broad as suggested by Wheeler and Shaw's (2006) account of the peat : "….much of the valley infill near the broad is of relatively similar depth (5–6 m). Unusually, brushwood peat is only well developed at the very edge of the valley and much of the infill, both beneath and beyond the broad, is a distinctive, thick, fresh moss peat (with much *Homalothecium nitens* and *Paludella squarrosa* – the latter now extinct in Britain). The peat type and sequence found here is characteristic of hydroseral successions in calcareous basins in parts of northern Britain, but is most unusual in a Broadland context. It is suggestive of a long-lived phase of quagfen, developed in especially wet, near-swamp conditions." The peat ceases just north of the second track (the track delimits the northern edge of the fen meadows). Thereafter the soils are mapped as Newchurch Series, developed in marine alluvium.

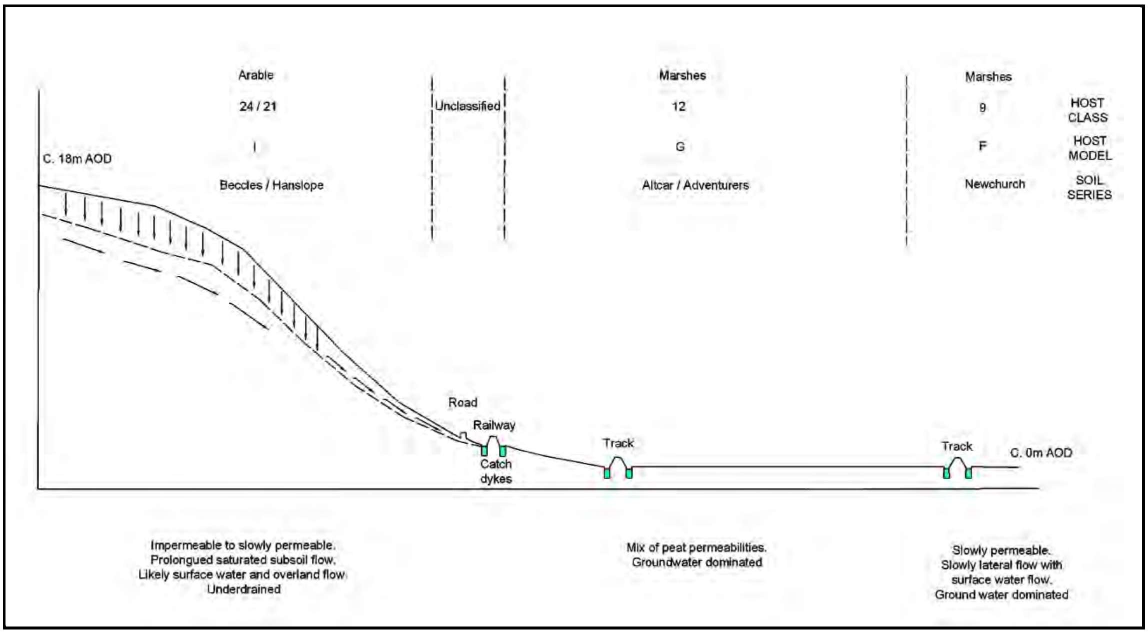
Transects and Cross Sections, Barnby Broad. Note that the sections are schematic and not to scale either vertically or horizontally.



Transect 1 Cross section:



Transect 2 Cross Section



Upland Soil characteristics (NSRI 2014g)	In terms of characteristics, the upland soils divide into two. The permeable soils west of Sandy Hill are developed from glaciofluvial and aeolian drift and till. They are described as free draining soils in unconsolidated sands or gravels with high permeability and high storage capacity (overall Host Class 5). They have high leaching capacity with little to moderate ability to attenuate non-adsorbed pesticides and other diffuse pollutants. Underlying groundwater is vulnerable to contamination. Risk of run-off is low. Natural fertility is low. Under semi-natural conditions would sustain acid to neutral grassland and woodland. East of Sandy Hill are the soils arising from chalky boulder clay. They are classed as impermeable soils of low or negligible storage capacity (in composite Host Class 24), through which pesticides are unlikely to leach. They have high runoff potential, but pollutants are unlikely to penetrate the soil layer into the groundwater or elsewhere because of their impermeability and their ability to absorb chemicals. The soil is naturally moderately fertile, and would support seasonally wet pastures and woods as its semi-natural habitat cover.
Hydrogeology (Wheeler and Shaw 2006)	Wheeler and Shaw reflect on how poorly this site is understood compared to many in Broadland. They note its "…obvious floristic and physiographic similarities with Upton Broad." They note that it is primarily groundwater fed, with clear evidence of such near the highland margin. It is possible that the Broad cuts into the groundwater and forms a route for that water to be discharged to the surrounding wetland. Direct evidence of this mechanism was not found.
Surface Water Drainage	The catch dykes run east-west along the highland margin. Because of their topographical position they drain both the slopes and shallow groundwater and the peatland along the southern margin of the site.

	Despite piped grips discharging to the inner catch dykes, the fen meadows remained wet at the surface. The marshes are densely dissected by dykes, often supplemented by footdrains. Although individual directions of flow were not obvious, in general the dyke network drains northward towards the alluvial marshes. From there they are pumped to the river Waveney by the Castle Marshes pump. Mr Rowley, the site manager, tells that there are two sluices which control dyke levels for the whole site. Boards are put into the sluice in March ready for the grazing season April-October. Mr Rowley suggests that the inner soak dyke would be nearly at marsh level when the sluice was fully raised. Water levels are dropped in winter to allow reasonable access to the broad.
Eco-Hydrological Summary for the Fen (Wheeler et al 2009, Wheeler and Shaw 2006)	WetMec 4 : Drained Ombrotrophic Surfaces in Bogs and Fens 4b Drained Ombrotrophic Fen WETMEC 11 (upland slope): Intermittent and Part Drained Seepages 11a Permeable part-drained seepage WETMEC 13: (Broad and surroundings): Seepage Percolation Basin 13c Seepage Percolation Water Fringe 13d Distributed Seepage Percolation Surface Wheeler and Shaw (2006) list WetMec 11a Permeable Intermittent and Part Drained Seepages as present on the site, presumably along the southern margin next to the highland. However, it is not discussed further there or in Wheeler and Shaw (2009) and it is not clear to which features they are referring, although the wet fen meadow with *Schoenus* and *Chara* seem likely. WetMec 11 in general refers to areas of groundwater seepage which are now mainly sub-surface due to drainage. Certainly, the catch dykes would stop any possibility of above ground seepage emissions (e.g. WetMec 10 Permanent Seepage Slope, a pre-drainage precursor). The Broad itself is an important source of water and feeds the floating raft of fen vegetation which surrounds it (WetMec 13c, Seepage Percolation Water Fringe). Groundwater feeds this mat through lateral water movement from the Broad, although the width of the zone of seepage beyond the narrow zone of hover is not certain. The sphagnacious element to the floating fen is essentially ombrotrophic, being kept above the base-rich broad water by the buoyancy of the raft. Much of the surrounding woodland and the remnant areas of open fen are believed to have colonised over the Broad and may be underlain by watery peat or even layers of watery mud much like Upton Fen. Similar hydrological mechanisms may therefore operate, although the complex pattern of peat diggings which affects lateral water movement at Upton do not appear to be recorded at Barnby. The site has received much less attention. Wheeler and Shaw (2006) refer to this wider area as WetMec 13d Distributed Seepage Percolation Surface, where groundwater from the highland margin is distributed around the fen and woodland hydroseral

	infill by the dykes which extend from the southern edge of the site. Because the Broad infill is loose and watery, the dykes can readily re-supply the peat. The sphagnacious fen meadows in the northern grazing marshes are most likely isolated from significant groundwater influence. The marsh surface is above the water table in the summer. They are surrounded by dykes and have a second pair of dykes parallel to the catch dykes, which could intercept any groundwater moving from the highland. The peat here is probably too humified for rapid transmission of water from the dykes, although high dykes levels will prevent the marshes draining. Water from the River Waveney, although it is known to seep through the banks, does not reach these marshes except perhaps in very exceptional circumstances. Therefore the most likely water supply mechanism is through storage of winter rainfall (perhaps even with surface inundation) together with summer rainfall. The base-poor fen meadow (M25) and the significant component of *Sphagnum,* suggests that there is at least a surface ground layer fed by rainfall, and in the case of the M25, perhaps a rainwater lens within the soil. However, the close juxtaposition of the base-poor M25 with base-rich M22 on similar ground is curious. The remaining base-rich vegetation may be supplied with cations by a potentially calcareous, base rich sedge-moss peat. Wheeler and Shaw (2006) and Wheeler et al (2009) refer the base-poor area to WetMec 4b, Drained Ombrotrophic Fen, sites which have become disconnected from their original water supply by drainage and are now principally rain fen. The surface may be maintained wet by a high underlying water table, but it remains essentially rain fed. As noted in Section 2, the ombrotrophic WetMecs can be quite complex mechanisms.
Main Issues	* Delivery to the site of agrochemicals, including nutrients. These may be transmitted by permeable and semi-permeable soils, and also brought to the site via seepage from the Hundred Stream. The significance of this factor is not known. It was related cautiously by Patrick Robinson at NE, who indicated it had been recognised as an issue but was cautious as there was no clear data to support the concern. As far as is known, none of the land to the south which discharges to the catch dykes is under-drained and there is no arable land north of the road. The fate of road washings is uncertain, but certainly all water washing off the railway lines would end up in the catch dykes. The issue requires further definition * Change of water quality through removal of groundwater. All of the shallow seepage water from the highland will be intercepted by the catch dykes. Some may be redistributed to the wider wetland area but certainly the southern fringe will be directly affected. This area may have been changed from WetMec 10 Permanent Seepage to WetMec 11a Permeable Intermittent and Part Drained Seepages. * Partial depletion of the water balance through capture and removal by dykes toward the pumped drainage system.

	Lateral penetration from dyke to fen is uncertain and probably varies across the site, but is likely to be low because of low conductivity peat and low hydraulic gradients. A high sluice retention level will reduce the significance of this issue. * Direct drainage of the wetland. The summer retention level and the season of raising and lowering will be key to understanding the significance of this issue. Topographic levels and an understanding of water level management are required. * Direct physical impact on potential groundwater seepages and their specific habitats, arising from dyke excavation and deposition of spoil. Construction of the railway line is also likely to be a contributory factor. * Disruption of wetland to dry land end of the hydrosere. Again the railway makes restoration of the hydrosere difficult.
Nature Conservation Constraints	* High quality fen and wetland, including potential SAC features, abut the catch dyke. There is no opportunity for accommodating major engineering works within the site.
Physical Constraints	* The presence of the railway line (and its need for drainage) significantly limits engineering works, infilling/change to the catch dykes or any prospect of restoring an uninterrupted wetland to dryland hydrosere. * Engineering works to construct the railway line itself may have had an effect, if for instance, the ground was altered with foundation materials, compaction or sheet piling, all of which could affect permeability and groundwater movement. * There are a number of houses between the road and the railway which may be affected by any proposed works.
Social Constraints	Stakeholders and their views have not been widely canvassed at this stage.

8.7.2 Potential Remedial Measures

There are two problems with devising remedial measures to the identified issues:

- Lack of detailed information. The nutrient issues, the management of surface water levels, the topographic variation across the site and the nature and distribution of the plant communities are all relatively ill defined, as is the nature of the substrate and the precise hydrological functioning of the site. Further investigation is needed.
- The presence of the railway line is likely to limit options for management of the catch dykes. The dykes will be important for the drainage of the line. Other than management of water levels of the inner catch dyke (which belongs to the estate), they are likely to remain in situ and unchanged. While there are engineering alternatives (such as creating a high-level dyke parallel to the inner catch dyke), the presence of SSSI/SAC feature habitats immediately adjacent to the soak dykes prevent their adoption.

Determination of remedial measures cannot be taken any further at this stage.

8.7.3 Conclusions and Recommendations

We recommend that the following work is undertaken to support development of remedial measures:

* A full NVC survey is required to provide a complete ecological understanding of the site.
* The aquatic communities should be included.
* This should be accompanied by a topographical survey and an investigation of the substrate.
* Evidence of eutrophication should be identified. This should be based on past records, the above vegetation survey and some water sampling.
* The management of dyke water levels should be investigated.
* Then, a better understanding of the wetland hydrological mechanism can be developed and management of water levels tied together with substrate and the requirements of particular plant communities.

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Appendix 1: The Host Classification (after Boorman et al 1995)

Numbers in bold are the Host Class**.** Models are described in Table 1**.** Those outlined in red are found in the Broads. IAC = Integrated Air Capacity. By-pass flow = through fissures and large cavities, i.e. a rapid flow that “by-passes” intergranular or porous flow.

<table>
<tr><th rowspan="2">Substrate Hydrogeology</th><th colspan="5">Mineral Soils</th><th colspan="2" rowspan="2">Peat Soils</th></tr>
<tr><th>Groundwater or aquifer</th><th>No impermeable or gleyed layer within 100cm</th><th>Impermeable layer within 100cm or gleyed layer at 40-100cm</th><th colspan="2">Gleyed layer within 40cm</th></tr>
<tr><td>Weakly consolidated, microporous, by-pass flow uncommon (Chalk)</td><td rowspan="6">Normally present and at >2m</td><td>1</td><td rowspan="6">13
Model B</td><td colspan="2" rowspan="6">14
Model C</td><td colspan="2" rowspan="6">15</td></tr>
<tr><td>Weakly consolidated, microporous, by-pass flow uncommon (Limestone)</td><td>2</td></tr>
<tr><td>Weakly consolidated, macroporous, by-pass flow uncommon.</td><td>3</td></tr>
<tr><td>Strongly consolidated, non- or slightly-porous, by-pass flow common.</td><td>4</td></tr>
<tr><td>Unconsolidated, macroporous, by-pass flow very uncommon.</td><td>5
Model A</td></tr>
<tr><td>Unconsolidated, microporous, by-pass flow common.</td><td>6
Model A</td></tr>
<tr><td>Unconsolidated, macroporous, by-pass flow very uncommon.</td><td rowspan="2">Normally present and at <2m</td><td colspan="2">7
Model E</td><td rowspan="2">IAC < 12.5 (< 1m d^{-1})
9
Model F</td><td rowspan="2"><b>IAC > 12.5 (>1md^{-1})
10
Model F</td><td rowspan="2">Pump Drained
11
Model G</td><td rowspan="2">Undrained
12
Model G</td></tr>
<tr><td>Unconsolidated, microporous, by-pass flow common.</td><td colspan="2">8</td></tr>
</table>

Slowly permeable	No significant groundwater or aquifer	**16**	**IAC > 7.5** **18** Model I	**IAC < 7.5** **21** Model I	**24** Model J	**26**
Impermeable (hard)		**17**	**19**	**22**		**27**
Impermeable (soft)			**20**	**23**	**25**	
Eroded peat						**28**
Raw peat						**29**

Appendix 2 : Summary of the Soils of Broadland

The following summaries describe the relevant attributes of the soils of Broadland, organised loosely by landscape position and then by Association. A Summary Table of Soil Series follows. Note that the following is simplified; inspection of soil surveys and work undertaken for the case studies indicates there are more soil series present in the study area, but the following aims to outline the most important.

Floodplain

The lower reaches of the valleys are formed from the **Newchurch 2 Association**. They are clayey, groundwater gleys, mostly calcareous, developed from marine alluvium. All are Host Class 9. The ***Newchurch Series*** predominates. It is a deep, stoneless, calcareous, clayey and gleyed soil. Where the profile is decalcified, the otherwise similar ***Wallasea Series*** is found. Acid sulphate soils occur where the clay thins out over peat at the valley margins. The Thurne catchment has suffered extensive problems with drainage of these marginal acid sulphate soils. Artificial drainage is required to control groundwater levels. Traditionally in the Broads, much of this Association is under permanent pasture with some arable conversion. It is the type soil for Broads grazing marsh.

Towards the headwaters of the northern rivers, Newchurch 2 soils give way to the **Altcar 2 Association**, earthy, deep peat soils over mineral substrate, which can be very acid. All components are Host class 11 or 12 depending on the presence of pumped drainage. There are three main component series. The ***Altcar Series*** has earthy, peaty topsoil overlying partly humified semi-fibrous or fibrous peat. It occupies around half of the Association in the Broads. In the ***Adventurers Series***, around one third the area of the Association, the peat is humified, non-fibrous and amorphous throughout the profile. Profiles of both soils can be shallow, less than 1m of peat usually over marine alluvium. The ***Mendham Series*** is similar to the Adventurers series but is an acid-sulphate soil, more restricted than the others, but especially common in the Waveney valley. Occasionally, where the water table has remained close to ground surface throughout the year, fresh peat continues to the top of the profile without an earthy peat topsoil. This gives rise to the ***Ousby Series***. The Association can include both pumped and undrained areas. Land use is wetland, woodland and rough grazing (especially Altcar Series), but arable is possible with comprehensive drainage (Adventurers and Mendham Series). High risk of acid sulphate drainage issues, especially in the Thurne catchment where the Mendham Series is more common. The peats of the Altcar 2 Association are of critical conservation concern because of the habitats they support and the problems their drainage can cause.

