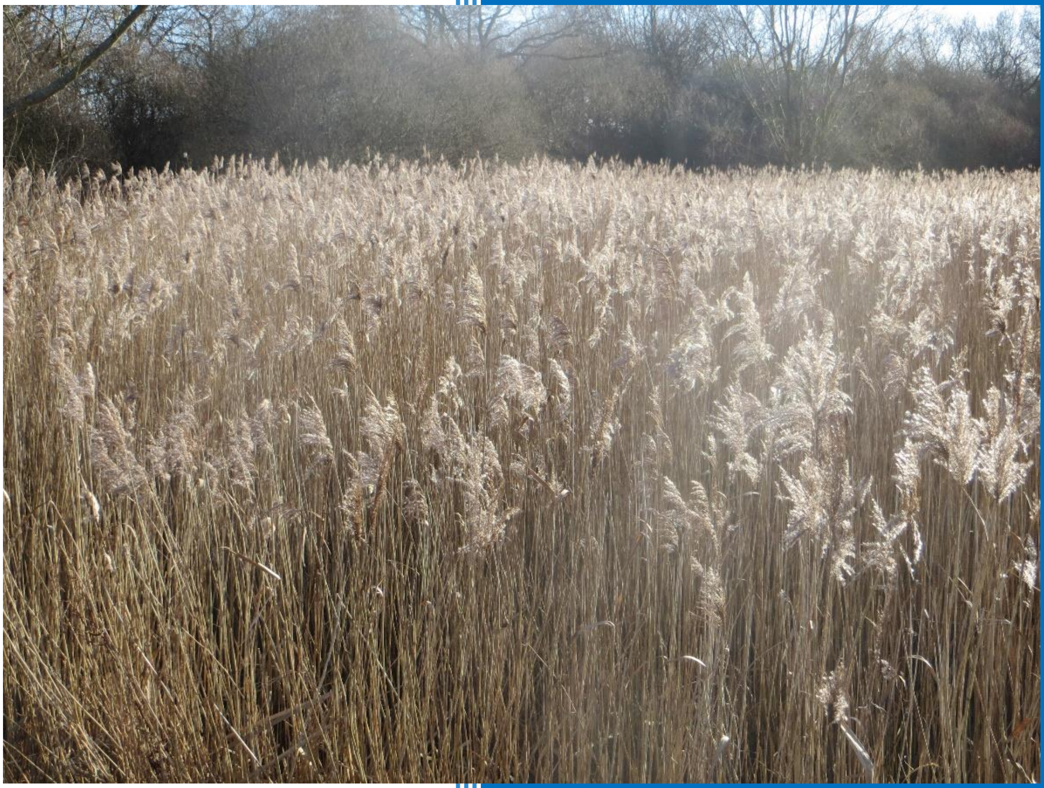
Darlow’s Farm

Wetland feasibility, design and creation – Phase 1



Prepared for the

Lincolnshire Wildlife Trust and

Fens East Peat Partnership

12/6/2024

PR168/R1.1B

Quality control

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Document history

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Contents

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1 Introduction

1.1 Background

The Fens East Peat Partnership (FEPP) have been awarded funding through the Nature for Climate Peatland Discovery Grant Scheme (NCPDGS), which is managed by Natural England (NE). The funds are intended to be used to undertake preliminary investigative works to explore and identify solutions to address the barriers to peatland restoration.

The objectives of the NCPDGS are to:

- reduce emissions from peat by 5.7 megatonnes of carbon dioxide equivalents cumulatively by 2050;
- establish the process of restoring 35,000 hectares of degraded peat in England by March 2025; and
- provide wider benefits such as improved ecosystems and biodiversity, better water quality, natural flood management, protection of historic environment features, and connecting people with nature.

Designated as a Site of Special Scientific Interest (SSSI) in 1985, Woodwalton Fen supports a range of wetland plant communities characteristic of once extensive areas of the Cambridgeshire, Suffolk and Norfolk fens but now confined to a few sites. Covering 208 hectares. The site has also been designated as a Wetland of International Importance (Ramsar site), a National Nature Reserve (NNR) and a Special Area of Conservation (SAC). Since 2002, efforts have been made through the Great Fen project to consider fen restoration at a large scale and link Woodwalton Fen NNR with the nearby Holme Fen NNR, which is approximately 2.5km to the Northeast, through habitat restoration efforts across an extensive area of degraded peatland.

Based on the latest condition assessment, almost 45% of the NNR is classed as 'unfavourable – declining'. One of the key pressures on the condition of the site, and on the ditch plant communities in particular, is the poor water quality entering the site from the surrounding catchment including the Great Raveley drain. Water quality challenges arise both from chronically polluted continuous inflows and as a result of episodic flood events when the site acts as a flood storage area.

Water transfers to the site from Great Raveley Drain and direct precipitation form the primary water sources for the site. Transfers from the drain are primarily in the summer and early autumn when there is a rainfall deficit and water level management on the site requires an additional water supply to maintain the appropriate eco-hydrological conditions. Whilst the water quality in the drain has shown signs of improvement in recent years, the nutrient levels, and total phosphorus in particular, are still relatively high compared to natural conditions, placing sensitive ecological receptors at risk.

FEPP are interested in evaluating the potential for restoring a dedicated area of degraded peatland to the north of the NNR on Darlow's Farm (Figure 1). This opportunity should not only look to restore the degraded peatland but also needs to consider the creation of a new wetland to provide wider water quality benefits. The design of the new wetland would need to focus on the potential to reduce nutrients as well as its hydrological functioning during times of rainfall deficit so as to maintained the restored peatland.

1.2 Project specification

The specific aims of the project, as set out in the invitation to tender document, are to:

- Review the existing data available and obtain further if necessary.
- Review past reports and on-line databases and assessment systems to understand the context of Woodwalton Fen, its eco-hydrological functioning and pressures, especially water quality issues to define a conceptual model of the site and its surroundings.
- Assess the proposed option as currently developed and determine of it will work for the intended function, including success evaluation criteria or consider other areas of restoration land if necessary.
- Design a wetland system (possibly a Typha bed) to meet the desired function – this may include but not limited to ascertaining the size of wetland needed relative to the estimated water usage, design of system, provision of water storage on site for drier times of year, beds of suitable wetland plant to strip nutrients (including landscaping), interconnection of waterways that transfer water into and out of the fen, any additional sluices needed to hold water in the area, pumps to transfer the water into the adjoining Woodwalton Fen, any new ditches required to enable the required water movements. The design should aim to complement the restoration plan for the rest of the new Speechly's land area.
- Review likely sustainability under climate change.
- Provide detailed final design, considering any constraints identified during the study.
- Identify the relevant permissions and consents that will be required in order the for the restoration work to take place.
- Provide costed designs of work ready for Natural England to put out to tender for delivery by mid Feb 2024 - with detailed specifications of work involved to deliver and should include;
- All necessary documentation to be compliant with CDM legislation.
- Undertake detailed design and produce drawings of the works.
- Include details of plans for dealing with all waste materials generated by the scheme.
- Take full account of protected species occurring on site – particularly water vole so that suitable habitat is incorporated into final design.
- Identify any potential legacy issues (such as who will take responsibility for maintenance of engineered structures) or requirements for statutory permissions.
- Recommend any future monitoring or data collection needed to achieve the require performance of the systems and evaluate its success

Further to discussions with FEPP, the specification described above has been divided into two phases. Phase 1 of the work, reported on herein, addresses the following elements:

- Initial start-up meeting
- Desk-based data review
- Initial site visit
- Field investigations and data verification
- Ecohydrological conceptualisation
- Concept design development
- Reporting
- Review meeting with the client

Following the completion of the work described in this report, and reviewed with the client, it is possible that a more detailed and costed design will be provided for the peatland to be restored.

2 Desk and field data review

2.1 Introduction

Woodwalton Fen NNR (TL229845) is approximately 13km south-east of Peterborough and 5km west of Ramsey. The NNR is a rare and isolated remnant of once extensive fenland habitat lying at the lowest, most westerly point of the East Anglian fens. Originally, the site was part of a raised bog that was dug for peat in the 19th Century, removing the acidic peat and exposing the underlying fen peat (Godwin and Clifford, 1938). The communities present today reflect this historical change.

The NNR covers approximately 210ha (Figure 1) and holds multiple designations. The condition of more than 60% of the site is considered to be unfavourable and less than 15% of the features have been assessed as being in favourable status. One of the main reasons for the adverse conditions at the site is considered to be poor water quality resulting from pollution from the influent water sources.