The mid and upper reaches of the Waveney are dominated by the **Mendham Association**, deep peat soils associated with clay over sandy soils. It can also be acid sulphate, with prone soils being patchily distributed everywhere, and problematic on drainage. Ochre is frequent in the Waveney valley, but because comprehensive deep drainage is rare the issues are mild compared to the Thurne. It is a complex association with the component soil series disposed according to local histories of river sedimentation and peat accumulation. The main division is between peat profiles (***Mendham*** and ***Adventurers Series,*** HOST Class 11/12) and predominantly silty or clayey soils (***Shotford, Midelney, Fladbury*** and ***Wensum Series***, HOST Class 9). The silty/clay series are found most commonly near to rivers and therefore less likely to be encountered when working with catch dykes. It is the complexity of the association, through the small scale inclusion of the silty/clayey profiles, which distinguishes the Association from the Altcar 2 Association. The Mendham Association also appears to have more common acid sulphate conditions. Soil patterns can be affected by spoil disposal from ditching and other works.

Very narrow upper and tributary valley bottoms, sometimes outside of the Broads area (as in the upper Bure and Ant), are occupied by the **Hanworth Association** (Host class 10). These are ground water gleys with humic or peaty topsoils and generally non-calcareous sub-soils. They are developed in aeolian drift and peat over coarse glaciofluvial or terrace deposits, and are generally deep, permeable coarse loamy profiles, strongly affected by groundwater. The two main mineral profiles***, Hanworth*** and ***Sustead Series***, can be associated with the peat ***Adventurers Series*** (which has Host Class 11 or 12). This association is likely to play a minor role in catch dyke work.

Valley Margin, Slopes and Plateau

Most of the Broads valleys have a relatively simple progression with floodplain soils grading into a different Association which often rises to the very gentle plateau top surface. The topographical slope may give rise to changing soil series within the Association but otherwise the sequence is simple. The Waveney valley is more complex, however, passing through one or two bands of intervening Soil Associations before reaching the plateau top Beccles Association which is the high Suffolk and Norfolk chalky boulder clay soil group. The following deals firstly with Associations mostly of the valley slope and then summarises the upper/plateau Associations.

Along both sides of the Waveney, and very locally from Salhouse-Ranworth on the south side of the Bure, the margin is composed of glaciofluvial drift in a range of **Newport Associations**, including Newport 1, 3 and 4. They are all Typical Brown Sands, deep, coarse, well drained, sandy soils with gleying rare and restricted to toe slope situations. They are predominantly HOST Class 5. The **Newport 4 Association**, which is perhaps dominant of the three in East Anglia, is a heath soil and underlies the Sandlings, North Norfolk and West Norfolk Heaths. The Association divides mostly into the brown sands of the ***Newport Series*** or the humo-ferric podzols of the ***Redlodge Series***, the latter being uncommon in the study area. The **Newport 1 Association** can be zoned according to topographical situation with the Newport series on more elevated ground with ***Ollerton Series*** and then ***Blackwood Series*** (Host Class 10) on progressively lower slopes, the latter being similar soils distinguished by degree of groundwater mottling in the lower soil horizons. The least common **Newport 3 Association** is similar to the preceding soils but fringes chalky boulder clay, providing a significant calcareous influence. It is found along parts of the north side of the Waveney Valley and to the south of the valley near Lowestoft. Movement of fines from upland tills can provide a loaminess to soil texture. The component soils are the sandy ***Newport Series*** in elevated or free-draining situations (Host Class 5), or the ***Wighill Series*** where groundwater causes mottling of lower, siltier horizons, and there is a loamy element to the soil. Host Class is then 18.

Along the southern side of the Yare valley are predominantly brown earth soils derived from chalky till and glaciofluvial drift. Between Norwich and the River Chet is the **Burlingham 3 Association.** From the River Chet east, and curling round into the north of the Waveney, is the

Burlingham 1 Association. Both are argillic (i.e. showing significant clay enrichment in lower horizons) brown earths. They contain deep, loamy soil groups, variably coarse or fine, with slowly permeable subsoils often gleyed. They have a range of component series with varying HOST classes, making assigning a single Class to the associations difficult. They form a wide belt reaching southwards to the top of the plateau where they eventually meet the **Beccles Association.**

Two thirds of the area of the **Burlingham 1 Association** is HOST Class is 18, the remaining third Class 5. The ***Burlingham Series*** is the principle soil with increasingly fine loamy ***Ashley Series*** (both HOST Class 18) and a little of the clayey ***Hanslope Series*** (Host Class 21)**.** The first two are typically on the highest slopes adjacent to the clay soils of the Beccles Association, or on spur crests. Other brown earths are also found in the association, the ***Wick Series*** (Class 5) and the ***Wighill Series*** (Class 18). There are also significant areas of the ***Newport Series*** (Class 5), a brown sand soil on glaciofluvial deposits.

The **Burlingham 3 Association** has similar characteristics. Host Class 18 still dominates but much less so with 30% each Host Classes 5 and 1. The ***Burlingham*****,** ***Ashley*** and rarely the ***Honingham Series***, all stagnogleyic brown earths developing over less impermeable till, and the ***Wighill Series*** in less permeable head deposits. All four have mottled profiles indicating the influence of groundwater, and provide two thirds of the land cover of the Association. Where the till is more permeable, usually where it is thinner and overlying gravel or chalk, dryer soils without mottling or strong influence of groundwater, are developed. They are all well drained brown earths of the ***Melford, Weasenham, Maxted*** and ***Barrow Series***, differentiated by their texture into fine, clayey or coarse loams with or without clayey lower profiles. These are minor components and are not described in Soil Series Table. There are also inclusions of ***Newport Series*****.**

The southern slope of the Waveney Valley carries a narrow band of the **Hanslope Association**. This is a slowly permeable clayey soil, mostly calcareous, developed from chalky till, subject to deep cracking in dry seasons. It is all HOST class 21. The subsoil is mottled. It grows productive cereal crops. It consists principally of the ***Hanslope Series*****,** which is calcareous throughout its profile and the ***Faulkbourne Series*** which is similar but is decalcified in the upper horizons. Representation of other soil series are very minor.

In most of the northern Broads area, the valley slope soils continue to the plateau interfluves in the dominant soil group of north-east Norfolk – the **Wick 2 Association**. It is a deep, well drained, coarse loamy “brown earth” soil, mostly without gleying in the lower horizons. The Association is complex in its HOST Class but is predominantly mapped as Class 5. Some profiles can have slowly permeable sub-soils with risk of waterlogging. The Wick 2 Association provides high value arable land. The more extensive ***Wick Series*** (HOST Class 5) is characteristic of dryer, free draining areas on higher ground and where the aeolian drift is thickest, the stoneless ***Sheringham Series*** (Host Class 6). ***Wickmere Series*** (HOST Class 13) occurs where groundwater causes gleying on lower slopes. It is the more likely of the two to grade into the Altcar 2 and Newchurch Associations of the floodplains. South-west of Acle, the ***Burlingham Series*** replaces the Wickmere Series where the till is chalky and includes small chalk stones.

Between the Ant and Thurne Valleys, the **Gresham Association** forms most of the gentle valley slopes and interfluve. It often grades into the floodplain, almost always abutting the peat soils of the Altcar 2 Association. The Gresham Association includes slowly permeable, seasonally waterlogged , coarse loamy soils that have developed in aeolian drift over till, the latter (Happisburgh Formation) forming a deep subsoil. They are not calcareous soils and are often gleyed above 40cm, with a clay enriched sub-soil. HOST Class 14 is dominant. They are also usually used intensively for crops. The main component is the ***Gresham Series*** (HOST Class 14) developed on the more frequent thinner aeolian drift and consequently has finer, clayey loam beneath the coarser upper horizon. Where the aeolian drift is thickest, the ***Sustead Series*** (HOST Class 10) is found which is coarse loamy throughout its profile. It occupies more footslope positions than the Gresham series which lie on upper slopes and crests. Both are seasonally waterlogged and show mottling in lower horizons.

The Waveney Valley grades upwards on both sides, through Associations described above, to the **Beccles 1 Association,** the chalky boulder clay "plateau" of high Suffolk and Norfolk. Like the Gresham Association it is a Typical stagnogley soil, but all HOST Class 24. It is a slowly permeable seasonally waterlogged fine loamy over clay soil. It has developed from chalky till. The Association very rarely meets the floodplain floor. The most common soil type is the ***Beccles Series*** which has a fine loamy surface horizon over clayey subsoil, and the ***Ragdale Series*** which is similar but clayey to the surface. The clayey subsoils of both are relatively impermeable causing slow lateral flow at shallow depth in winter.

Table Summarising the Principle Soil Series of Broadland. Note that only the more frequent or significant Series are described. Other could be encountered.

Landscape Position	Soil Series	Parent Material	Main characteristics	Reference for Detailed Description	Associations (Main in bold)
Floodplain – lower reaches	Newchurch	Marine Alluvium	Stoneless, clayey, **calcareous**, alluvial gley. Moderately permeable but requires pumped drainage to control groundwater. Risk of acid sulphate. HOST Class 9.	Hodge et al (1984) p.432	**Newchurch 2**
	Wallasea	Marine Alluvium	Stoneless, clayey, **non-calcareous**, alluvial gley. Moderately permeable but requires pumped drainage to control groundwater. Risk of acid sulphate. HOST Class 9.	Hodge et al (1984) p.438	**Newchurch 2**
Floodplain – mid and upper reaches	Ousby	Peat over alluvium	Fibrous or semi-fibrous peat, little or no humification, from depth more or less to ground surface. Often saturated throughout the year, mostly undrained, growing or stable peat surfaces and loose successional infill. HOST Class 11 or 12, former being pump drained, rare in drained situations.	Burton and Hodgson (1987) p.19.	**Altcar 2**
	Altcar	Peat over alluvium	Earthy, peaty topsoil overlying partly or non humified, semi-fibrous or fibrous peat. Transmissive and permeable. Variable depth usually over clay base. HOST Class 11 or 12, former being pump drained.	Outline: Hodge et al (1984), p86 Detail: Jarvis, 1973 p56	**Altcar 2**
	Adventurer's	Peat over alluvium	Earthy, peaty topsoil overlying amorphous (humified) peat throughout, few visible plant remains. Low and variable permeability. Risk of acid sulphate. HOST Class 11 or 12, former being pump drained.	Outline: Hodge et al (1984), p86 Detail: Seale 1975, p.84	**Altcar 2** Mendham Hanworth
	Mendham	Peat over alluvium	As Adventurers, but subsoils very acid on drainage	Hodge et al (1984),	**Mendham**

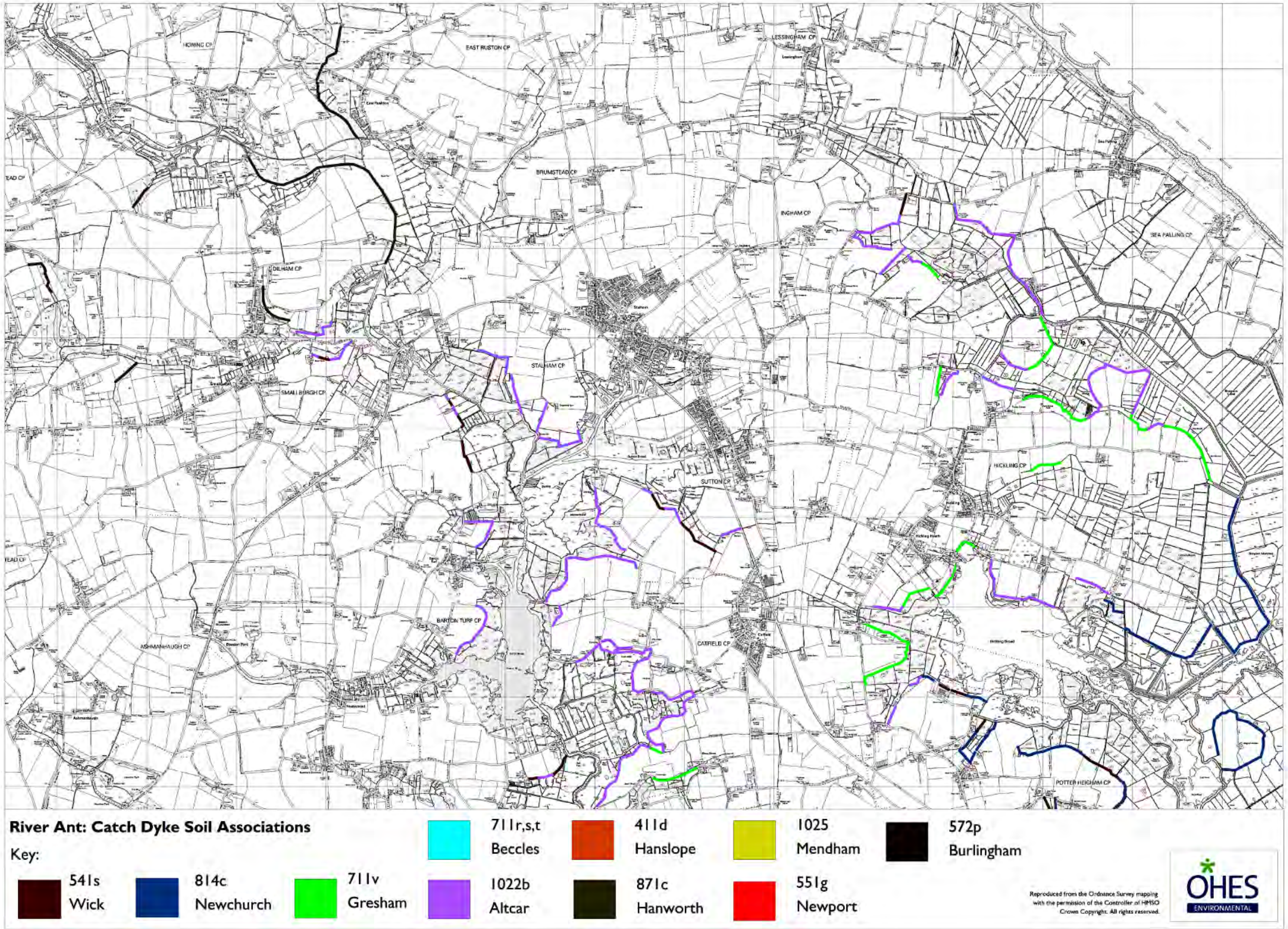
			of pyritic layers introduced by brackish water. Mostly HOST Class 11, being pump drained.	p31	Altcar 2
	Shotford	River alluvium.	Sulphuric alluvial ground water gley. Clay over coarse loam or sand, sometimes with brushwood or other peat at depth. Calcareous upper horizon over sulphuric lower horizons. Very acid when drained. Usually near river margins. HOST Class 9.	Outline: Hodge et al (1984), p248 Detail: Corbett 1979 p.80	**Mendham**
	Hanworth	Aeolian drift and peat over glaciofluvial or terrace deposits (alluvial sands and gravels).	Humic gley. Humose or peaty topsoil over coarse loamy subsoils, gleyed, coarse stony below 60cm. Often saturated to the surface by groundwater for long periods, carrying wetland vegetation. HOST Class 10.	Outline: Hodge et al (1984), p213 Detail: Tatler and Corbett 1977 p.53	**Hanworth**
Valley Margin	Ollerton	Glaciofluvial Drift	Gleyed brown sand. Permeable sandy or loamy sandy soil, affected by groundwater and with some mottling. Non-calcareous in upper layers. HOST Class 7.	Outline: Hodge et al (1984), p285 Detail: King 1977 p.65	**Newport 1**
	Blackwood	Glaciofluvial Drift	Typical sandy ground water) gley. Deep, permeable sandy and sandy-loam soil. Slightly stony. Similar to Ollerton but a lower slope position, more affected by groundwater and with mottling higher in the profile. HOST Class 10.	Outline: Hodge et al (1984), p128 Detail: Hollis 1978, p.101	**Newport 1**
	Wighill	Glaciofluvial Drift over Chalky Till at depth	Stagno-gleyic brown earths. Coarse sandy loam soils with significant clay in the lower horizons, which are mottled and affected by groundwater. HOST Class 18.	Detail: Hodge et al (1984) p.440.	**Newport 3** Burlingham 1 Burlingham 3
	Sustead	Aeolian drift over glaciofluvial or terrace deposits.	A cambic ground water gley soil has mottled sandy silt loam throughout with no clay in lower horizons. Develops on lower slopes where Aeolian deposits are thickest. HOST Class 10.	Detail: Hodge et al (1984) p.436	**Gresham**
	Quorndon	Sandy head and aeolian drift over glaciofluvial or terrace	Ground water gley developed in coarse loamy Head with sands and gravels at depth. Usually occurs as narrow strips adjacent to the floodplain. High water	Detail: Tatler and Corbett (1977).	**Wick 2**