Woodwalton Fen lies within the larger Great Fen Project area (Figure 1. Location map.Figure 1) (Mountford et al., 2002). The Great Fen project commenced in the early 2000s with a vision to create a more sustainable future for the area and the restoration of habitats within a 14 square mile area of the former fens. Specific objectives included the connection of Woodwalton Fen with Holme Fen to the east; the creation of an extensive mosaic of wetland habitats that will support a variety of wetland plants and wildlife; and the delivery of a protected area resilient to disturbance. Natural England have been progressively purchasing land contiguous with Woodwalton Fen since the early 2000s as a component of the wider Great Fen Project. Land purchase includes Darlow's Farm, which wraps around the north-west boundary of the NNR (Figure 1). Since 2002, this area of former arable land has undergone a gradual process of restoration to wet grassland through a change of land management and a raising of water levels in the ditches.

Much of the Great Fen Project area is underlain by degraded peat deposits. In 2021, the UK Government announced the NCPDGS. The objectives of the scheme are to reduce emissions from peat; set in train the process of peatland restoration; and provide wider societal benefits. Funding for this project is being delivered through the overall NCPDGS. Therefore, the desk and field data review has focussed on both the potential to stem peat degradation and to catalyse peatland restoration whilst also creating an area of wetland which has the potential to improve the water quality entering Woodwalton Fen.

2.2 Context

The hydrology of Woodwalton Fen is dependent on inputs from direct rainfall and abstraction from the adjacent Great Raveley Drain. Historically, the water quality in the Drain was characterised by relatively high levels of nutrients, with phosphate (PO_4) values in excess of 5mg/l being recorded in the 1970s (APEM, 2017). Whilst the water quality in the drain has improved over recent decades (see section 2.3), concerns remain that transfer of water from Great Raveley Drain into Woodwalton Fen are resulting in an ongoing degradation of the ecology of the site.

The purchase of Darlow's Farm provides the dual opportunity to restore an area of peatland and by doing so to create a dedicated 'treatment' wetland to improve the quality of water abstracted from Great Raveley Drain. In this report, the objective is to address the project specification as set out in section 1 and to inform the feasibility, ecohydrological conceptualisation and design of a proposed area of restored peatland as a 'treatment' wetland at Darlow's Farm.

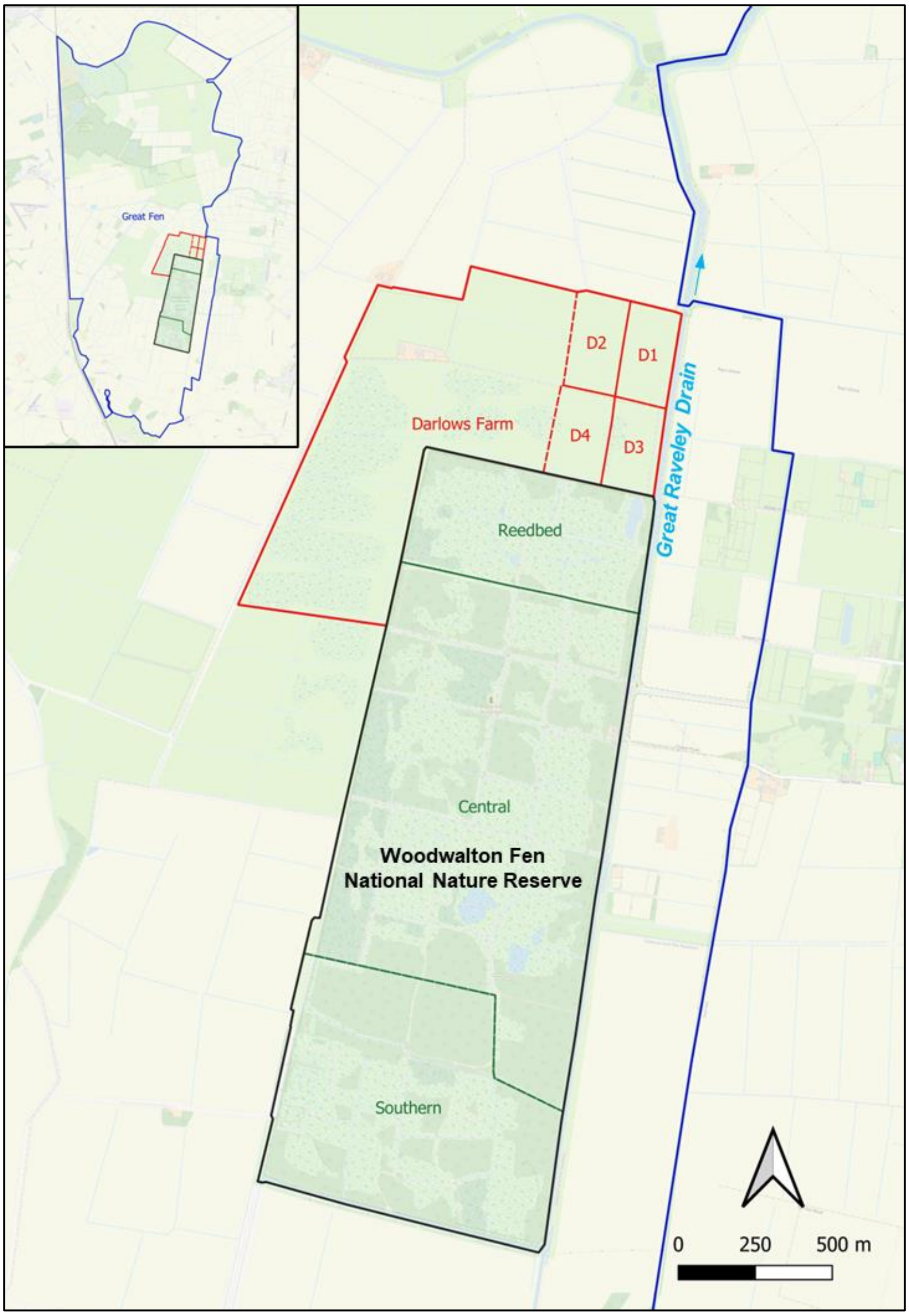

Figure 1. Location map. (Great Fen Project boundary in blue (inset); Woodwalton Fen NNR boundary in dark green; Darlow's Farm boundary in red. Darlow's compartments D1 to D4).

2.3 Topography

Woodwalton Fen and the contiguous Darlow's fields occupy a relatively low-lying area at the southwestern edge of the wider fenland (Figure 2). As an artefact of historical land use in the area, the ground surface in Woodwalton Fen is elevated by between 1.25 and 2.0m in comparison to the adjacent landscape, with ground surface levels generally being between 0.00 and -0.50mAOD. At nearby Holme Fen, metal posts sunk into the peat in 1851 suggest soil wastage since then has been about 4 m (Fillenham, 1963). The four compartments of Darlow's immediate to the north of Woodwalton Fen are approximately 1.25m lower in elevation than the NNR with ground levels generally being between -1.00 and -1.70mAOD (Figure 3). Moving water from Darlow's into Woodwalton Fen would therefore be against the current gradient and not possible by a gravity feed; it would require pumping using wind or solar pumps or a combination. The four Darlow's compartments (D1 to D4, Figure 1) are all bounded by ditches. The bed level of the ditches is characteristically up to 1.0m below the adjacent ground levels.

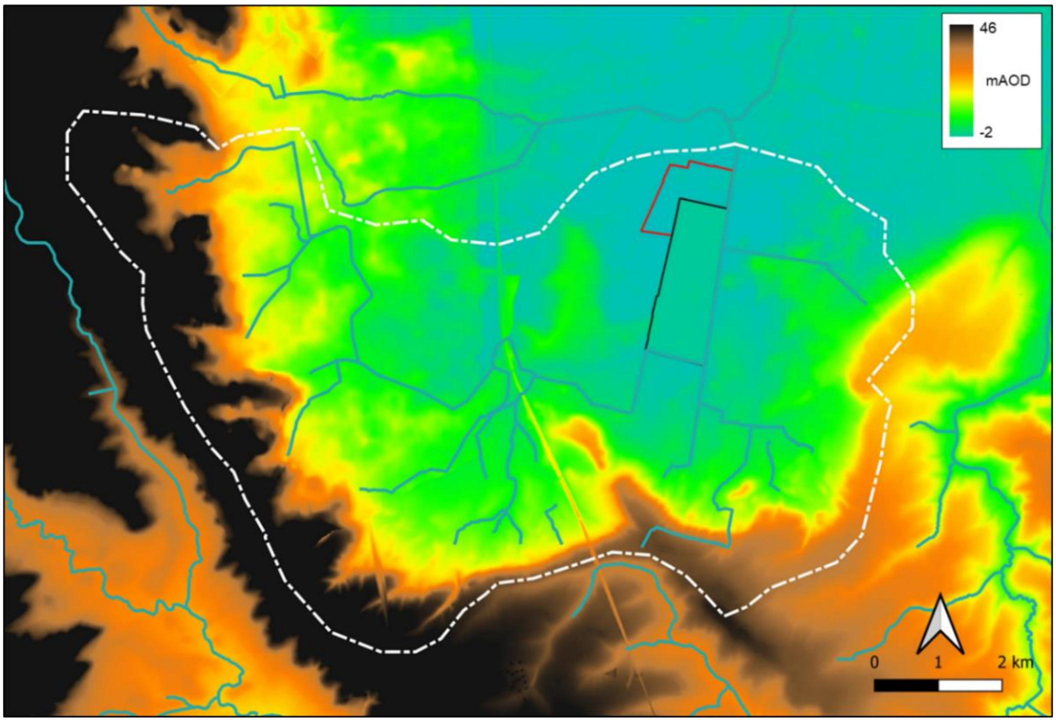

Figure 2. Surface topography around Woodwalton Fen.

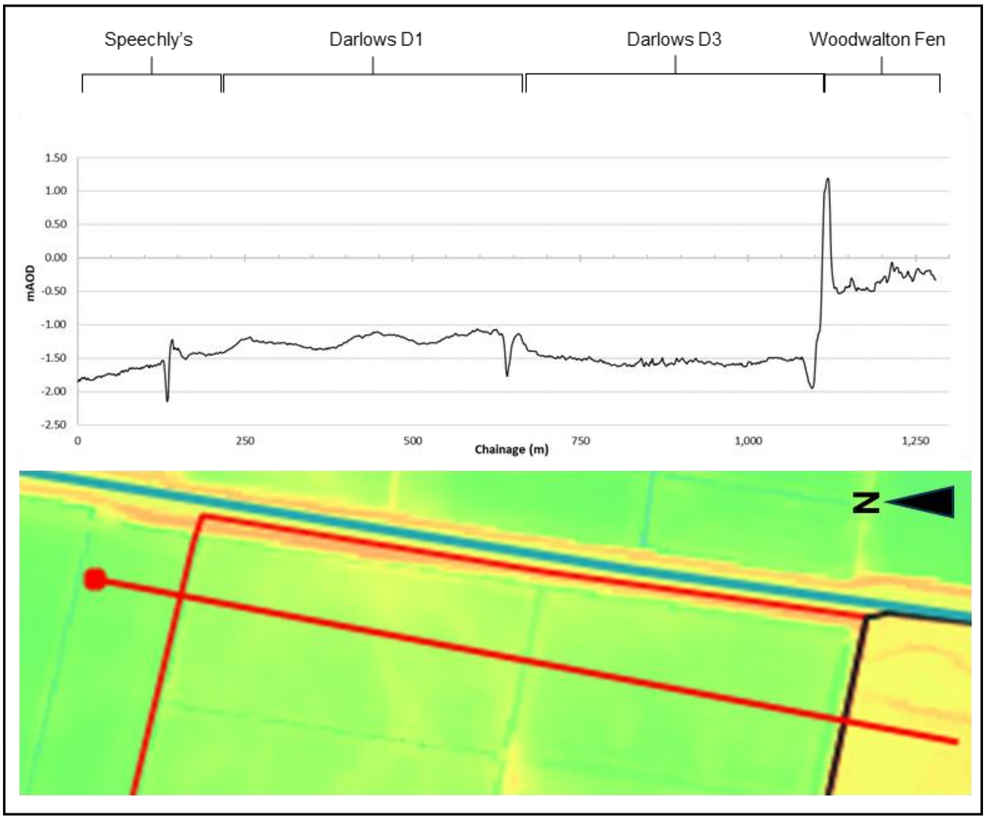

Figure 3. Cross section through the topography of Darlow's and Woodwalton Fen.

2.4 Soils

The area around Woodwalton Fen and Darlow's is underlain by Oxford Clay. Historically, peat has developed over the impermeable Oxford Clay. The surface of the basal clay layer is not uniform and reflects historic palaeoenvironments and the slow evolution of the Fenland landscape (Hall, 1992).

Numerous investigations have assessed the soils in the vicinity of Woodwalton Fen. Peat depths and condition have been assessed by various observers. Surveys conducted by N. A. Duncan in 2002 suggest that the peat depths across Darlows vary from approximately 0.5m in the south-western corner of compartment D4 to in excess of 1.7m in the north-eastern corner of compartment D1. The depth to the surface of the Oxford Clay was assessed by OHES Environmental in 2023 was greater than 2.0m across all four compartments at Darlow's.

Field observations conducted through hand-augering have verified the results of previous soil investigations. The soils in Darlow's are all characterised by an upper, degraded peat ploughed horizon extending some 0.5m below ground level. This ploughed layer, an artefact of historical arable practices, is underlain by an earthy, partly degraded layer of peat that demonstrates evidence of drainage and oxidation. This layer can extend to below 0.7m below the ground surface. Below 0.7 to 1.0m, the peat remains relatively undegraded and intact.

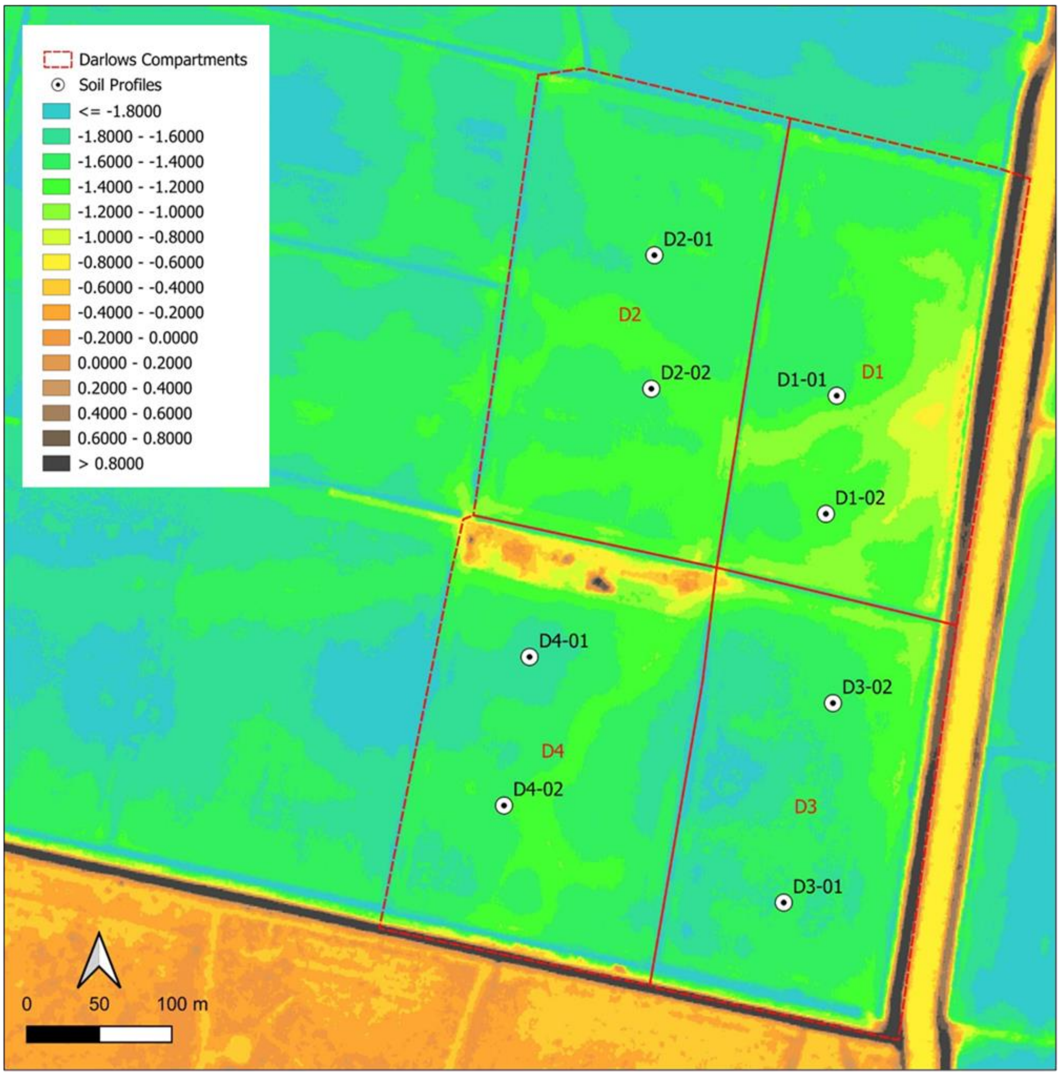

Figure 4. Soil sampling locations.