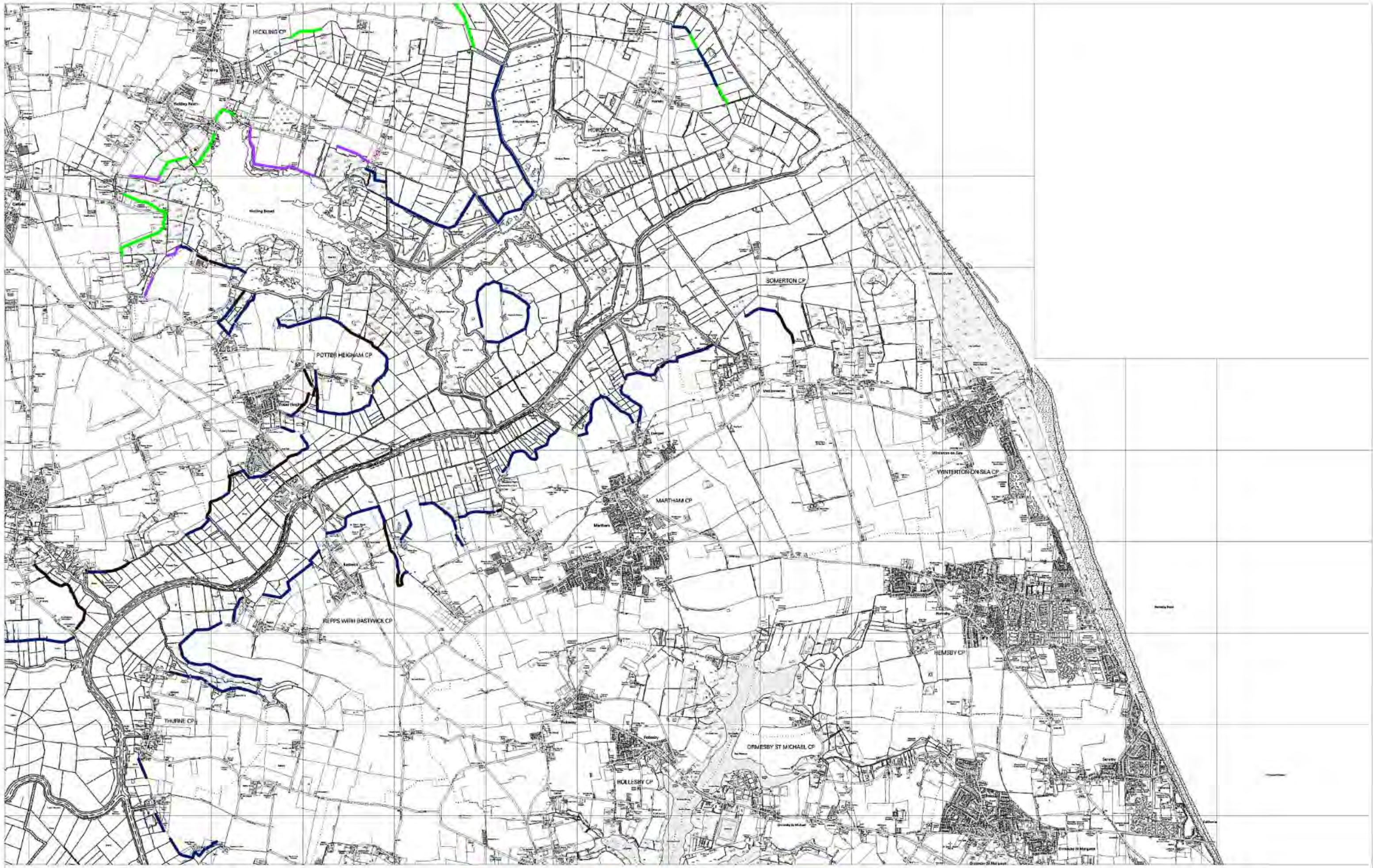
		deposits.	tables, often pasture. HOST Class 10		
Valley Margin to Plateau Tops	Wick	Thin aeolian drift over till or glaciofluvial sands	Typical brown earths, permeable. Coarse loamy, with sandy subsoils. Contains stones. Generally unaffected by groundwater, unmottled. Plateau tops, slopes and higher ground. HOST Class 5. Formerly mapped in the area as Hall Series (Tatler and Corbett 1977) but re-interpreted (Hodge et al 1984).	Outline: Hodge et al (1984), p270 Detail: Hollis 1978, p.101	**Wick 2** Newport 1 Burlingham 1
	Newport	Glaciofluvial Drift (sands and gravels over Happisburgh Formation, sometimes Crag)	Typical brown sand, well drained. Upper slopes and crests, generally unaffected by groundwater. Often with Wick Series. Slightly and very stony soils are described as different phases. HOST Class 5.	Outline: Hodge et al (1984), p270 Detail: Jones 1975, p.38	**Newport 1, 3, 4** Burlingham 1 Burlingham 3
	Sheringham	Deeper aeolian drift over till or glaciofluvial sands.	Typical brown earths with no mottling and generally stoneless. Non-calcareous. Developed in deeper aeolian deposits than Wick, often associated with it. Host Class 6	Outline: Hodge et al (1984), p347 Detail: Corbett and Tatler (1974) p.75	**Wick 2** **Wick 3**
	Aylsham	Deeper aeolian drift over till or glaciofluvial sands.	Gleyic brown earth, in depressions, on the floor and lower slopes of minor valleys. Non-calcareous, similar to Sheringham but showing effects of groundwater gleying. Lies between Sheringham and Sustead in terms of gleying and influence of water table. HOST Class 8.	Detail: Corbett and Tatley (1974).	**Wick 2**
	Wickmere	Thin aeolian drift over till or glaciofluvial sands (Happisburgh Formation)	Stagno-gleyic brown earths, stoneless, with a brown, loamy sub-soil. Permeable surface, moderately permeable subsoils. Mottled, affected by groundwater, lower slope positions. HOST Class 13.	Detail: Hodge et al (1984) p.439	**Wick 2**
	Burlingham	Aeolian sands over chalky till (boulder clay)	Stagno-gleyic brown earth. Fine loamy throughout with clayey lower horizons. Calcareous above 80cm, with chalk stones. Mottled, affected by groundwater. HOST Class 18.	Outline: Hodge et al (1984), p133 Detail: Clayden and Hollis 1984, p.101	**Burlingham 1** Wick 2 Burlingham 3

	Ashley	Glaciofluvial sands over Chalky Till	Stagno-gleyic argillic brown earth. Similar to Burlingham but with sandier upper horizons, clayey in lower profile. Calcareous with chalk stones. Mottled, affected by groundwater. HOST Class 18.	Outline: Hodge et al (1984), p141 Detail: Reeve 1978 p.99	**Burlingham 1** Burlingham 3
	Hanslope	Chalky Till	Typical stagnogleyic pelosol. Clayey throughout, with slowly permeable sub-surface horizons. Calcareous with chalk stones. Mottled, affected by groundwater. Often with Ashley Series. HOST Class 21.	Outline: Hodge et al (1984), p210 Detail: Corbett 1979, p40.	**Burlingham 1** **Hanslope**
	Faulkbourne	Chalky Till (Boulder Clay)	Argillic pelosols. Very similar to the Hanslope Series (and usually closely associated with it) but decalcified in the upper horizons. Clayey to the surface, slowly permeable. HOST Class 21.	Outline: Hodge et al (1984), p210 Detail: Reeve 1976, p104	**Hanslope**
	Honingham	Aeolian drift over Chalky Till (Boulder Clay)	Stagno-gleyic argillic brown earths. Permeable, sandy loam over clayey sub-soil, calcareous at depth with chalk pebbles. Mottled and affected by groundwater. HOST Class 18.	Outline: Hodge et al (1984), p285 Detail: Eldridge 1980 p.73	**Burlingham 3**
	Gresham	Aeolian drift over till (Happisburgh Formation)	Typical stagnogley soil with mottled subsurface horizons. Fine, clayey loam beneath the coarser upper horizons in aeolian sand, often separated by a thin sand layer. Generally stoneless but with flints along the boundary with the underlying till. Crests, tops and gentle slopes. HOST Class 14.	Detail: Hodge et al (1984) p.425	**Gresham**
	Beccles	Chalky Till (Boulder Clay), with cover of Aeolian drift.	Typical stagnogley. Decalcified sandy clay loam topsoil derived from aeolian sand, deeper than the Ragdale Series. Calcareous lower horizons with chalk stones. Impermeable clay lower layers within 60-75cm causing poor drainage unless under drained. In the Waveney, associated with Ashley, Hanslope and Ragdale, elsewhere with Wick. HOST Class 24.	Detail: Corbett and Tatler (1970), p.30	**Beccles**
	Ragdale	Chalky Till (Boulder	Pelo-stagno-gley. Shallow sandy clay loam topsoil	Detail: Corbett (1979)	**Beccles**

		Clay) with thin cover of Aeolian drift.	with clay profiles below. Impermeable or slowly permeable clay horizons often within 30-40cm of the surface. HOST Class 24.	p.62.	

Appendix 3: Soil Associations Associated with Catch Dykes.



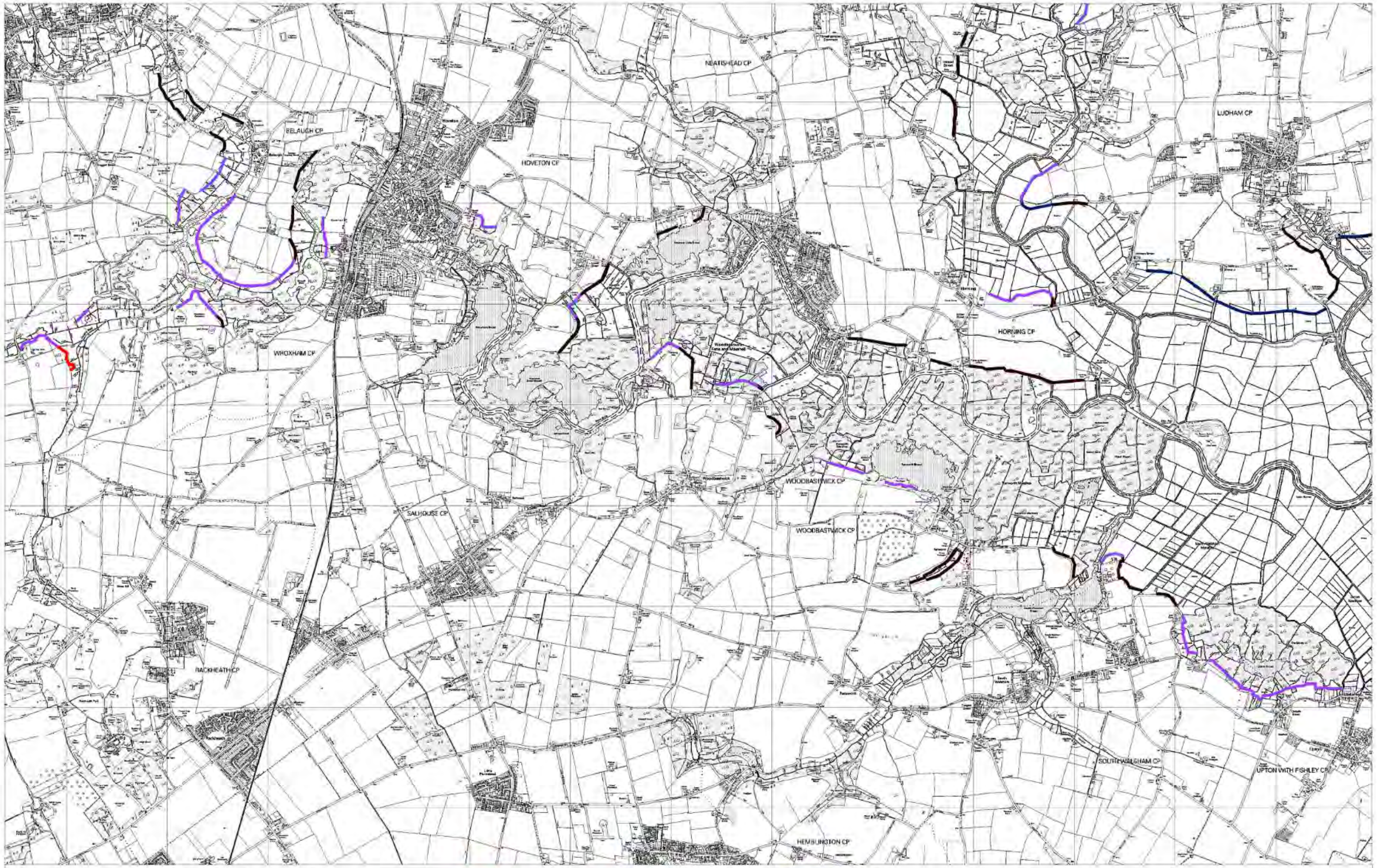


Upper River Thurne: Catch Dyke Soil Associations

Key:

- 541s Wick
- 814c Newchurch
- 711v Gresham
- 711r,s,t Beccles
- 1022b Altcar
- 411d Hanslope
- 871c Hanworth
- 1025 Mendham
- 551g Newport
- 572p Burlingham

OHES ENVIRONMENTAL



River Bure: Catch Dyke Soil Associations

Key:

541s	Wick
814c	Newchurch
711v	Gresham
711r,s,t	Beccles
1022b	Altcar
411d	Hanslope
871c	Hanworth
1025	Mendham
551g	Newport
572p	Burlingham

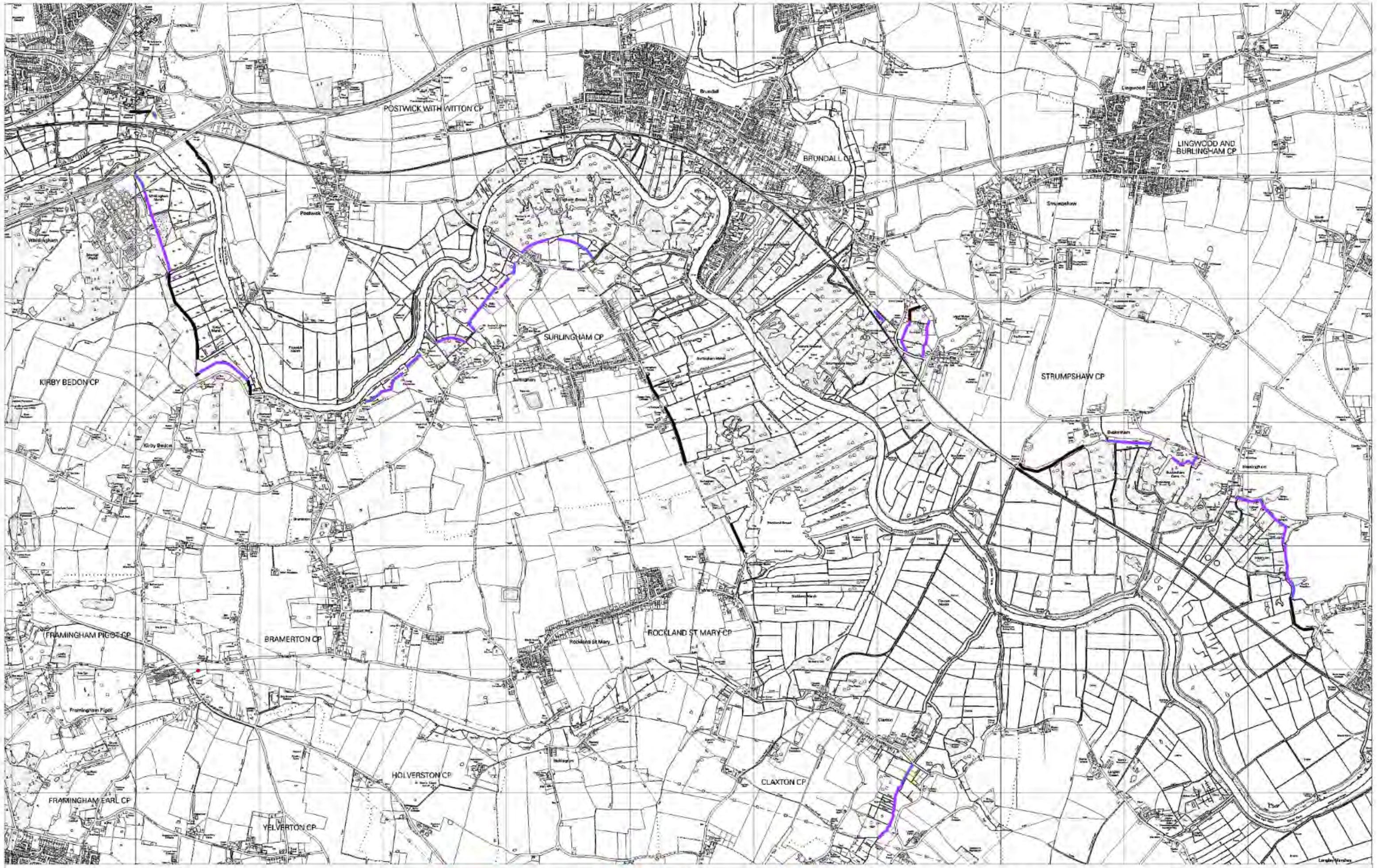
OHES ENVIRONMENTAL

Lower River Bure: Catch Dyke Soil Associations

Key:

541s	Wick
814c	Newchurch
711v	Gresham
711r,s,t	Beccles
1022b	Altcar
411d	Hanslope
871c	Hanworth
1025	Mendham
551g	Newport
572p	Burlingham

OHES ENVIRONMENTAL

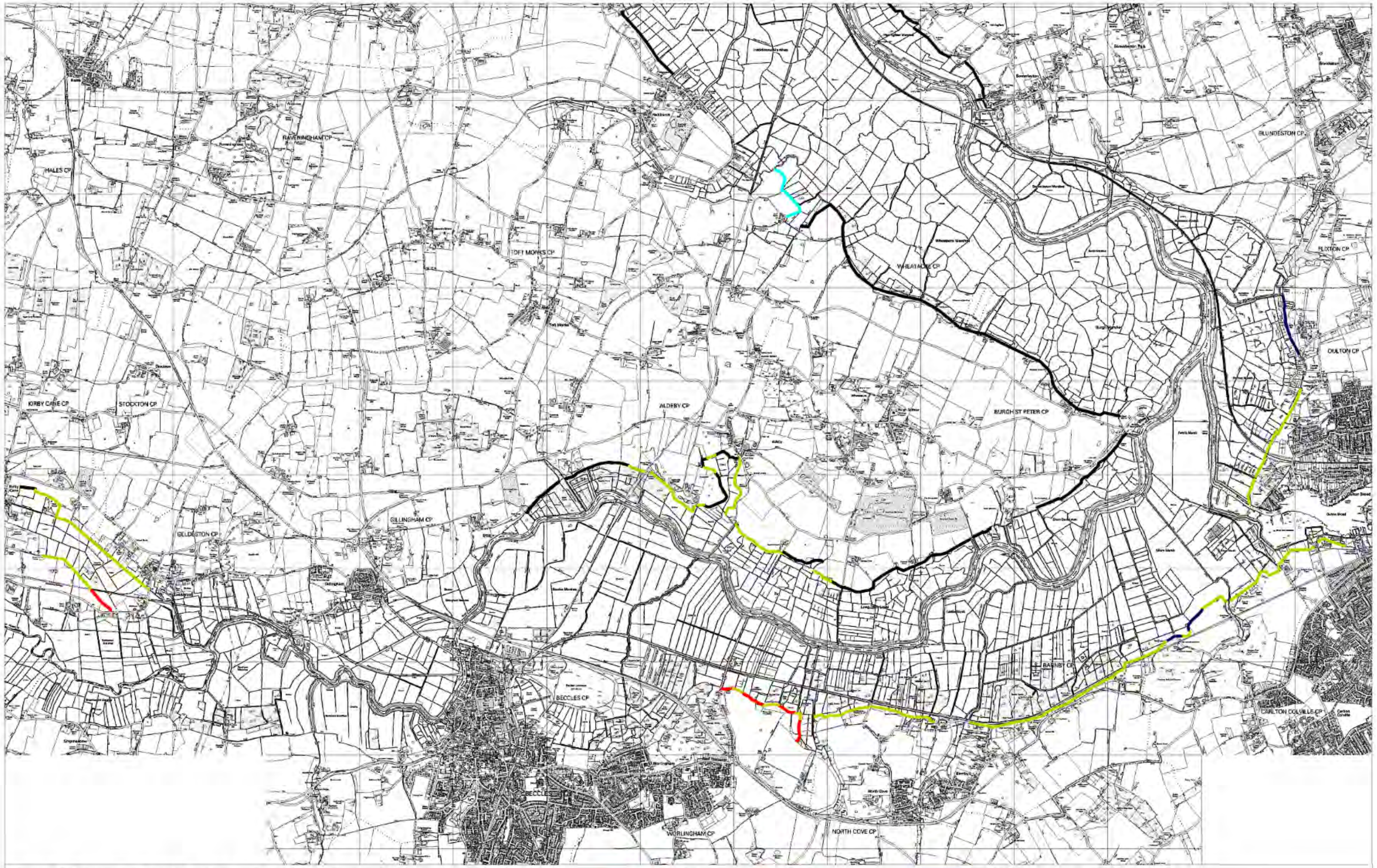


River Yare: Catch Dyke Soil Associations

Key:

541s	Wick
814c	Newchurch
711v	Gresham
711r,s,t	Beccles
1022b	Altcar
411d	Hanslope
871c	Hanworth
1025	Mendham
551g	Newport
572p	Burlingham

OHES ENVIRONMENTAL

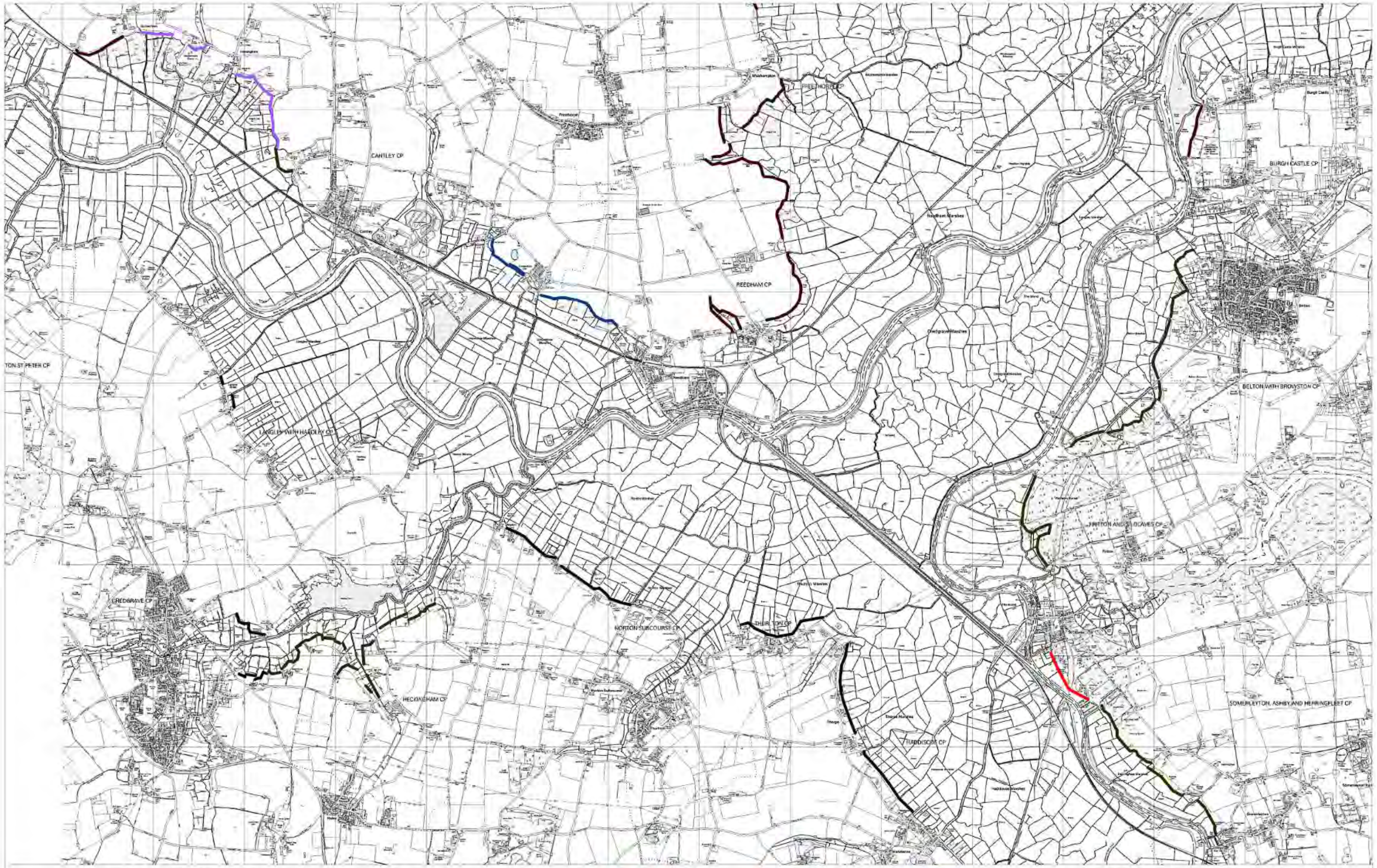


River Wavney: Catch Dyke Soil Associations

Key:

711r,s,t	Beccles
411d	Hanslope
1025	Mendham
572p	Burlingham
541s	Wick
814c	Newchurch
711v	Gresham
1022b	Altcar
871c	Hanworth
551g	Newport

OHES ENVIRONMENTAL



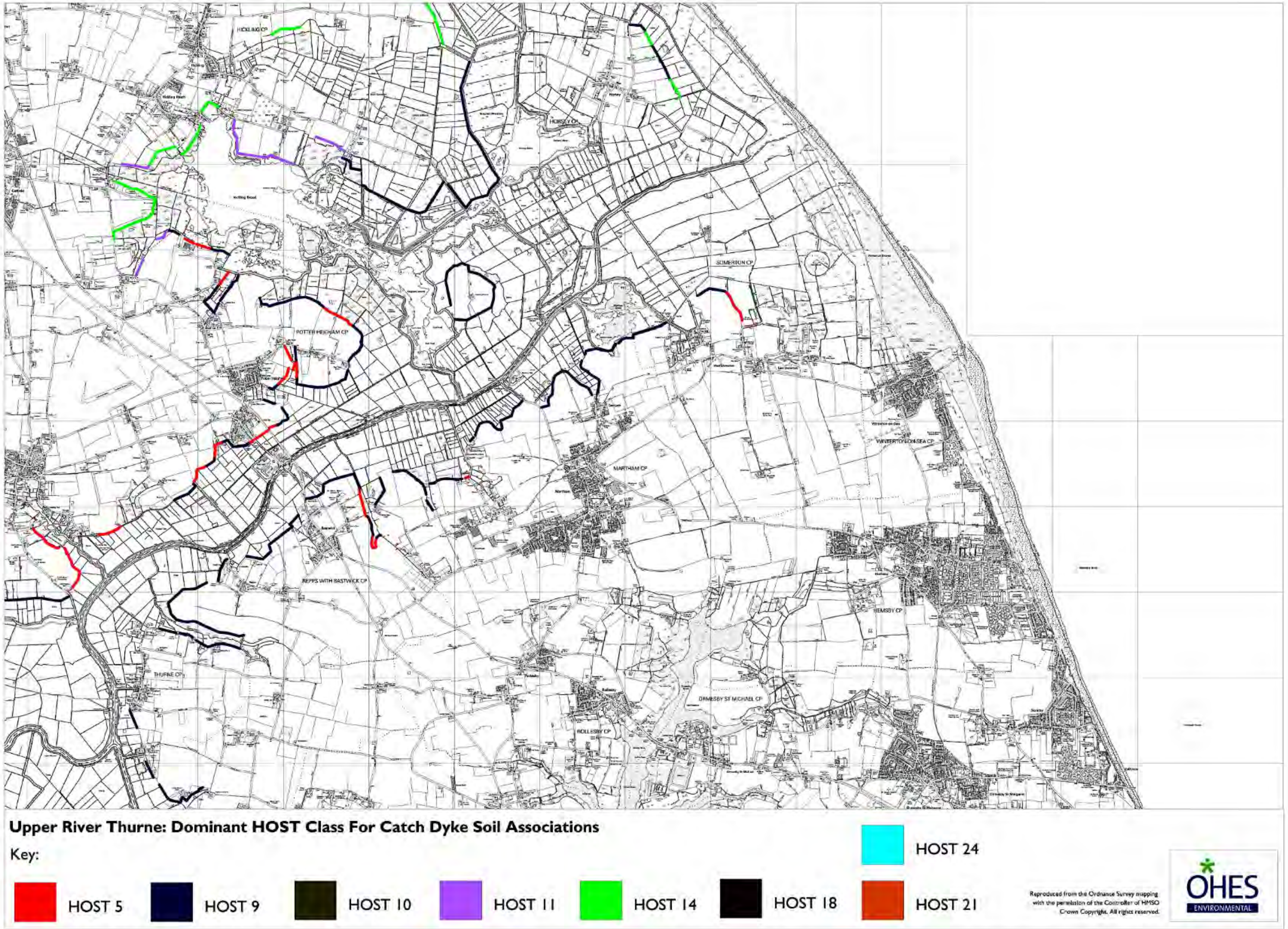
Lower River Yare and River Wavney: Catch Dyke Soil Associations

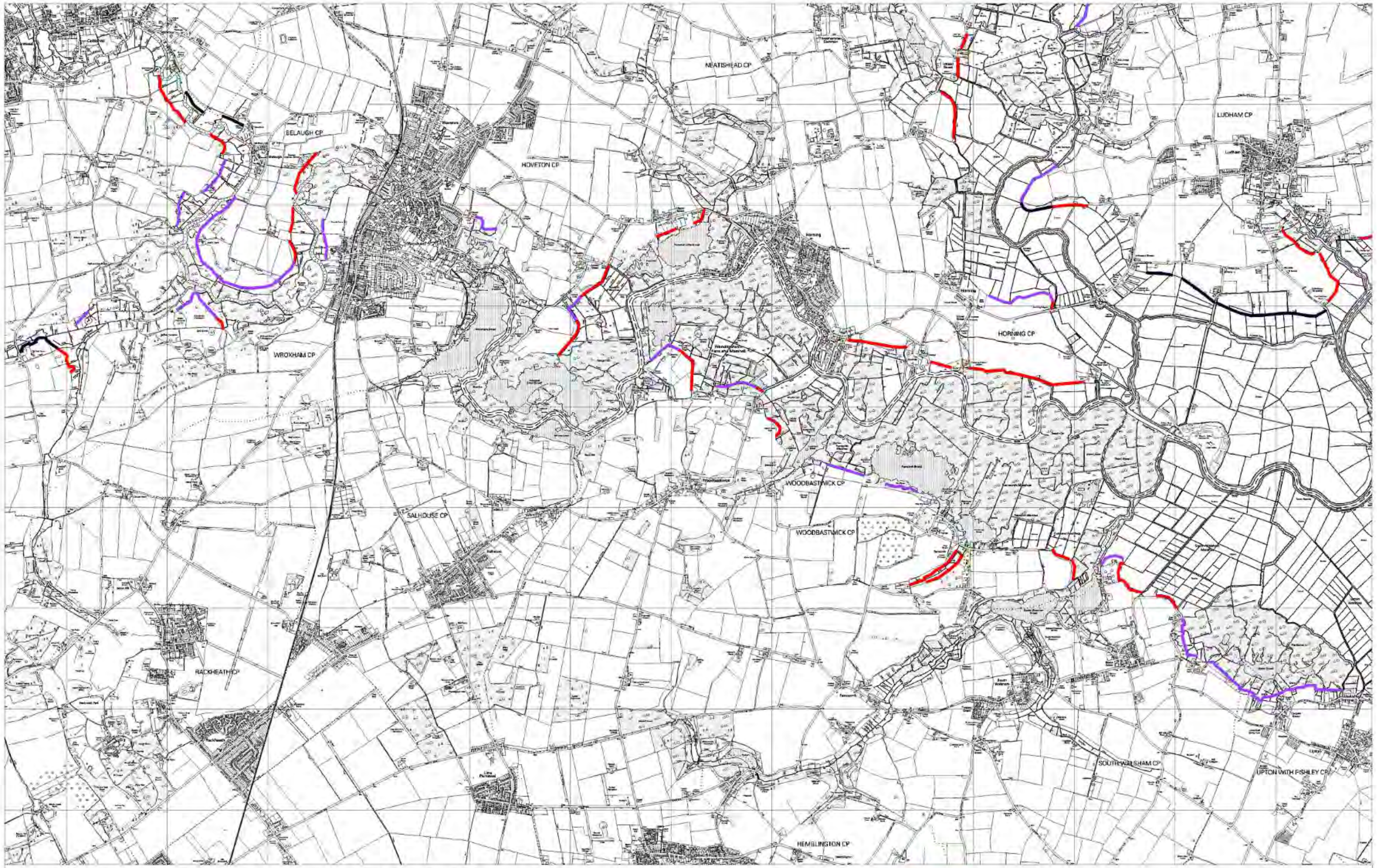
Key:

541s	Wick
814c	Newchurch
711v	Gresham
1022b	Altcar
711r,s,t	Beccles
871c	Hanworth
411d	Hanslope
551g	Newport
1025	Mendham
572p	Burlingham

OHES ENVIRONMENTAL

Appendix 4 : Host Classes for Catch Dykes

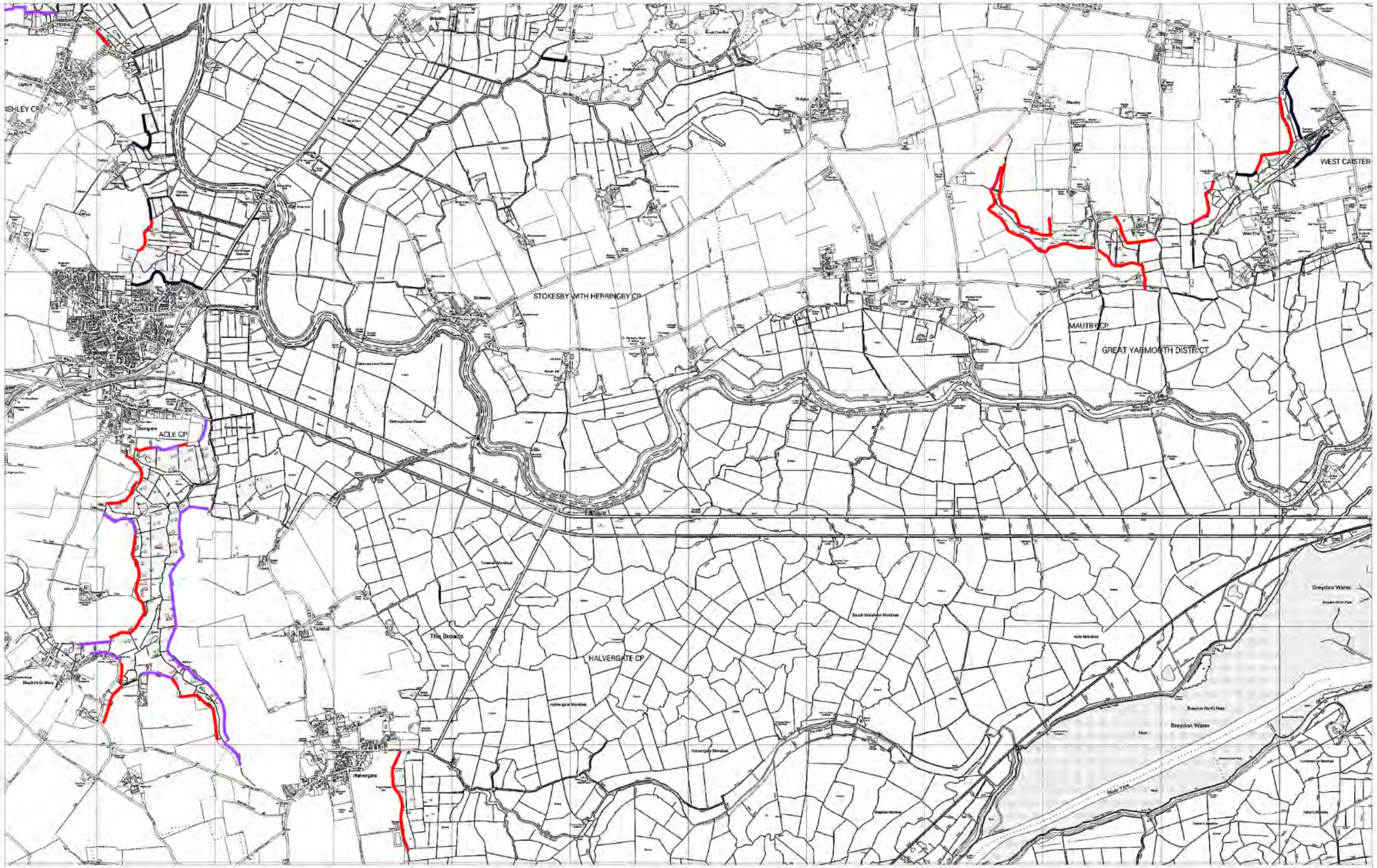




River Bure: Dominant HOST Class For Catch Dyke Soil Associations

Key:

HOST 5
HOST 9
HOST 10
HOST 11
HOST 14
HOST 18
HOST 21
HOST 24

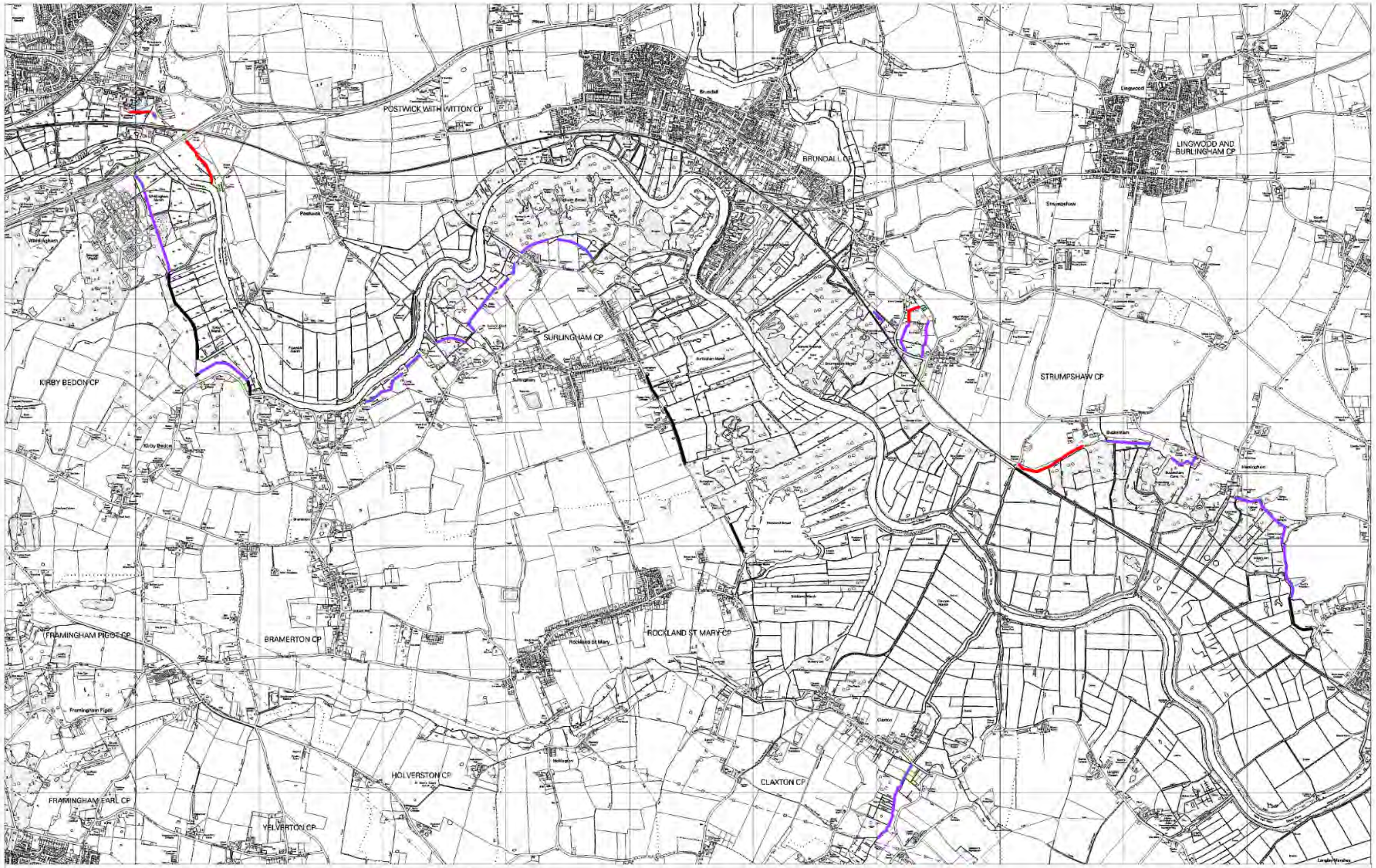


Lower River Bure: Dominant HOST Class For Catch Dyke Soil Association

Key:

- HOST 5
- HOST 9
- HOST 10
- HOST 11
- HOST 14
- HOST 18
- HOST 21
- HOST 24

OHES ENVIRONMENTAL

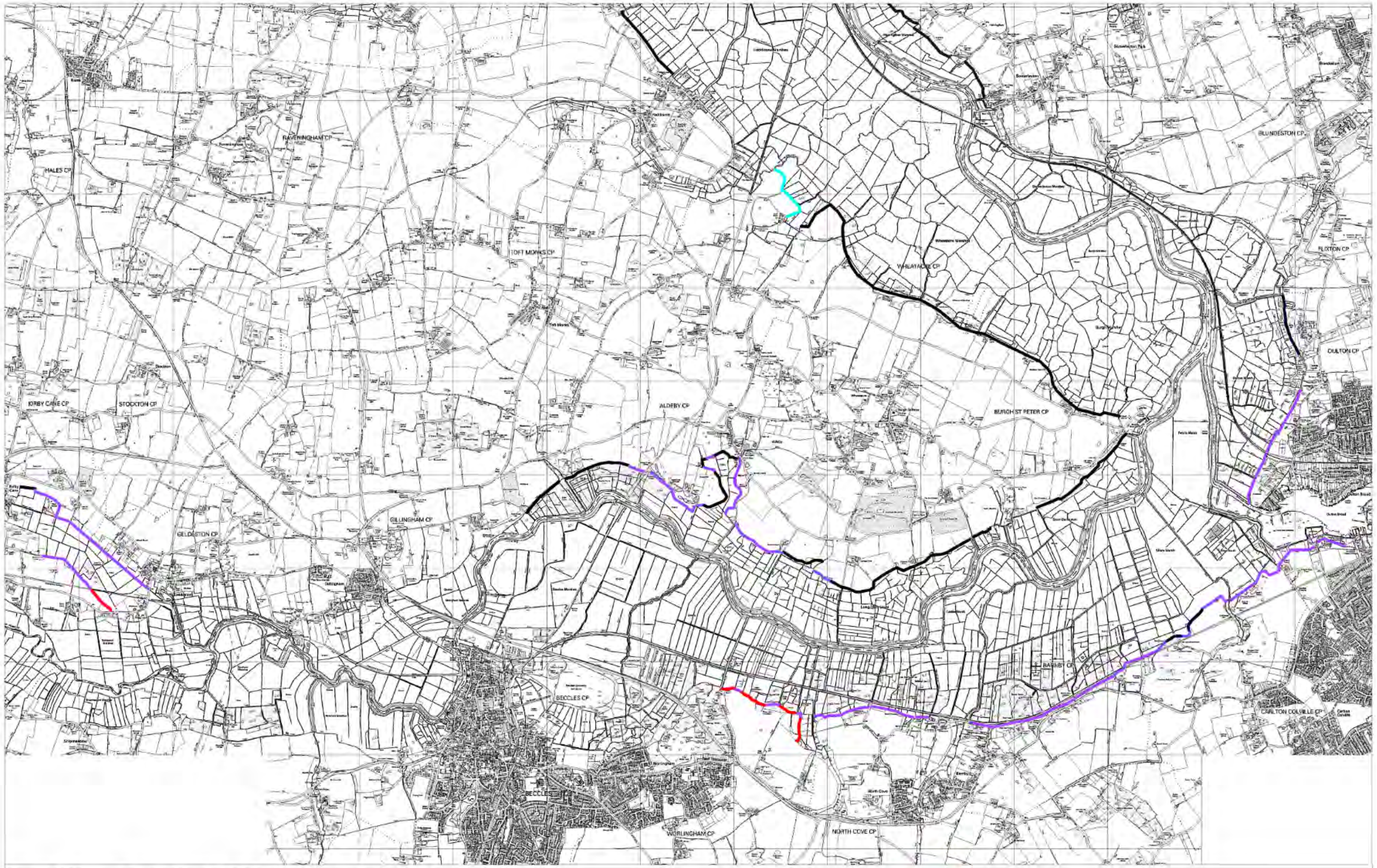


River Yare: Dominant HOST Class For Catch Dyke Soil Associations

Key:

HOST 5
HOST 9
HOST 10
HOST 11
HOST 14
HOST 18
HOST 24
HOST 21

OHES ENVIRONMENTAL

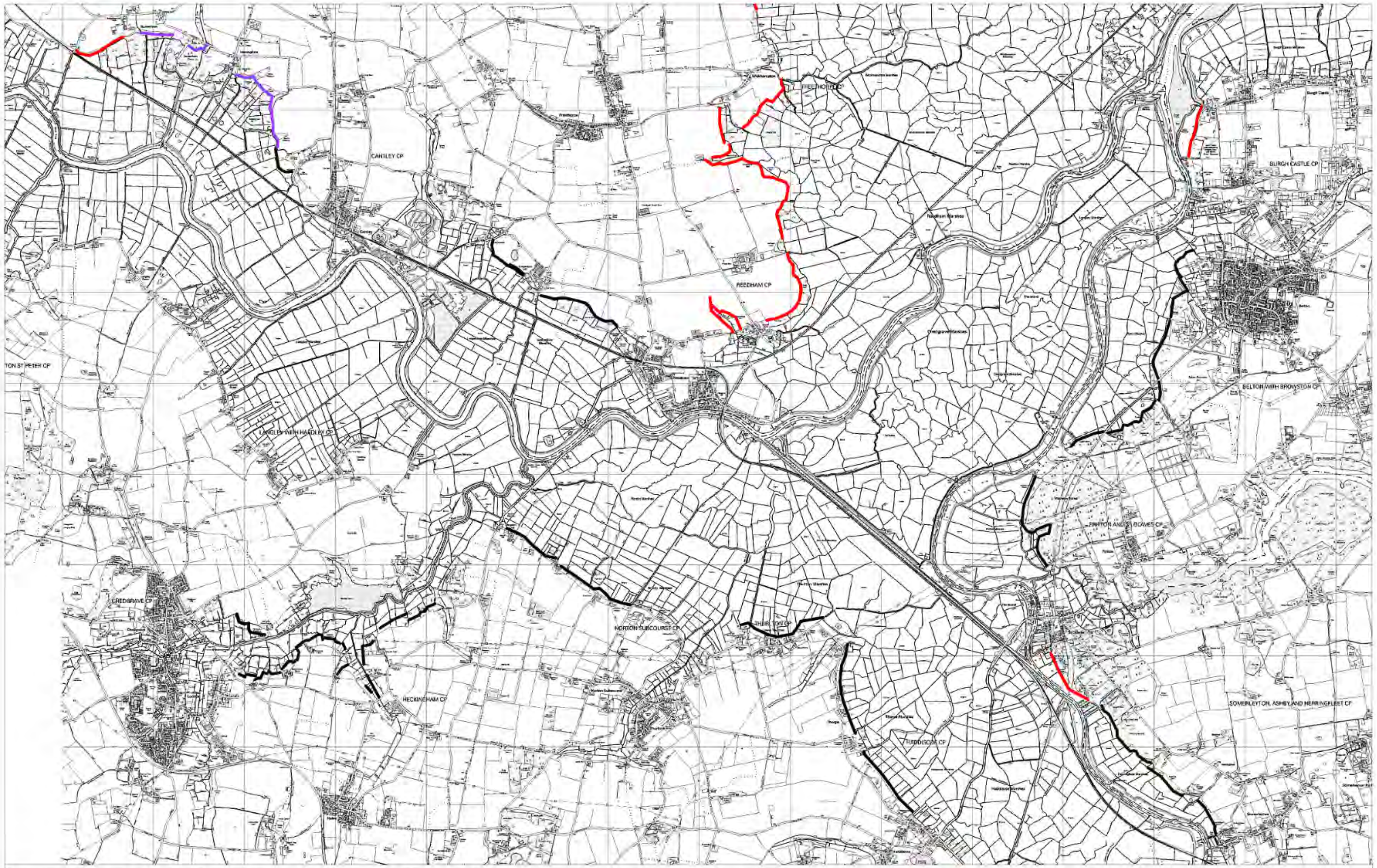


River Wavney: Dominant HOST Class For Catch Dyke Associations

Key:

HOST 5
HOST 9
HOST 10
HOST 11
HOST 14
HOST 18
HOST 21
HOST 24

OHES ENVIRONMENTAL



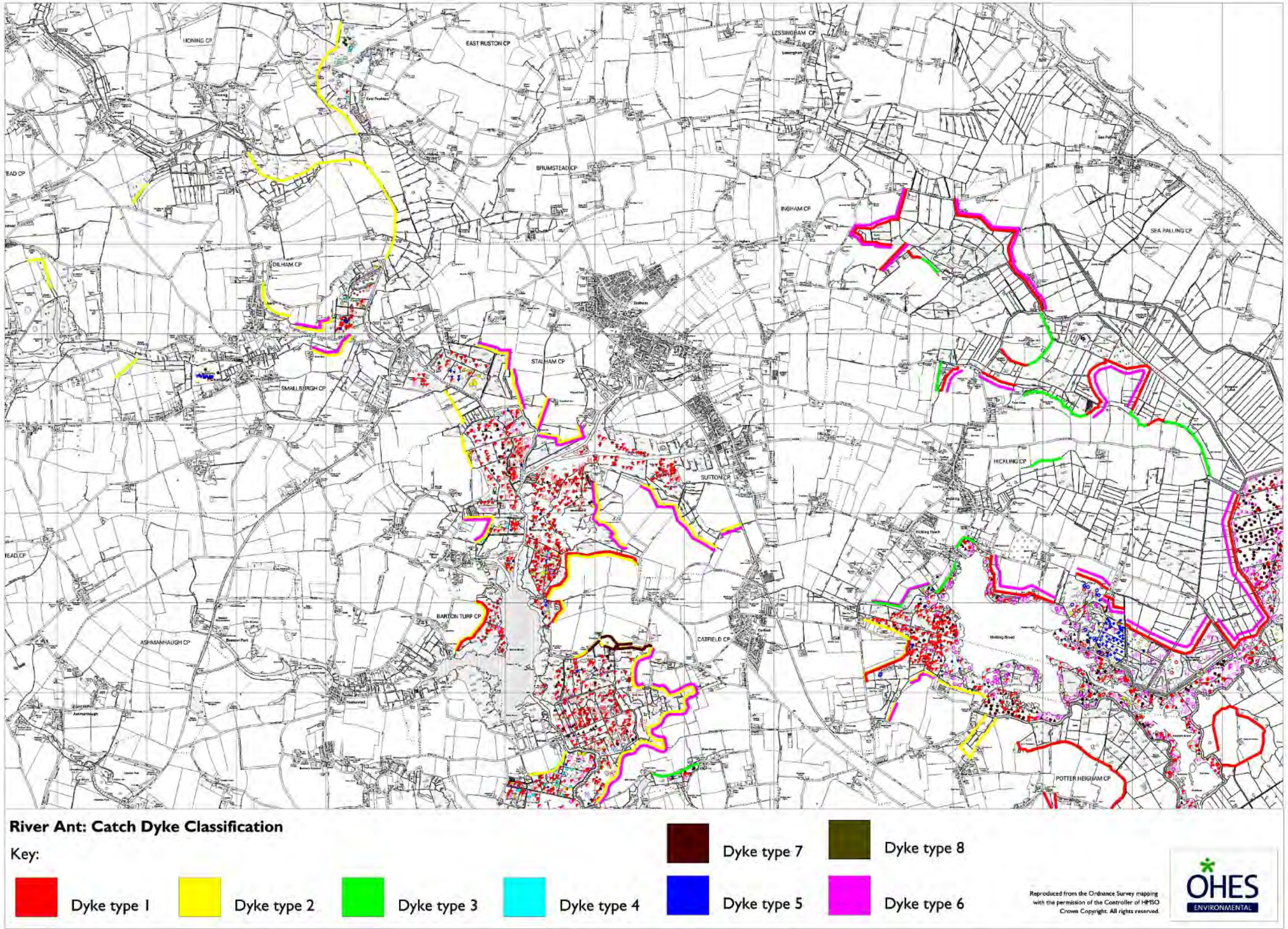
Lower River Yare and River Wavney: Dominant HOST Class For Catch Dyke Soil Associations

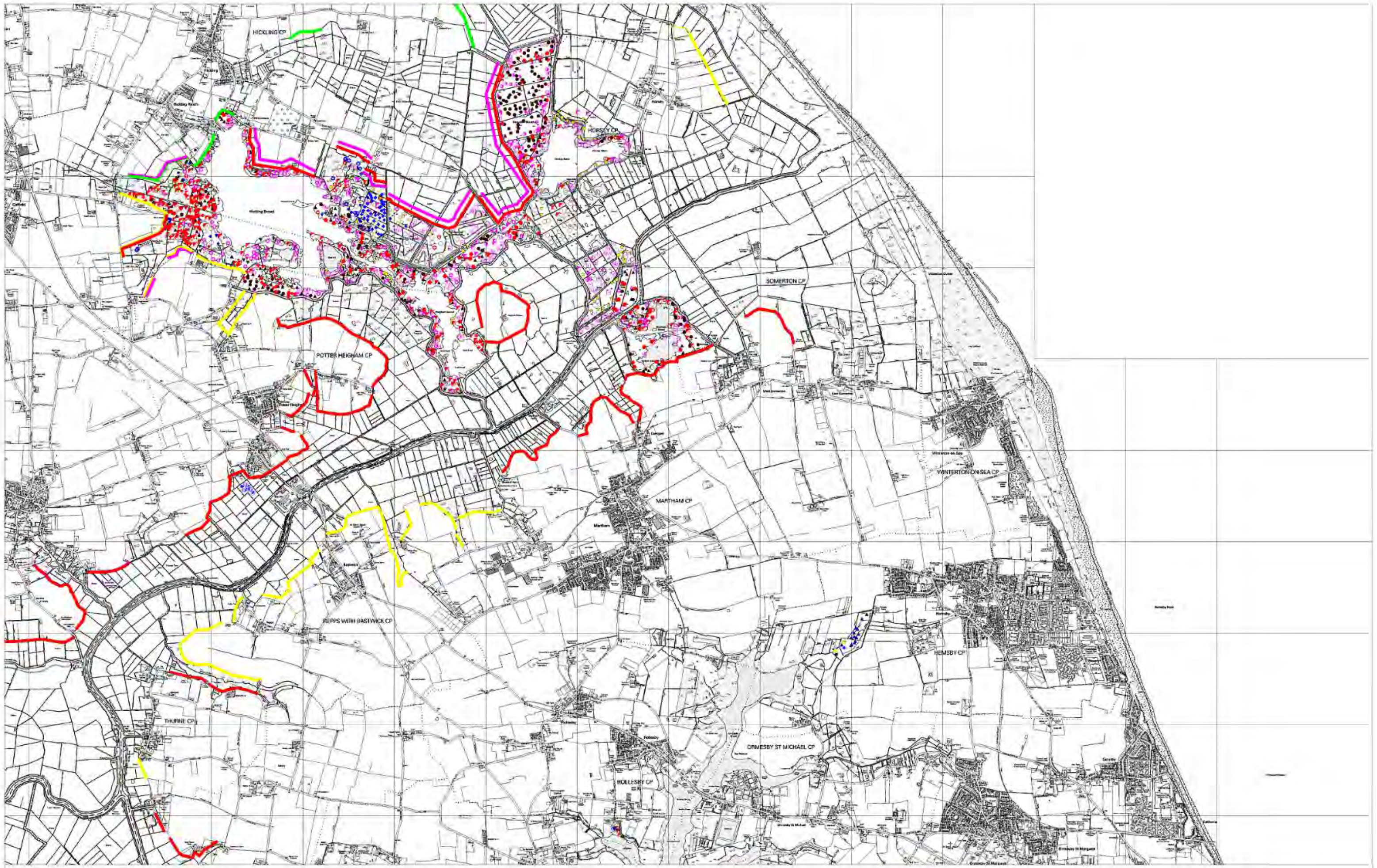
Key:

HOST 5 · HOST 9 · HOST 10 · HOST 11 · HOST 14 · HOST 18 · HOST 21 · HOST 24

OHES ENVIRONMENTAL

Appendix 5 : Type of Catch Dyke





Upper River Thurne: Catch Dyke Classification

Key:

Dyke type 1

Dyke type 2

Dyke type 3

Dyke type 4

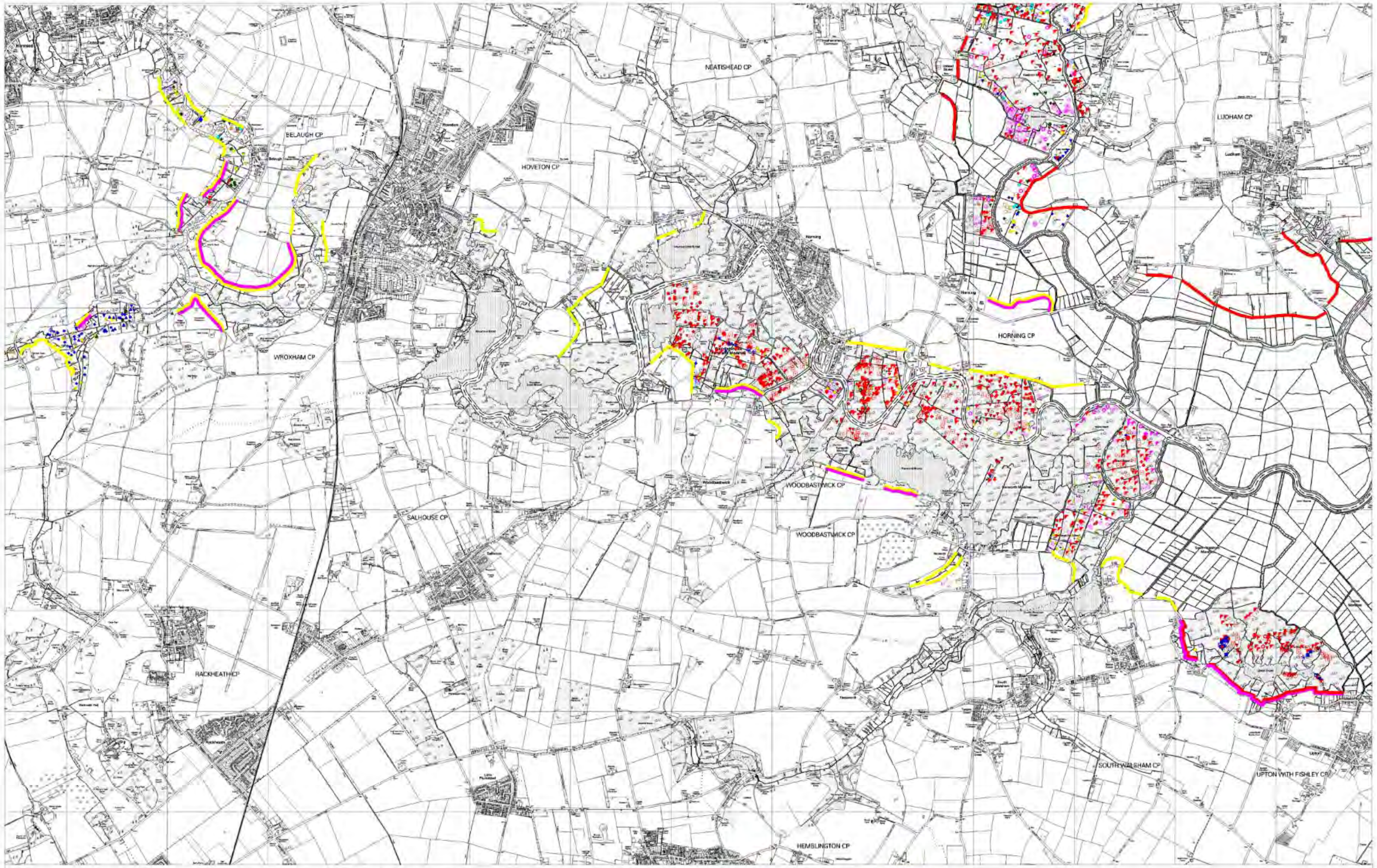
Dyke type 5

Dyke type 6

Dyke type 7

Dyke type 8

OHES ENVIRONMENTAL

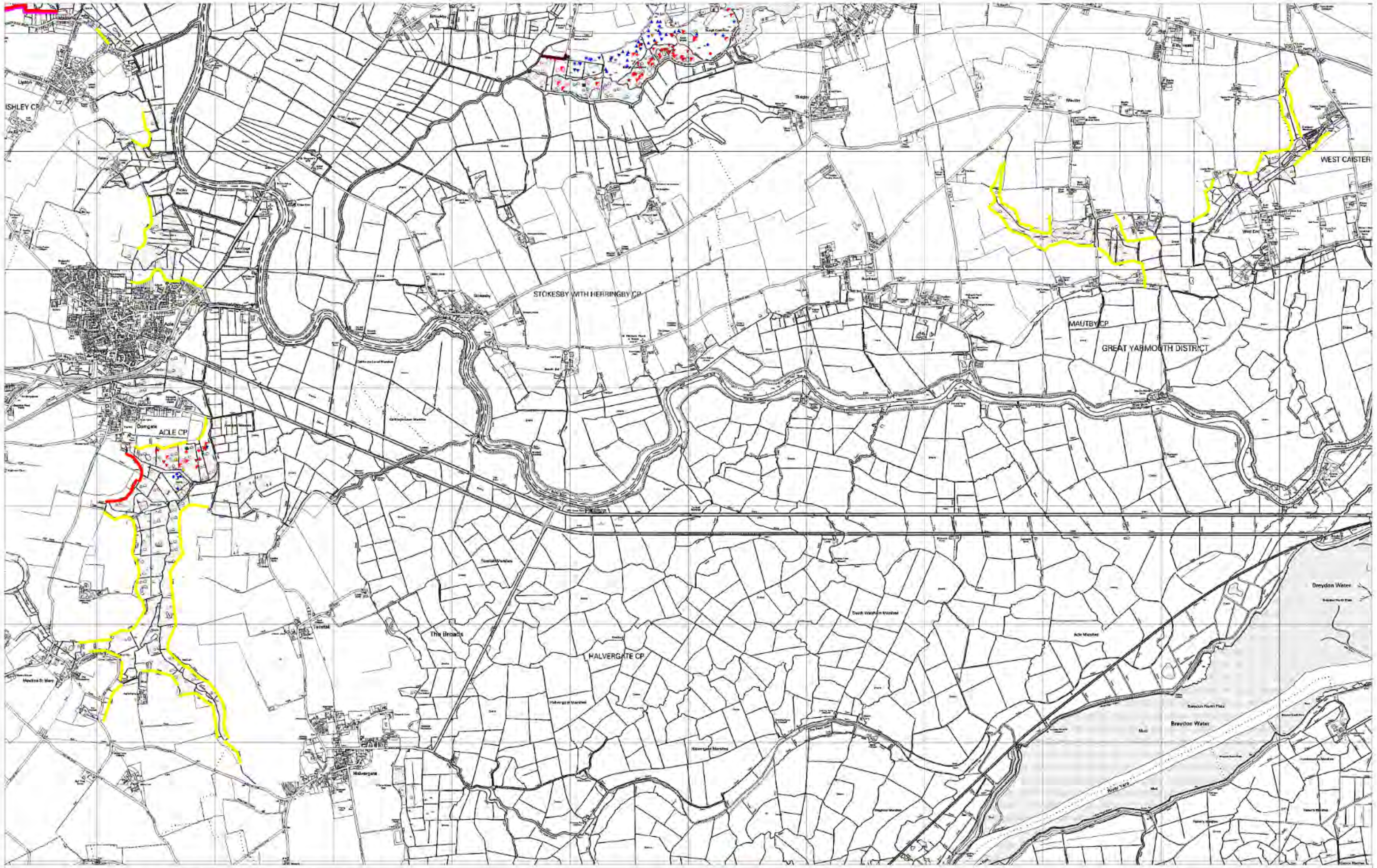


River Bure: Dominant HOST Class For Catch Dyke Soil Associations

Key:

Dyke type 1
Dyke type 2
Dyke type 3
Dyke type 4
Dyke type 5
Dyke type 6
Dyke type 7
Dyke type 8