Soil samples were collected from eight locations across Darlow's, two in each compartment (Figure 4). Sampling locations were selected based on the presence of a relatively uniform vegetation community and consistent topography. Composite samples across a depth range were collected from within the soil profile for laboratory analysis. The objective was to assess the soil chemistry and physical properties corresponding to the three different peat states: heavily degraded topsoil (TS) (0-0.25m), partly degraded subsoil (SS) (0.25-0.5m) and relatively intact peat (IP) (0.5-1.0m). Samples were collected and refrigerated until receipt by the laboratory for analysis. The objective of the soil analysis was to understand the potential risk of releasing phosphorus from rewetting the soils, to understand potential toxicity associated with iron release and also to provide an insight into the relative change in greenhouse gas emissions to infer the net radiative forcing and the impact on climate change of proposed changes. The following parameters were analysed: organic matter through loss on ignition (LOI) (%), bulk density (g/l), total iron (Fe) (mg/kg), total aluminium (Al) (mg/kg) and total phosphorus (P) (mg/kg) (Table 1Table 4).

Table 1.Soil analysis results.

Sample reference	Soil state	Average depth of sample (mBGL)	Ground-surface elevation (mAOD)	Organic Matter (LOI) (%)	Bulk Density (g/l)	Total Al (mg/kg)	Total P (mg/kg)	Total Fe (mg/kg)	Fe:P ratio
D1.01 A	TS	0.12	-1.52	16.20	772	29897	1010	28494	28.21
D1.01 B	SS	0.37	-1.77	6.00	832	24397	560	27694	49.45
D1.02 A	TS	0.12	-1.45	21.10	723	33797	1060	29294	27.64
D1.02 B	SS	0.37	-1.70	22.70	671	31697	1070	30094	28.13
D1.02 C	IP	0.65	-1.98	68.60	369	6237	427	23194	54.32
D2.01 A	TS	0.12	-1.57	26.10	639	30597	1070	27494	25.70
D2.01 B	SS	0.37	-1.82	28.80	631	35997	957	32494	33.95
D2.01 C	IP	0.70	-2.15	72.80			1111		
D2.02 A	TS	0.12	-1.55	26.10	651	28697	925	30694	33.18
D2.02 B	SS	0.37	-1.80	17.60	675	32097	726	35494	48.89
D3.01 A	TS	0.12	-1.74	30.20	612	37377	1310	30980	23.65
D3.01 B	SS	0.37	-1.99	29.80	564	42977	1310	31480	24.03
D3.01 C	IP	0.70	-2.32	68.40	406	8877	529	26980	51.00
D3.02 A	TS	0.12	-1.59	27.30	633	40677	1090	30180	27.69
D3.02 B	SS	0.37	-1.84	23.90	650	47577	980	32480	33.14
D3.02 C	IP	0.75	-2.22	73.00		3867	152	6400	42.11
D4.01 A	TS	0.12	-1.82	40.90	515	33077	1720	31980	18.59
D4.01 B	SS	0.37	-2.07	40.20	546	34077	1720	33180	19.29
D4.01 C	IP	0.65	-2.35	53.70	436	25177	1240	31380	25.31
D4.02 A	TS	0.12	-1.53	24.90	664	35377	1330	30980	23.29
D4.02 B	SS	0.37	-1.78	20.00	722	51777	1060	33080	31.21
D4.02 C	IP	0.70	-2.11	67.40	316	12477	351	32080	91.40

It has been recommended that 'peat' soils are defined as possessing greater than 30% organic matter (Joosten et al., 2017). By this definition, with the exception of D4.01 and D3.01, all of the TS and SS samples cannot be classified as peat. However, peat was proven at depth in all eight locations. The bulk density values are similar to those recorded for peat soils elsewhere in the East Anglian area where values between 337 and 1006g/l have been recorded (Evans et al., 2016).

Computation of Pearson correlation coefficient demonstrated that there was a strong significant negative correlation observed between organic matter content and the bulk density (r(19)=-.974, *p*<0.0001), with the percentage of organic matter increasing with depth (Figure 5). The organic matter content in the topsoil and subsoil samples was significantly correlated (r(5)=.836,*p*=0.038) but was considerably higher in the intact peat (Figure 5). This suggests that the upper 0.5m of the soils may well have been equally degraded due to historical agricultural practices such as drainage, ploughing and cultivation.

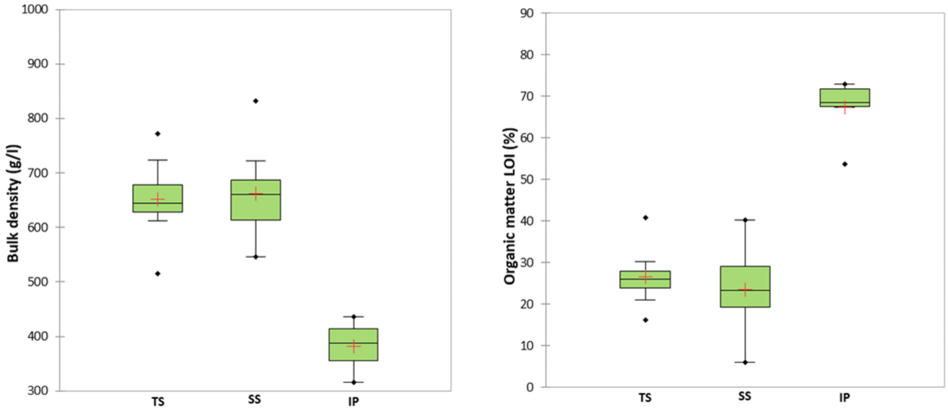

Figure 5. Bulk density and organic matter univariate plots. (See text for abbreviations).

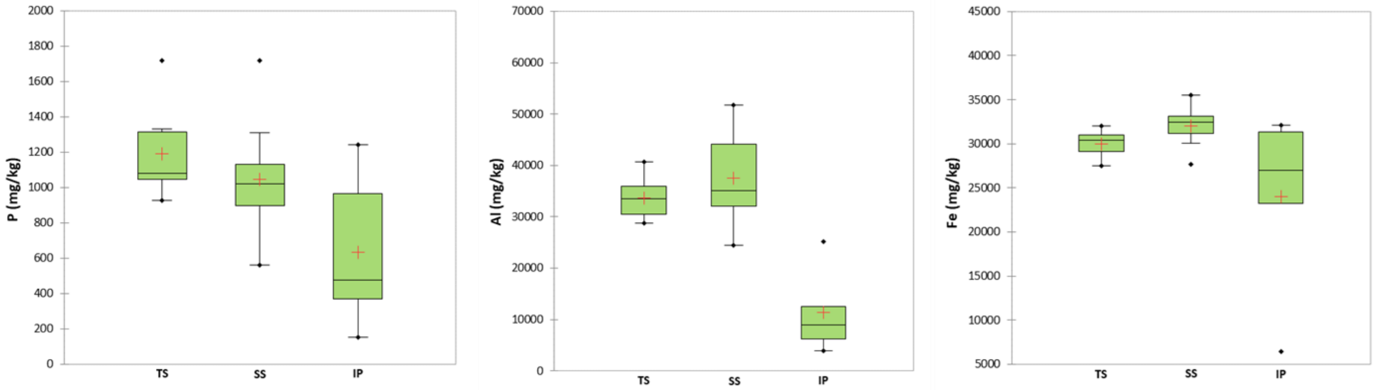

Figure 6. Total phosphorus, aluminium and iron univariate plots. (see text for abbreviations).

Total P decreases with depth in the soils. However, both Al and Fe demonstrate a marginal increase in the degraded subsoils in comparison to the topsoils (Figure 6). Values of Al and Fe are relatively lower in the intact peat (Figure 6). There is a significant positive correlation between Al and Fe (r(19)=.610, *p*=0.004) and P and Al (r(19)=.610, *p*=0.004). However, there is only weak positive correlation between Fe and P. The higher levels of Fe in the subsoils may be a result of oscillating redox conditions as the water table fluctuates through this part of the soil profile and the repeated transformation of ferric (Fe^{3+}) to ferrous (Fe^{2+}) iron and the reverse process increases the availability of iron in the subsoils.

Lucassen et al. (2000) demonstrated that drained fen peats, such as though at Darlow's, can potentially accumulate large amounts of oxidized iron in the aerobic topsoil. The rewetting of the peat soils can lead to high iron concentrations in the pore water. The transformation of Fe^{3+} to Fe^{2+} under anoxic conditions arising from rewetting can produce conditions that may be toxic for some rich fen species, especially bryophytes. The removal of topsoil has been advocated to reduce the potential toxicity of Fe, and other potentially negative impacts, from rewetting peat soils (Zak et al., 2017). An alternative restoration strategy would be to slowly raise water levels to between 0.2 and 0.4m below ground level (mBGL) and to avoid surface water flooding of the degraded peat surface.

The determination of Fe:P ratios in peat soils can be used as a predictive tool for the assessment of potential P fluxes in rewetted peats (Zak et al., 2010). Zak et al. (2010) indicate that if Fe:P ratios are low (<10) there is a greater potential risk of P release into pore waters, and subsequently surface waters, under flooded or anoxic conditions. Across all depths at Darlow's, the Fe:P ratios recorded at Darlow's were between 18.59 and 91.40 (Figure 7). The highest ratios were recorded in the intact peat as a result of relatively low levels of P. The lowest ratios are recorded in the upper soil profile. However, all of the values recorded are considered to be high (>10) and potentially represent a low risk of P release.

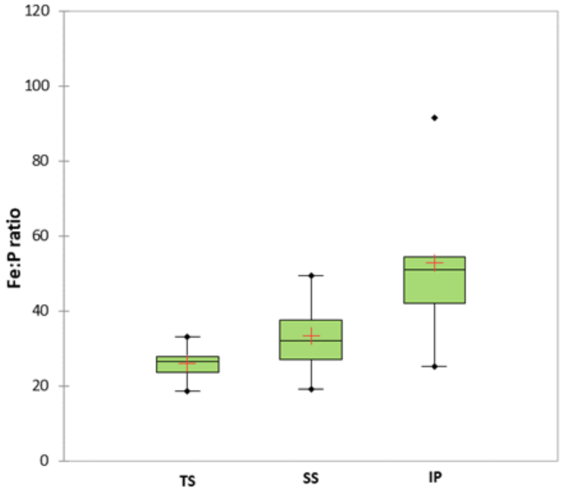

Figure 7. Fe:P ratios univariate plots. (See text for abbreviations).

It has been established from studies conducted in Germany and the Netherlands that following inundation and rewetting of the peat surface, reduction of oxidised soil complexes (such as iron(hydr)oxides) can not only influence nutrient availability, and particularly P, but emission of greenhouse gasses (methane (CH_4) and nitrous oxide (N_2O)) (Zak et al., 2018; Harpenslager et al. 2024). The relative change in fluxes of greenhouse gases (CO_2, CH_4 and N_2O) will vary over time and as a result of the peat restoration approach implemented (Zak and McInnes, 2022). The removal of the upper 0.4 to 0.5m of degraded peat would minimise increasing the emissions of greenhouse gases, through the flooding of the peat soils at Darlow's or through the creation of surface water wetland to treat water quality. Under a topsoil removal strategy, the relative atmospheric fluxes of CO_2, CH_4 and N_2O would revert to those associated with an intact, naturally functioning peatland, and a CO_2 sink, within 10 to 50 years. However, topsoil removal might be problematic, in terms of loss or remobilisation of carbon and disposal of the arisings.

An alternative strategy that might be feasible for peat restoration, but would not be appropriate for the establishment of a surface water treatment wetland, would be to slowly raise water levels over time (termed 'slow rewetting' by Zak and McInnes, 2022). Even though the analysis of the Fe:P ratios suggests that the risk of P remobilisation is low, slowly raising the water levels to between 0.4 and 0.2mBGL across the four compartments at Darlow's would reduce further the risk of P release and also the generation of CH_4. Furthermore, creating conditions where water levels remain a few decimetres below the current ground surface can generate redox conditions that are unfavourable for CH_4 production and will support the consumption of CH_4 by methanotrophic bacterial communities resulting in supressed methane emissions. If slow rewetting is conducted in combination with harvesting and removal of the existing biomass, the bioavailability of the labile nutrient pool present in the degraded peat soils will be reduced potentially resulting in the establishment of a more diverse rich-fen plant community.

2.5 Hydrology and water quality

Surface water hydrology

The surface water hydrology is dominated by a pump-drained network of ditches controlled by the Internal Drainage Boards (IDBs). Three IDBs (Sawtry IDB, Ramsey, Upwood and Great Raveley IDB and Woodwalton IDB) manage the surface water hydrology in the vicinity of the Great Raveley Drain and Darlow's (Figure 8). The drainage in the Great Raveley Drain is controlled by inputs from the west and south from the Sawtry IDB, from the east from the Ramsey, Upwood and Great Raveley IDB and to the north of Woodwalton Fen from the Woodwalton IDB. The drainage across this area is controlled by a series of pumps, sluices and other water control structures within the ditch network (Figure 9).

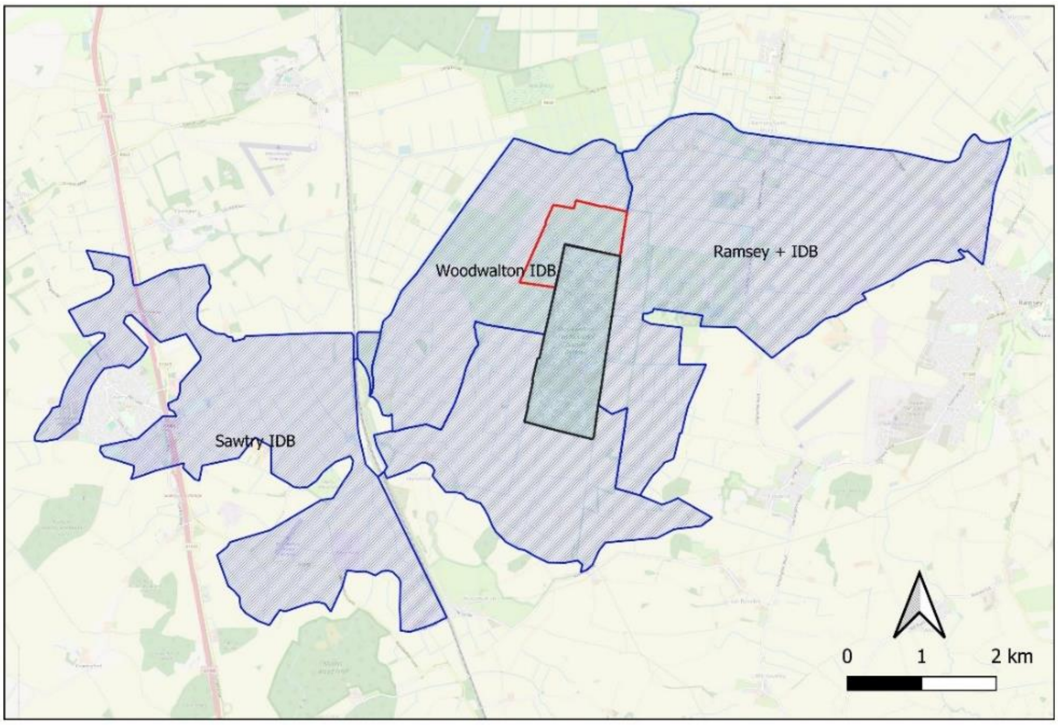

Figure 8. Internal Drainage Boards (IDB) in the vicinity of the study area.

The four Darlow's compartments are fed from an intake structure on the Great Raveley Drain (Figure 9). A pipe runs from the Drain through the embankment into a sump on Darlow's Farm about 1 km north of the bridge that provides access to the NNR. Abstraction is limited by the size (300mm diameter) of the pipe and water flow into the pipe is controlled by a penstock sluice located on the bank of the Drain. The inflow rate to Darlow's is currently managed by Natural England and licenced through an abstraction licence with the Environment Agency. The water entering Darlow's at this point flows to the east across the other Darlow's fields of the Great Fen area before reaching Speechley's Pumping Station (Figure 9).