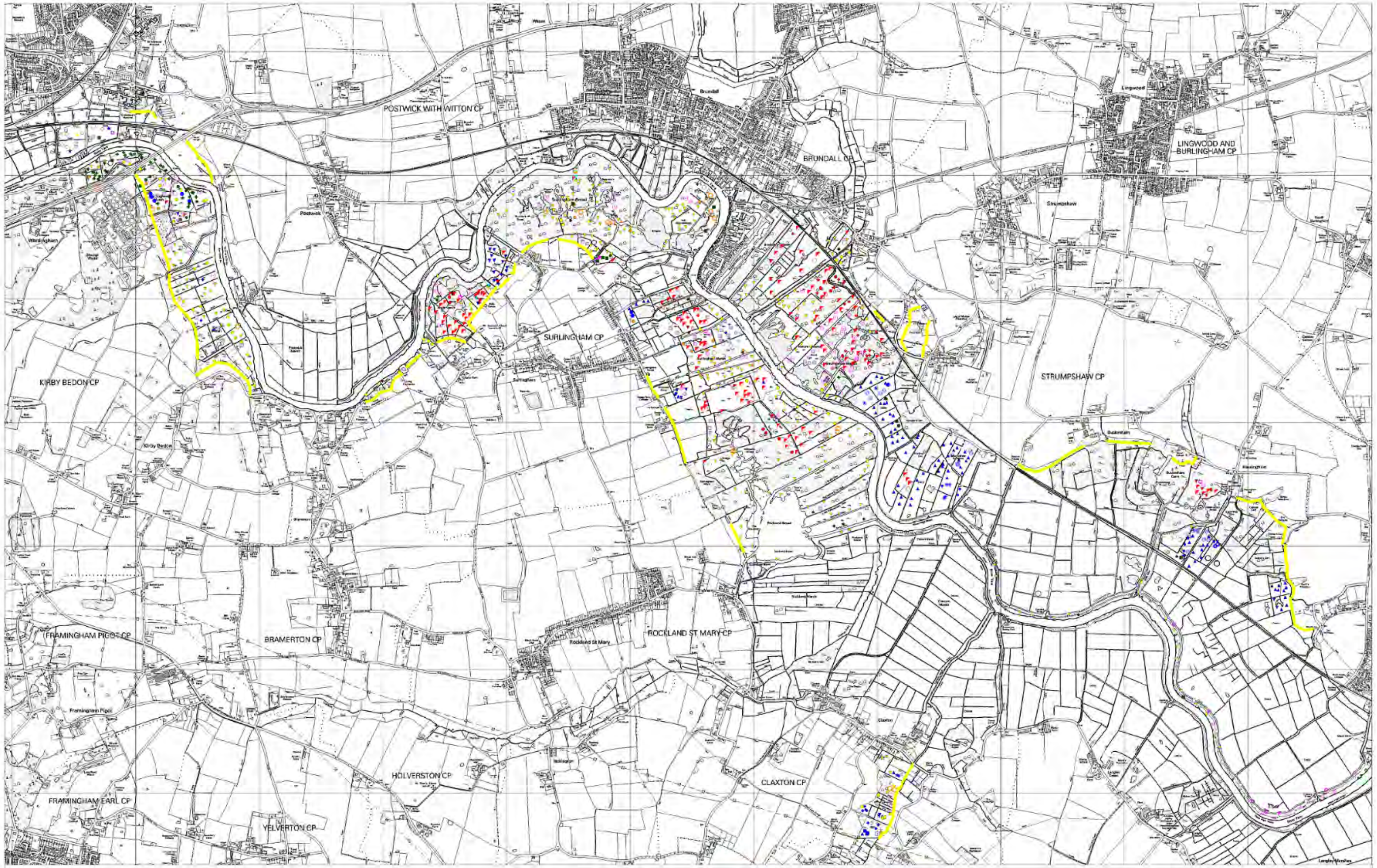
OHES ENVIRONMENTAL



Lower River Bure: Catch Dyke Classification

Key:

- Dyke type 1
- Dyke type 2
- Dyke type 3
- Dyke type 4
- Dyke type 5
- Dyke type 6
- Dyke type 7
- Dyke type 8



River Yare: Catch Dyke Classification

Key:

Dyke type 1
Dyke type 2
Dyke type 3
Dyke type 4
Dyke type 5
Dyke type 6
Dyke type 7
Dyke type 8

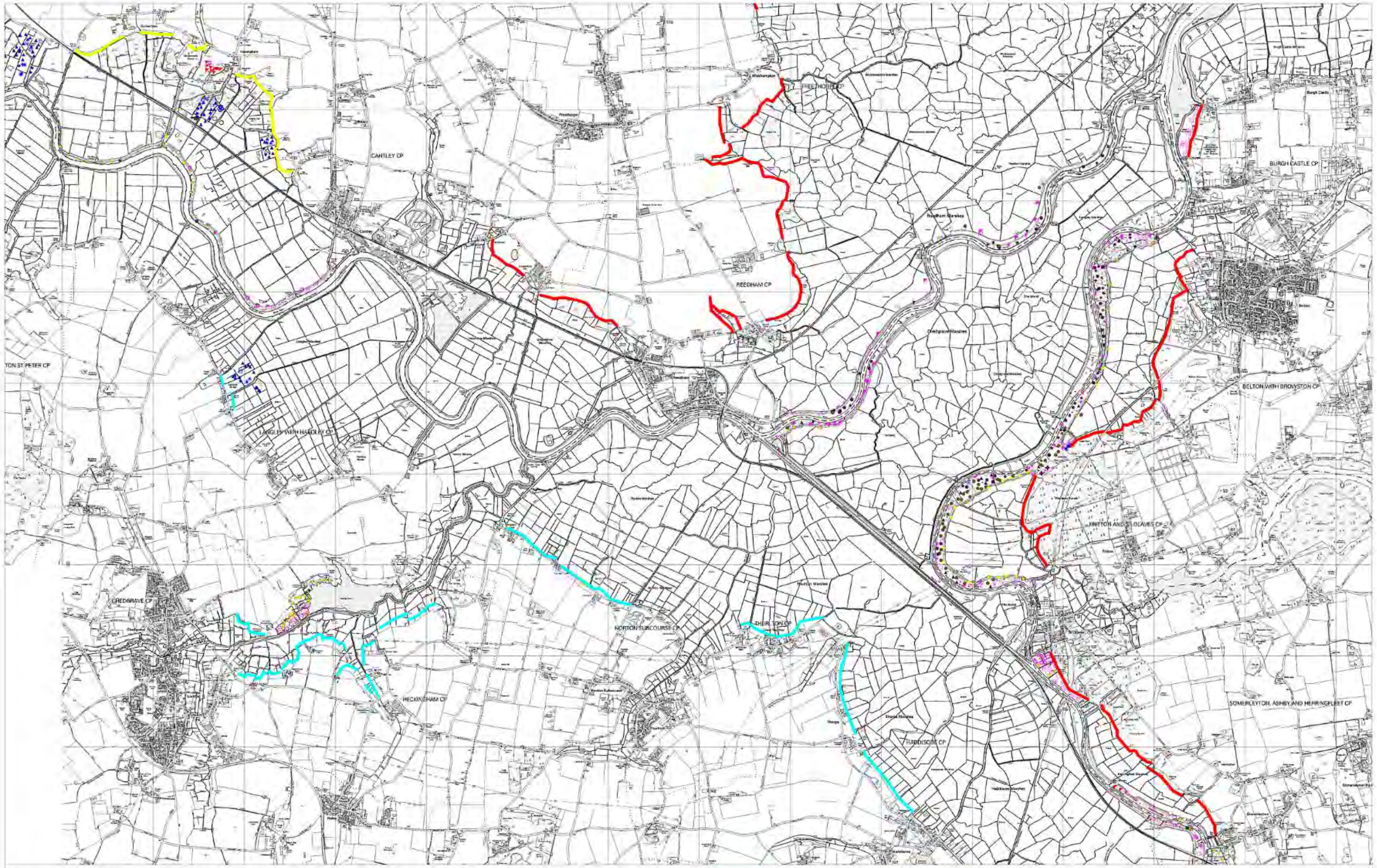
OHES ENVIRONMENTAL

River Wavney: Catch Dyke Classification

Key:

- Dyke type 1
- Dyke type 2
- Dyke type 3
- Dyke type 4
- Dyke type 5
- Dyke type 6
- Dyke type 7
- Dyke type 8

OHES ENVIRONMENTAL



Lower River Yare and River Wavney: Catch Dyke Classification

Key:

- Dyke type 1
- Dyke type 2
- Dyke type 3
- Dyke type 4
- Dyke type 5
- Dyke type 6
- Dyke type 7
- Dyke type 8

OHES ENVIRONMENTAL

Appendix 6 : Soil Core Logs Recorded For The Case Studies

SITE: Upton Fen **DATE: 5-03-14** **RECORDERS: Mike Harding, Alix Pitcher**

CORE	DEPTH (cm)	DETAILS
1		TG 38401 12648. Arable – winter cereals. On crest near to field boundary. Closest to the stoneless **Sheringham Series**
	0-45	Mid-brown silty fine soft sand, loamy at the surface, sandier with depth, stoneless.
	45-65	Mid orangey yellow brown, silty fine soft sand. Occasional stones 2-3cm. Becoming sandier and stoneless with depth.
	65-80	Light yellowy-orange brown coarse sand, little silt, stoneless, structureless.
	80-	Orangey-brown coarse sand with black (organic) inclusions. Sand is initially clayey but this declines with depth. Getting moister. Fine soft sand at base. Stoneless. Coring ceased at 110cm.
2		TG 38528 12843 Winter cereals. Between **Wick and Sheringham Series.**
	0-35	Dark brown silty clayey very fine sand. Quite sticky. Occasional small stones.
	35-65	Mid-brown, slightly orange, slightly silty fine sand. Moderately stony, moist. Grading to:
	65-	Orange-brown, slightly silty coarse sand, with rare larger stones 2-3cm. Becoming sandier with little or no silt with depth, progressively wetter, very soft and structureless. Coring ceased at 110cm.
3		TG 38603 12962. Winter cereals. Closest to **Wickmere Series**.
	0-15	Dark brown clayey fine sandy loam, slightly stony.
	15-40	Dark brown silty fine sand.
	40-90	Mid orange-brown clayey fine sand, occasional small stones, sandier with depth with larger (c.3cm) stones, dampness increasing, mottled in lower parts.
	90-105	Pale grey-brown stiff clayey sand, strong orange-red mottling, clay reducing with depth.
	105-	Orange very slightly silty coarse sand, very soft. Coring ceased at 120cm.
4		TG 38702 13113 Grass margin of arable field, near catch dykes. **Quorndon Series.**
	0-30	Mid-brown silty fine sand slightly stony, very moist.
	30-100	Pale grey-brown very slightly silty soft sand, slightly stony, silt disappears with depth, modest orange mottling becoming strong mottling after 50cm. Structureless, becoming stonier with depth including some larger stones to 3cm. Almost pure sand below,

		increasingly coarse, becoming wetter, difficult to pick up.
	100-	Grey coarse sand with layer of gravel, orange mottling. Coring ceased at 115cm.

SITE: Catfield and Myhill's **DATE:** 03/03/14 **RECORDER:** Mike Harding, Alix Pitcher

CORE	DEPTH (cm)	DETAILS
		Mrs Myhill's Side
1		TG 40136 21601. Arable field winter sown cereal. Surface sandy with flints. Closest to **Aylsham Series**, stonier.
	0-40	Light brown, silty sand, fine sand, occasional small stones.
	40-85	Orangey-brown slightly silty sand, occasional stones to 5cm, some greyish sand with mottling, hard to penetrate, yellower and coarse sandier with depth.
	85-	Very wet, difficult to pick up, pale yellowish brown to grey, coarse sand with fine gravel. Coring ceased 116cm.
2		TG 40136 21542. Arable field winter sown cereal. Surface sandy with flints. Crest of field. **Newport Series**, perhaps more loamy/silty than normal.
	0-30	Light brown, silty sand loam, fine sand, occasional small stones.
	30-70	Orangey-brown loamy sand, some large stones to 5cm otherwise stoneless, some areas dark grey with orange mottles, sandier with depth.
	70-90	Orangey sand, very soft, almost stoneless, some rare clayey inclusions.
	90-	Gravely, coarse pale orange sand, very wet at base. Coring ceased 120cm
3		TG 40150 21332 Arable field winter sown cereal. Intermediate between **Aylsham and Sustead Series,** stonier.
	0-45	Mid-grey brown sandy silt loam, occasional gravel and small stones to 1cm, drier with depth and becoming sandier.
	45-75	Grey-brown silty fine sand, substantial orange mottling.
	75-	Saturated. Pale orangey coarse sand with fine gravel and some clay, significant mottling. Coring ceased 110cm
4		TG 40158 21316 Grassland permanent pasture. Intermediate **Sustead** with base of grey alluvium from the **Newchurch Series.**
	0-30	Mid-grey brown sandy silt loam, occasional gravel and small stones to 1cm.
	30-80	Pale grey silty sand with strong orange mottling. Slightly stony with some large stones, quite wet. Grading to pale browny grey coarse sand with variable but less silt, with strong orangey mottling.
	80-90	Pale orangey coarse sand with fine gravel, saturated.
	90-	Grey, firm, sandy clayey silt. Strong orange mottling. Varied from soft to stiff. Coring ceased 110cm.

5		TG 40174 21297. Rush pasture 5m from dyke edge. **Fordham Series**.
	0-10	Pale grey silty fine sand with orange mottles. Possibly spread material from base of dyke?
	10-20	Black, fibrous loamy peaty layer, stoneless.
	20-40	Mid grey-brown silty sand with fine orange mottles associated with root runs.
	40-	Mid-pale grey sandy silt with clay in places and especially deeper, mostly stiff, orange mottles. Woody fragments at 100cm. Coring ceased 115cm
6		TG 40177 21286 in fen recovering from scrub clearance on Myhills Marsh, 3m from dyke edge. **Fordham Series**.
	0-17	Dark brown, sandy, humose loamy topsoil with abundant fresh roots.
	17-45	Grey with orange mottles, silty sand, rather dry.
	45-70	Grey sandy clayey silt with orange mottles and black organic inclusions.
	70-80	Grey sandy, silty clay with some fine gravel.
	80-	Pale grey, coarse sandy silt with some fine gravel, saturated, almost running sand. Coring ceased 110cm.
7		TG 40190 21273 in open base poor S27-M5 fen on Myhills Marsh. C. 10cm surface water. Very uneven surface. **Newchurch Series**, transitional to **Downholland Series.**
	0-10	Dark brown to black humose silty loam, many fresh fine fibrous roots.
	10-55	Brown, humose stoneless silty loam, anoxic smell, reed rhizomes.
	55-	Grey slightly sandy silty clay, often very stiff, rather bluish with depth. Sandy clay with stones around 80cm, saturated water table at 95cm, with gravel and small stones, hard to core. Reed rhizomes at 100cm. Coring ceased 110cm
8		TG 40195 21266. 5m from edge of pond in open base poor S27-M5 fen on Myhills Marsh. C. 10cm surface water. Very uneven surface. **Newchurch Series**, transitional to **Downholland Series.**
	0-10	Peaty loam topsoil, many reed rhizomes.
	10-	Grey slightly sandy silty clay, very stiff and in places felt dry. 0.75-0.90 layer of gravel and small stones within. Coring ceased at 90cm
Catfield Dyke Side		
9		TG 40133 21670 Grassland, near to track. Horse-grazed pasture. **Aylsham Series**.
	0-40	Dark brown fine sandy loam, stoneless, gradual transition to:

	40-50	Mid-light brown, silty sandy loam, faint orange mottles.
	50-70	Pale brown sandy clayey loam with orange-brown mottles.
	70-	Pale grey-brown silty coarse sand with strong orange mottles. Becomes reddish-orange sand with depth with little silt or clay, saturated at 100cm and very loose. Becoming gritty with fine gravel at 125cm. Coring ceased at 125cm.
10		TG 40154 21740. Grass pasture. **Sustead Series**.
	0-40	Dark brown sandy silty loam, sparsely stony and very moist, becoming more silty at 30cm and with faint orange mottles at 35cm.
	40-60	Light grey-brown silty coarse sand with frequent fine gravel, frequent small orange mottles.
	60-90	Pale grey clayey coarse sand, with fine gravel, becoming coarser sand with more gravel at depth. Strong orange mottles, very wet to saturated at 70cm.
	90-	Pale grey coarse sandy clay, very stiff strong orange mottling, gritty with gravel. Coring ceased at 120cm.
11		TG 40167 21744. Young alder at pole stage. 5m from catch dyke. Water table at 5cm. Series not determined.
	0-20	Dark brown humose silty sandy loam.
	20-50	Mid-brown sandy silty clay with occasional fine gravel. Frequent orange mottling. Becoming more gravelly with depth.
	50--	Two layers in four alternating bands, with diffuse boundaries, of: • Pale browny orange silty coarse sand with gravel. (50-60, 70-90) • Pale grey brown coarse sandy clay, very stiff, with orange mottles (60-70, 90-) Coring ceased at 110cm
12		TG 401158 21762 Fen side of catch dyke, dyke edge 5m, slight slope away from catch dyke spoil bank. Reed-*Calamagrostis* mix. Difficult to place; closest to **Newchurch Series** with humic top, transitional to **Downholland Series**.
	0-10	Humified peat with roots.
	10-20	Dark brown silty loam, very little sand.
	20-50	Pale browny-grey silt with fine sand, some orange mottling. Reed rhizomes.
	50-	Pale browny grey becoming grey with depth, fine sandy clay, increasingly stiff, black humose inclusions around roots and rhizomes. Orange mottles, declining with depth. Anoxic smell. Sand becoming coarser towards base, fine gravel at 80cm becoming denser to base.