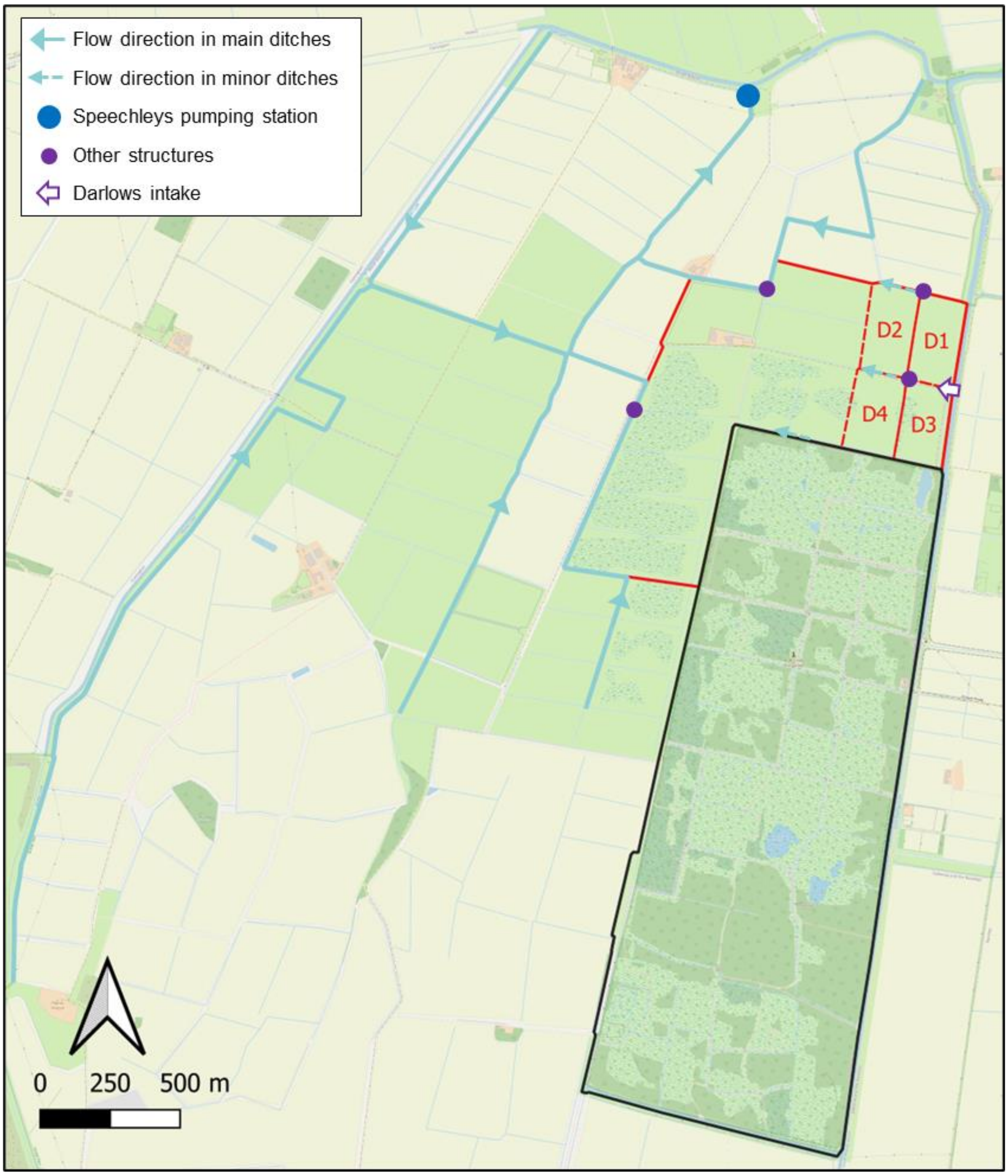

Figure 9. Surface drainage network in the vicinity of Darlow's.

Monthly minimum and maximum water level data were available for a gauge board next to the bridge at the entrance to Woodwalton Fen (Figure 10). The land around Woodwalton Fen is relatively flat and there was no appreciable slope on the water surface during the visit of 20 March 2024. Therefore, water level can be assumed to be broadly the same at the pipe intake to Darlow's as on the gauge board. This was confirmed by surveying and use of LiDAR data on the Drain water surface, the bridge and the embankment near the pipe inlet as a benchmarks. Water levels in the Drain were converted to head level above the pipe inlet using survey data collected on 20 March 2024. Importantly the water level did not fall below the pipe inlet level during the period of observation (2016-2024), which is estimated to be -0.85 mAOD (dotted line in Figure 10 and Figure 11) during the period of record, so there was always potential for flow in the pipe. This piped inlet would supply the dedicated 'treatment' wetland.

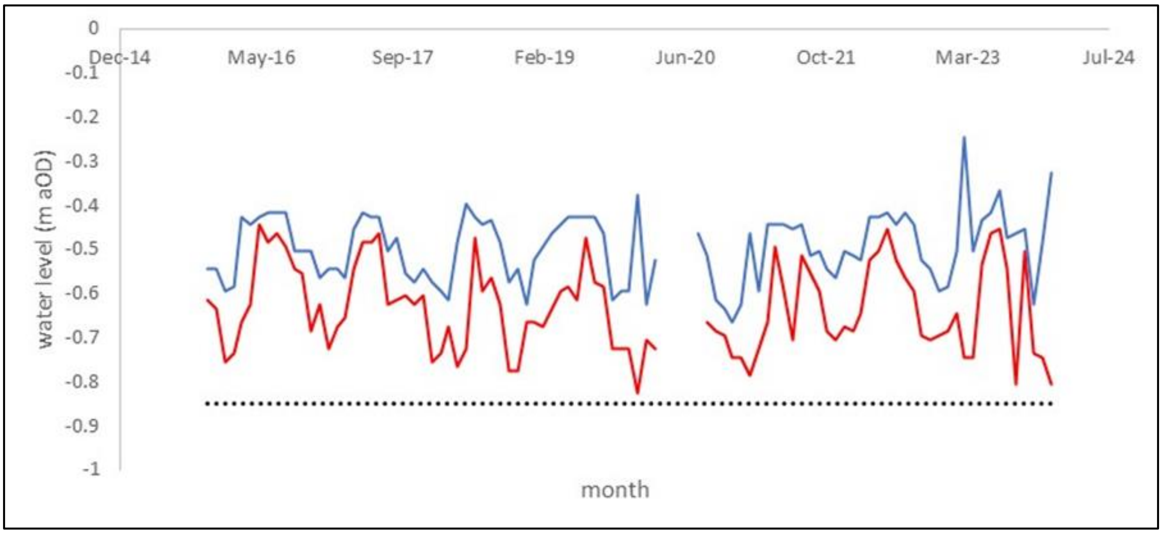

Figure 10. Monthly maximum (blue) and minimum (red) water levels on the Great Raveley Drain.

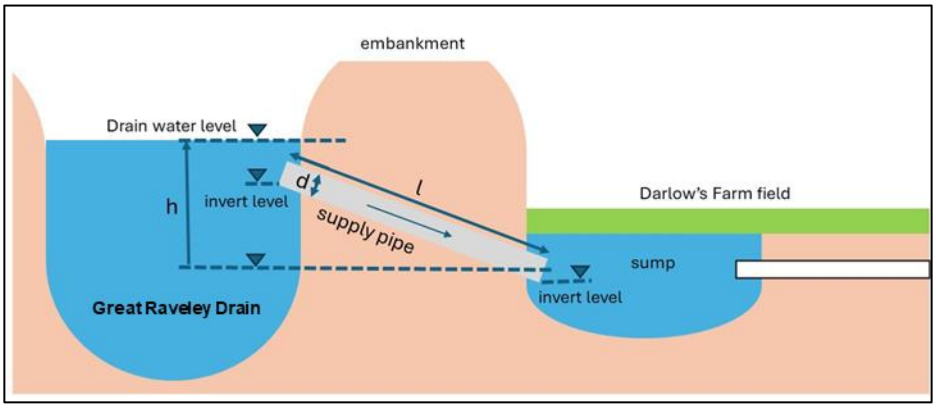

Figure 11. Cross section showing water supply from Great Raveley Drain to Darlow's Farm relationship with Great Raveley

The maximum flow possible through the pipe was calculated using the Hazen–Williams equation that relates the flow to the physical properties of the pipe and energy slope:

$$q = a\,k\,c\,r^{0.63}\,s^{0.54} \qquad \text{(Equation 1)}$$

where:

q is flow (m^3/s)
k is a conversion factor for the unit system (k = 0.849 for SI units)
c is a roughness coefficient (150 for plastic)
r is the hydraulic radius (m)
s is the slope of the energy line (head loss per length of pipe)
a is the cross-sectional area of the pipe (m).

Applying Equation 1 to the pipe (diameter 300mm, length 15m, fall 1.463m) gives a maximum flow of 0.501m^3/s through the pipe from the Drain to the sump in the Darlow's ditch. This assumes that flow out of the pipe end is not restricted. To determine the actual flow through the pipe, the Great Raveley Drain can be assumed to act as a tank and the pipe as a tank drain. Using Bernoulli's equation, the flow in the pipe is dependent on the elevation (head) of water above the pipe and the pipe's diameter

$$q = a\, c\, (2\, g\, h)^{1/2} \qquad \text{(Equation 2)}$$

where:

q = outlet flow (m^3/s)
c = coefficient (water 0.98)
g = acceleration of gravity (9.81 m/s)
h = head (m)
a is the cross-sectional area of the pipe.

The interaction of water viscosity and the pipe wall creates a jet beyond the pipe exit with a slightly smaller diameter than that of the pipe. This is accounted for by a coefficient c, whose value is given as 0.98 in the online calculator[1] (though this may be different for water arriving into the sump). Applying equation (2) to the monthly water level data (Figure 10) gives an estimate of the maximum and minimum flow data for the period November 2015 to January 2024. It can be seen from that the flow would be in the range 0.35 to 0.42 m^3/s if the penstock was opened completely throughout this period (Figure 12).

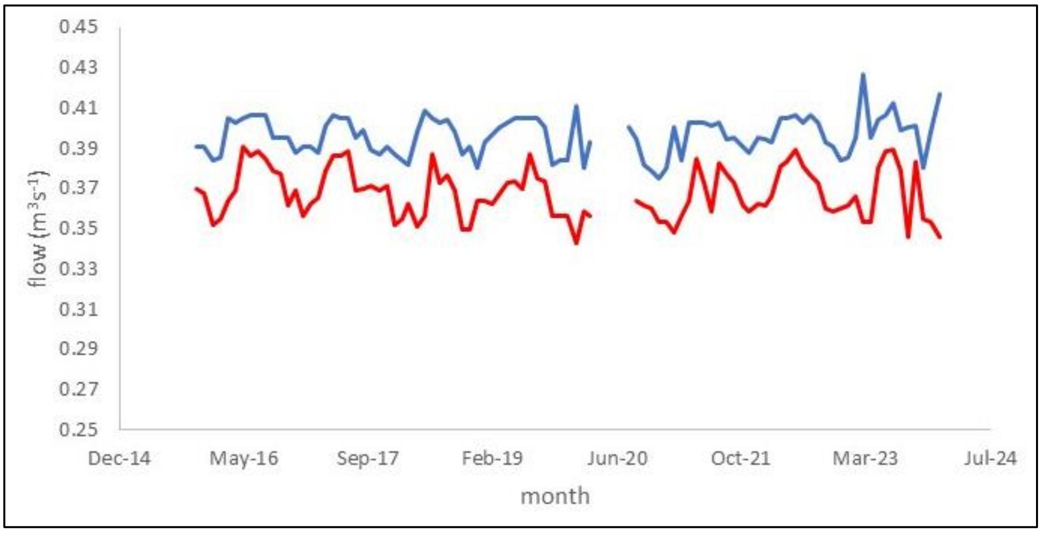

Figure 12. Monthly maximum (blue) and minimum (red) potential water flow through the pipe from the Great Waverley Drain to Darlow's Farm.

The calculations provided above are theoretical. However, it is strongly recommended that the flow rate calculated are checked in the field. This can be achieved by closing the penstock on the pipe and partially draining the sump to a known level. The penstock can then be reopened fully and the time taken for water level in the sump to reach a higher level recorded. By surveying the shape of the sump, the volume held between the two levels can be determined and by applying the elapsed time, the flow rate can be quantified and used to verify the theoretical calculations.

The Darlow's land not only receives water from the offtake from Great Raveley Drain, but also from direct precipitation. Water losses are currently via the managed surface drainage network and evapotranspiration to the atmosphere. Limited losses to ground are expected due to the presence

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[1] https://www.efunda.com/formulae/fluids/draining_tank.cfm

of the underlying Oxford Clay even though some lateral flow through the peat might occur. Currently, the hydrology of Woodwalton Fen is similar to Darlow's, even though it is perched at a higher level, and depends on direct rainfall inputs and pumped water from the Great Raveley Drain (effected by a wind pump). Darlow's is predominantly grassland, whilst the NNR is a mosaic of different wetland habitats including reedbeds, wet woodland, open water and wet grassland.

Reference evaporation data for Darlow's Farm were obtained from the UK Centre for Ecology & Hydrology, who operate an eddy covariance flux system on the Farm. Water table level measurements suggested that the site was not very wet during the measurement period, so it was assumed that the evaporation data were representative of well-watered grass as prescribed by Penman (1948). Acreman *et al*. (2003) measured evaporation from wet grassland (raised water level area) and reed beds on the Somerset Levels and Moors. They found that evaporation from wet grassland was about 10% higher than Penman reference data and evaporation from reedbeds was around 15% higher than wet grassland. These figures are used in this report as adjustment factors for Penman reference data.

Herbst & Kappen (1999) found in Germany that annual evaporation from the reedbeds generally exceeded the annual evaporation from the open water surface of a lake surface, with the ratio ranging between 1.5 and 2; a ratio of 1.5 was adopted producing an adjustment factor for Penman of 1.1. No equivalent factors were found in the literature for wet woodland. Roberts *et al*. (2005) studied evaporation from beech woodlands on Chalk downs. They found that evaporation from the grassland was 3% higher over an 18-month. In this report we assumed that the adjustment factor for wet woodland was the same as for wet grassland.

Using the precipitation data for Darlow's Farm obtained from the UK Centre for Ecology & Hydrology, who operate a weather station on the Farm, it is possible to evaluate whether there is sufficient water to meet the demand of the areas at Darlow's and also the target recipient of water with reduced nutrients, the central region of Woodwalton Fen. The data suggest that evaporation is partly or fully satisfied by precipitation in many months.

Table 2. Areas of fields and evaporation adjustment factors for Darlow's farm.

Zone	Section	Cover type	Total area (m^2)	Adjustment factor to apply to Penman for cover type
Darlow's Farm	All	Wet grassland	846,100	1.10
	D1	Wet grassland	53,359	1.10
	D2	Wet grassland	54,456	1.10
	D3	Wet grassland	54,102	1.10
	D4	Wet grassland	49,561	1.10
Woodwalton Fen	Central	All	1,176,363	1.10
		Woodland	470,545	1.10
		Grassland	294,091	1.10
		Reedbed	294,091	1.65
		Open freshwater	117,636	1.10
Great Fen Fields	All	Emergent vegetation	340,000	1.30
Treatment wetland	Cell D1	Emergent vegetation	28,857	1.30
	Cell D2	Emergent vegetation	31,778	1.30
	Cell D3	Emergent vegetation	29,887	1.30
	Cell D4	Emergent vegetation	23,080	1.30

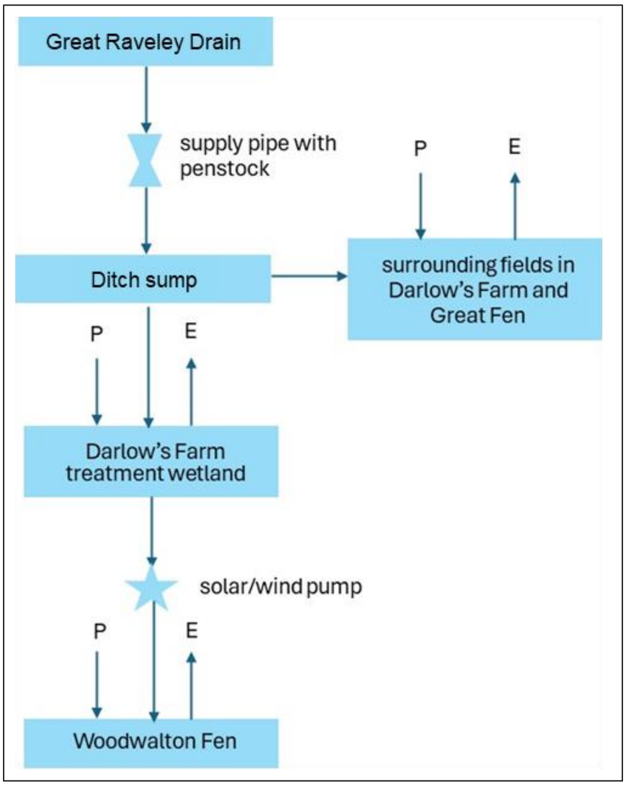

Figure 13. Conceptual hydrological model.

Precipitation and evaporation data were adjusted for area and land cover type (Table 2) to calculate volumes of water arriving and departing on a monthly basis. Evaporation minus precipitation, when greater than zero, provides a measure of additional water required to satisfy the deficit (ie keep the site 'wet'). This additional water is to be sourced from the offtake structure on the Great Raveley Drain. Conceptually, the assessment of water demand needs to consider the current situation, but also the future scenario of restoring an area of peatland by converting the four Darlow's compartments into a 'treatment' wetland to remove nutrients prior to discharge into the central part of Woodwalton Fen. Provision also needs to be made for water to pass through the 'treatment' wetland at Darlow's into the fields to the west and beyond into the Great Fen area to provide future opportunities for wider peatland restoration. The conceptual framework is shown in Figure 13.

It is assumed that the four areas requiring water supplied via the Great Raveley Drain inlet pipe are:

- Darlow's Farm 'treatment' wetland (within D1 to D4);
- The other Darlow's Farm fields;
- Great Fen fields south of Darlow's Farm; and
- Woodwalton Fen (central section).

Results for the four land areas are shown graphically in Figure 14. It can be seen that the peak water demand, the amount of water required to address the losses arising from evaporation, for the central area of Woodwalton Fen is around 90,000 m^3 per month. All the other areas also would have required additional inputs of water to ensure that target water levels are maintained. The hypothetical 'treatment' wetland located within the four Darlow's compartments also requires additional inputs to satisfy the summer water demand and to ensure that it does not dry out.