		Coring ceased at 110cm.
13		TG 40172 21795 *Cladium* bed on flat, almost sumpy ground between catch dyke and Catfield dyke. Water table a few cm above ground. Closest to **Altcar Series** but essentially fresh peat over marine alluvium.
	0-55	Dark brown, loose, fresh peat, fibrous with undecomposed plant remains, fully saturated.
	55-	Grey stoneless sandy clay with many fine roots and reed rhizomes. Some blackish humose inclusions around roots. Coarser sand with gravel at depth. Coring ceased at 105cm.

SITE: Limpenhoe Meadows DATE: 14.03.13 RECORDER: Mike Harding, Alix Pitcher

CORE	DEPTH (cm)	DETAILS
Transect 1		
1		TG 39955 3570. Dry heathy pasture, top of hill. **Newport Series**
	0-30	Dark brown, slightly loamy coarse sand top soil with many stones from fine gravel to stones 3-4cm. Very hard to core.
	30-	Orangey-brown coarse sand and gravel with large stones up to 6cm. Becoming impenetrable. Coring ceased at 60cm.
2		TG 39871 03464 Dry grass on steep slopes. Opposite reservoir. **Newport Series**
	0-35	Mid-brown clayey sandy loam. Coarse sand, some gravel and stones to 2cm, becoming more clayey with depth
	35-	Light to mid-brown slightly orangey, fine sandy clay, with pale yellow-grey marl-like inclusions. Rare small stones increasing frequency with depth. Stiffness increasing with depth. Coring ceased at 115cm.
3		TG 39838 03388. Grassland on lower slopes. **Quorndon Series**
	0-40	Dark brown clayey fine sandy loam.
	40-55	Mid-yellowy brown, silty coarse sand. Infrequent and faint orange mottles. Becoming sandier with depth.
	55-100	Yellow-brown slightly silty fine sand, occasional small gravel, wetter and softer at depth as silt declines. Marked orange-brown mottling. Some large stones at depth, up to 5cm.
	100-	Orangey-brown fine to coarse sand with fine gravel, saturated, becoming running wet sand impossible to pick up. Coring ceased at 112cm
4		TG 39824 03364. Toe slope 10m from edge of catch dyke. **Fordham Series.**
	0-25	Dark browny-black, humose silty fine sandy loam, damp.
	25-45	Mid dark brown slightly clayey coarse sand, humose, increasingly damp, orange mottling. Water table at 45cm.
	45-85	Pale grey coarse sand, saturated, some small gravel up to 2cm, increasingly difficult to auger. Becoming stonier with depth with large stones. Occasional yellow-orange, diffuse mottling.
	85-	Grey coarse sandy clay, stiff, some fibrous plant material, some stones, becoming softer with depth. Occasional yellow-orange mottling.
5		TG 39809 03338. *Carex paniculata* swamp. Water table at surface. Linear feature – possibly an old (catch) dyke? **Altcar Series.**

	0-20	Dark brown largely humified peat with contemporary roots.
	20-190	Brown, semi-fibrous, peat, modest humification. Very soft and loose.
	190-	Black, humified, slightly granular peat with some fibrous and woody inclusions. Coring ceased at 235cm.
6		TG 39795 03327. M22 fen meadow. **Adventurers Series** but note comparatively shallow peat.
	0-55	Dark browny-black humified peat, slightly loamy, many fresh roots, becoming browner with depth, moist. Water table at 50cm.
	55-	Dark browny-grey silty clay, soft and buttery. Humose at top declining rapidly with depth. Stoneless but with some roots. Increasing difficult to pick up. Coring ceased at 230cm
7		TG 39735 03273. M22 fen meadow, closely grazed. **Adventurers Series,** perhaps less humified at depth than typical, with a thin mineral layer too indistinct for Prickwillow Series. It could represent a sediment layer in an old peat pit.
	0-45	Dark brown, loamy humified peat, fibrous with fresh roots.
	45-50	Dark browny-grey humic clay. Water table at 50cm. Very soft and buttery.
	50-	Dark brown, semi-humified silty peat, soft and buttery, structureless and getting sloppy with depth. Coring ceased at 235cm.
8		TG 39688 03184. MG10 rush pasture. Closest to a **peaty Downholland Series.**
	0-25	Water table +/- at surface. Dark blackish brown humified peat, slightly loamy, with fresh roots.
	25-	Mid browny-grey silty clay, very soft with plant remains. Very faint orange-brown mottling. Coring ceased at 230cm.
Transect 2		
9		TG 39946 03252. M22, Water table +/- at the surface. **Altcar Series**
	0-20	Dark brown, humified loamy peat, stoneless, many fibrous roots.
	20-	Mid-dark brown semi-fibrous, semi-humified wet peat becoming wholly fibrous brown peat with depth, mostly "brown moss" peat. Very soft and saturated and very difficult to pick up at depth. Coring ceased at 235cm.
10		TG 39919 03208. Mapped as M13 in NVC survey? WT at surface. Not quaking. **Ousby Series**
	0-60	Dark brown fibrous fresh peat, quite firm, apparently "brown moss" peat.

	60-70	Grey-brown, fibrous silty peat.
	70-	Dark brown fibrous fresh peat, quite firm, apparently "brown moss" peat. Wholly saturated, very loose and difficult to pick up. Coring ceased at 235cm.
11		TG 39891 03167. M24/*Sphagnum*. WT at surface. **Ousby Series**
	0-70	Dark brown fibrous peat, occasional siltiness, slightly humified.
	70-	Mid to pale brown fibrous peat, very sloppy often semi-liquid. Coring ceased at 235cm.
12		TG 39855 03101 M22? WT 5cm below surface. **Altcar Series**
	0-20	Dark brown slightly silty, slightly humified peat.
	20-100	Dark brown fresh peat only slightly humified.
	100-	Mid-light brown very soft fibrous fresh peat, very sloppy and semi-liquid.
13		TG 39983 03306 Grass Upland slope. **Newport Series**
	0-95	Light brown slightly loamy fine sand. Some small stones. Siltier with depth.
	95-	Orangey-brown soft sand, very little silt.
14		TG 40007 03356 Sandy grassland. **Newport Series**
	0-30	Mid-brown loamy fine sand with frequent small gravel plus some large stones 2-3cm.
	30-70	Orangey-brown slightly silty coarse sand. Some clayey layers with silt and clay components very variable with depth. Generally very soft material.
	70-80	Orangey brown stiff fine sandy clay.
	80-	Yellowy orange-brown soft fine sand. Coring ceased at 120cm.

SITE: Decoy Carr Acle DATE: 17 March 2014 RECORDER: Mike Harding, Alix Pitcher

CORE	DEPTH	DETAILS
Transect 1: North Slope		
1		TG 40679 09786 Grass field, ex-arable. Closest to **Burlingham Series**.
	0-35	Mid-brown slightly grey silty fine sandy loam, some small stones up to 2cm.
	35-	Pale orangey-brown sandy clay with occasional stones, becoming stonier with depth, very stiff. Coring ceased at 100cm.
2		TG 40707 09706. Sheep grazed ex-arable field. Between **Burlingham** and **Wick Series**
	0-35	Mid-brown, silty fine sandy loam.
	35-50	Orange-pale browny grey fine sandy clay.
	50-65	Orangey-yellow fine-coarse soft sand, slightly silty, some small gravel and stones.
	65-	Orange-pale browny grey fine sandy clay, as 30-50, some large stones and becoming very hard to core with depth. Coring ceased at 100cm.
		Probably the same sub-soil but with a bed of soft sand at 50-65cm.
3		TG 40743 09565. In alder scrub. Difficult to determine, closest to **Wickmere Series**.
	0-30	Mid-dark brown clayey silt loam, some fine sand. Some bits of fine charcoal. Becoming clayey with depth.
	30-45	Mid grey-brown clayey fine sand with some browny-orange mottles and some yellow-grey inclusions.
	45-	Orangey yellow clayey fine sand, faint mottling, clay declining with depth. Some large stones and gravel, increasing with depth. Becoming quite hard to core at depth. Coring ceased at 70cm.
4		TG 40728 09548. Alder woodland. Difficult to place closest to a rather clayey **Quorndon Series**
	0-25	Dark browny black humic fine sandy loamy clay.
	25-45	Pale greyish brown sandy clay with orangey brown mottles. Becoming greyer with depth, increasingly stiff.
	45-65	Greyish, very pale brown clayey fine sand, some orange brown mottling. Occasional small stones. Becoming moister with depth.
	65-70	Grey-brown slightly silty coarse sand with dense orange mottling. Saturated, difficult to pick up. Some fine gravel.
	70-	Bluey-grey, sandy clay, very stiff, some gravel. Becoming softer after 100cm, with coarse sand. Coring ceased at 110cm.

5		TG 40687 09436. Water table at 45cm. **Altcar Series**
	0-45	Dark brown fine sandy loamy, humified peat. Some marked sandy and clayey inclusions. Fresh roots.
	45-	Dark brown fibrous peat, fresh and unhumified. Mostly moss peat in the upper layers with a little reed rhizome. Very wet, soft, loose and difficult to pick up with depth, more grass and sedge peat below 100cm. Coring ceased at 230cm.
6		TG 40713 09389 Fen WT -20cm. **Altcar Series**
	0-20	Black humified peat, silty and very wet, almost gel like in consistency.
	20-135	Dark brown fibrous moss peat , minor humification, snail shells frequent, reed rhizomes. Soft and sloppy after 50cm but becoming firm again.
	135-	Brown moss and sedge, grass peat, very fibrous, no humification. No shells. Becoming very wet, structureless and sloppy, very difficult to pick up. Coring ceased at 230cm
Transect 2: West Slope		
7		TG 40036 09445 Arable. **Wick Series.**
	0-30	Mid to dark brown silty clayey loam. Some small gravel, becoming sandier with depth.
	30-60	Mid to light brown fine sandy silty loam. Becoming sandier, moister and more orange with depth.
	60-80	Light orange brown very fine sandy clay, Stiff. Becoming coarse sandy with depth, more orangey and with some larger stones.
	80-	Orangey slightly clayey coarse sand, soft, some stones 2-3cm. Coring ceased at 100cm.
8		TG 40267 09339. Arable. Difficult to place; **Ashley Series**.
	0-25	Mid-brown fine sandy clayey loam, occasional small stones.
	25-65	Pale brown, fine sandy clay, some small stones, stiff.
	65-85	Pale grey brown slightly sandy clay with small orange mottles, mottling becoming stronger with depth. Clay is very stiff. Sand becoming finer with depth.
	85-	Pale grey-brown coarse sandy clay, very stiff, strongly mottled, becoming coarser with depth. Coring ceased at 120cm.
9		TG 40361 09314. Grass margin near catch dyke. **Quorndon Series**, rather clayey.
	0-30	Dark brown, fine sandy clayey loam. Stoneless.
	30-75	Mid-brown sandy clay, stiff. Frequent orange mottles, softer and wetter with depth. Becoming pale grey-brown at depth, sandier.

	75-	Mid to pale brown slightly silty coarse sand, many stones, saturated, faintly mottled, becoming very gravelly. Coring ceased at 105cm.
10		TG 40450 09217 Carr woodland, WT 10cm below surface. **Altcar Series**
	0-25cm	Dark browny black loamy humified peat, very moist.
	25-100	Mid reddy-brown fibrous peat, slightly humified mossy peat, some reed rhizomes. Becoming sloppy and difficult to pick up with depth.
	100-230	Dark greyish brown clayey peat. Very fibrous sedge and reed peat.
	230-	Grey silty clay, very wet and loose, difficult to pick up.
11		TG 40682 09211 M22 WT at surface. **Altcar Series**
	0-60	Dark brown slightly silty humified peat. One layer (c.5cm thick) of fine silty clay within the peat, at about 30cm.
	60-180	Very soft wet sloppy but fibrous peat, very difficult to pick up.
	180-	Mid grey silty clay, very soft and structureless, saturated, stoneless. Coring ceased at 235cm.

SITE: Ebb and Flow **DATE:** 18 March 2014 **RECORDER:** Mike Harding, Alix Pitcher

CORE	DEPTH	DETAILS
Transect		
1		TG 36065, 16847. Arable field. Rather clayey **Wick Series.**
	0 - 30	Light to mid-brown, fine sandy loam. Few small stones. Becoming clayey at depth.
	30 - 70	Mid orange brown, sandy clay, slightly loamy. Stones 1 – 2 cm. Firm, getting more clayey with depth, stiffer.
	70-	Yellowy orange brown stiff sandy clay with frequent stones to 2cm. coring stopped 95cm
2		TG 36081, 16606. Bare arable crust with stones. **Newport Series.**
	0 - 30	Mid-light brown fine sandy loam, some gravel 1-2cm
	30 - 50	Orange yellow brown soft medium sand with occasional 1 – 2cm stones and much gravel with depth. Becoming reddish orange.
	50 - 70	Orangey brown coarse sand with gravel, becoming softer with depth, more stones
	70 -85	Yellow orange brown sandy clay with occasional gravel, stiff to very stiff
	85-	Orangey yellow brown slightly clayey sand. Stoneless, sandier with depth, becoming brighter orange, soft. Coring stopped at 100cm
3		TG 36100, 16473, arable field, same as above. **Newport Series**
	0 – 40	Mid brown, slightly silty medium sand, becoming loamier with depth.
	40 - 65	Slightly yellowy mid brown coarse slightly clayey sand with some small gravel
	65 - 80	Slightly orangey brown soft coarse sand, slightly silty, occasional small stones, some large, up to 5cm. Structureless. Silt decreases with depth.
	80 - 105	Coarse orangey brown sand with stones, up to 3cm. Very weak and soft. Coring stopped at 105m.
4		TG 36121, 16368, grass margin, 10m wide. **Aylsham Series**
	0 - 45	Mid brown sandy, slightly clayey loam. Stoneless. Damper with depth
	45 - 75	Slightly orangey mid-brown clayey fine sand. Occasional small stones. Small orangey-brown mottles.
	75 - 95	Grey to pale brown medium sandy clay, soft and moist, frequent small orangey brown mottles. Becoming clayey sand, paler grey-brown with depth, still mottled. Clay declining with depth, sand becoming orangey grey.
	95-	Pale grey orange, soft silty fine sand. Mottled, diffuse. Coring ends

		115cm
5		TG 36070, 16358 mixed reed fen. **Altcar Series**, but peat very shallow.
	0 - 20	Humified loamy peat with reed rhizomes, dark brown, WT at 10cm
	20 - 40	Semi-humified dark brown peat, fibrous including fresh roots, firm
	40 -	Stiff grey clay, firm, wet, reed rhizomes, some black organic material. Some browny mottling around roots. Stoneless. Becoming stiffer and drier with depth – silty clay. Coring ends 100cm.
6		TG 36064, 16313 mixed reed fen**. Ousby Series,** again shallow profile.
	0 - 60	Fresh peat, moderately humified, lots of fresh roots, soft, difficult to pick up. WT at surface
	60 -	Grey clay, soft and buttery, silty, difficult to pick up, stoneless. Coring ends at 110xm
7		TG 36058, 16257 Fen. **Altcar Series.**
	0 - 50	Dark brown / black humified loamy peat, some fresh roots. Quite silty. Reed rhizomes
	50 – 120	Mid – dark brown firm fibrous peat with reed rhizomes, sloppy and difficult to pick up with depth.
	120 –	Grey, silty, stoneless soft clay, very wet and weak. Coring stopped at 120cm