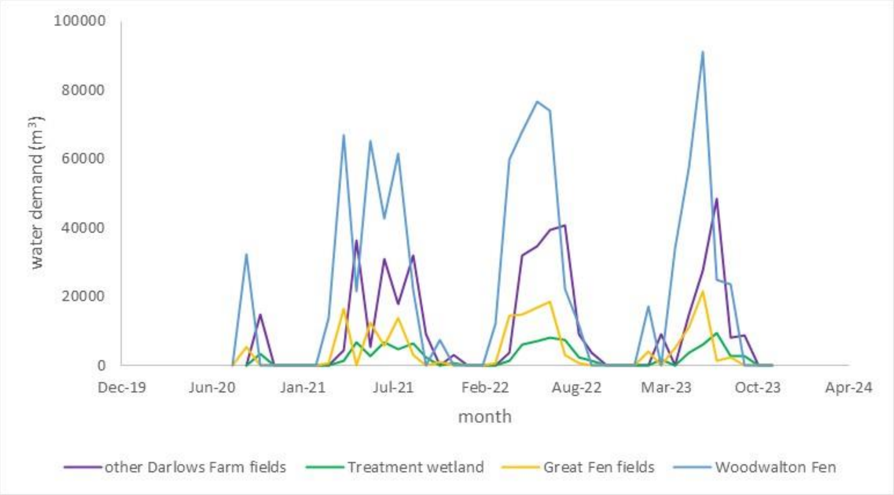

Figure 14. Monthly demand for water (evaporation minus precipitation) for Woodwalton Fen (central section), the 'treatment' wetland, Darlow's Farm other fields and the Great Fen fields.

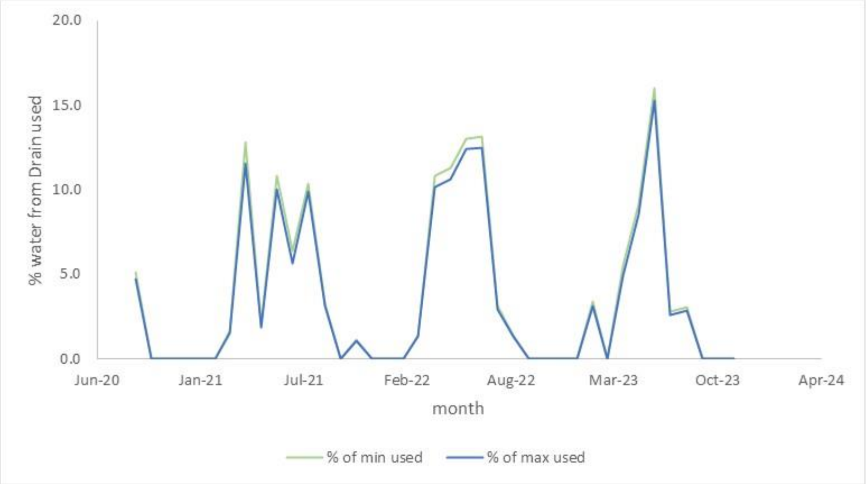

Figure 15. Total monthly demand for water (evaporation minus precipitation) for Woodwalton Fen (central section), the 'treatment' wetland, Darlow's Farm other fields and the Great Fen fields as a percentage of that available from Great Waverley Drain.

The demand for Woodwalton Fen (central section), the hypothetical 'treatment' wetlands, Darlow's Farm other fields and the Great Fen fields were summed to determine the total demand. The ability of piped water from the Great Raveley Drain to supply the total demand was calculated by comparing the two data sets. Figure 15 shows the total demand as a percentage of the maximum and minimum supply provided assuming the pipe from the Drain is fully open, as described above. It can be seen that demand is always 16% or less of the potential supply.

Implications for water input for design of the treatment wetland

The required input of water to the 'treatment' wetland must meet the needs (water deficit) of Woodwalton Fen plus the needs (water deficit) of the 'treatment' wetland itself and the fields beyond the four Darlow's compartments to ensure that the peatland at Darlow's Farm can be restored and that there is water available for wider peatland restoration activities. Figure 16 and Table 3 provide monthly mean water needed at the inlet to the 'treatment' wetland, to supply

Woodwalton Fen, to maintain the 'treatment' wetland itself and the total of both these requirements. Given that the water available from the Great Raveley Drain more than meets this requirement, the hydraulic design of the 'treatment' wetland should be to hold water and reduce flow rate to maximise water quality improvement, as any additional evaporation this may create can readily be supplied. Some throughflow of water, if required, through the Fen could also be accommodated.

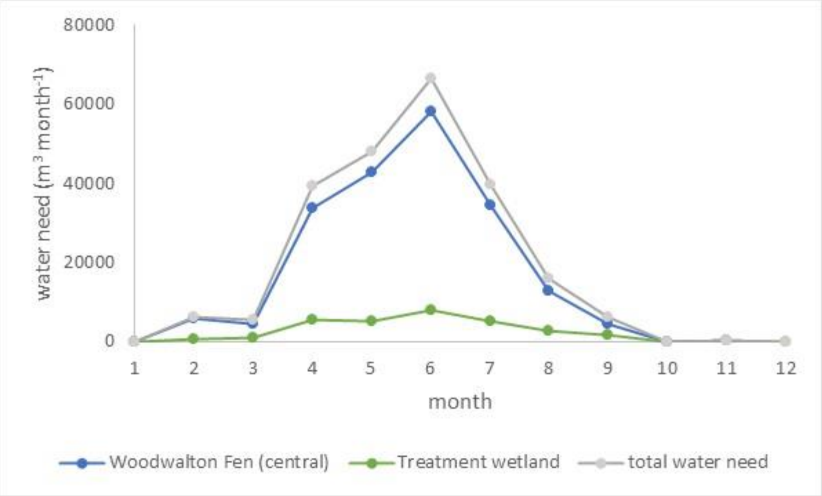

Figure 16. Total monthly mean water (m³) to be provided at the inlet to the 'treatment' wetland, to supply Woodwalton Fen, to maintain the 'treatment' wetland itself and the total of both these requirements.

Table 3. Total monthly mean water (m³) to be provided at the inlet to the 'treatment' wetland, to supply Woodwalton Fen, to maintain the 'treatment' wetland itself and the total of both these requirements.

Month	**Woodwalton Fen need**	**'Treatment' wetland need**	**Total need at inlet to 'treatment' wetland**
January	0.00	0.00	0.00
February	5712.91	589.73	6302.64
March	4635.86	1017.30	5653.15
April	33624.02	5575.91	39199.93
May	42659.79	5278.43	47938.21
June	58296.73	8120.38	66417.11
July	34562.49	5065.40	39627.88
August	13013.74	2875.83	15889.57
September	4466.37	1830.66	6297.03
October	0.00	0.00	0.00
November	209.29	209.29	418.57
December	0.00	0.00	0.00

Implications of climate change on the hydrology

Global average temperature increased over the 20th century, with the greatest warming in northern latitudes. Globally, 2015 was the hottest year on record, over 1°C warmer than the pre-industrial average. Across northern Europe rainfall increased significantly over the 20th century. In the UK all of the ten warmest years on record (that starts in 1910) have occurred since 1990, and 2015 was the hottest year on record, with 2018 having the hottest summer. Average annual rainfall has not changed significantly since records began in the 18th century, but in the last 50 years more winter rainfall has fallen in heavy events. This rainfall trend is expected to continue, and average winter rainfall may increase. The picture for summer rainfall is less clear. As the climate changes UK summer temperatures may increase by up to 4°C by the 2080s (Watts and

Anderson, 2016). Initial analysis of possible impacts on British wetland vegetation communities (Acreman et al., 2009) suggested that reduced summer rainfall and increased summer evaporation (projected by UK COP02) would put stress on wetland plant communities in late summer and autumn with greater impacts in the south and east. In addition, impacts on rain-fed wetlands would be greater than on those dominated by river inflows.

As a follow-up to the England Wetland Vision, a tool was developed to assess how climate change in the 2050s might impact on wetland ecohydrology in England and Wales through alteration of the freshwater hydrological cycle (Acreman *et al*., 2013; Skinner et al., 2014). It does not simulate any direct impacts such as temperature or carbon dioxide changes on vegetation growth. The tool uses climate scenarios for land regions of the UK provided by UKCP09 (Hadley Centre, 2017) and resulting river flows and groundwater levels provided by the Centre for Ecology & Hydrology and British Geological Survey. Results can be obtained for key NVC wetland plant communities including rain-fed wetlands (M16, M21, MG4, M13 and M24) and river-fed wetlands (MG8, S4, MG4, MG13 and S24). Outputs can be produced for a series of metric including

- Wetland hydrology – annual maximum and minimum water levels as mean values or 30-year extremes
- Eco-related - May and August water levels as mean values or 30-year minima, at critical times for plant communities.
- Plant water regimes - mean or maximum departures from generalised water regime tolerances of NVC plant communities (such as Figure 17; Wheeler *et al*., 2004)
- Birds – mean values or 30 years extremes of water levels in November to March for over-wintering birds, April to June for breeding birds.

The tool was applied to Woodwalton Fen to assess potential implications of climate change for general site hydrology, May and August water levels and specific NVC communities.

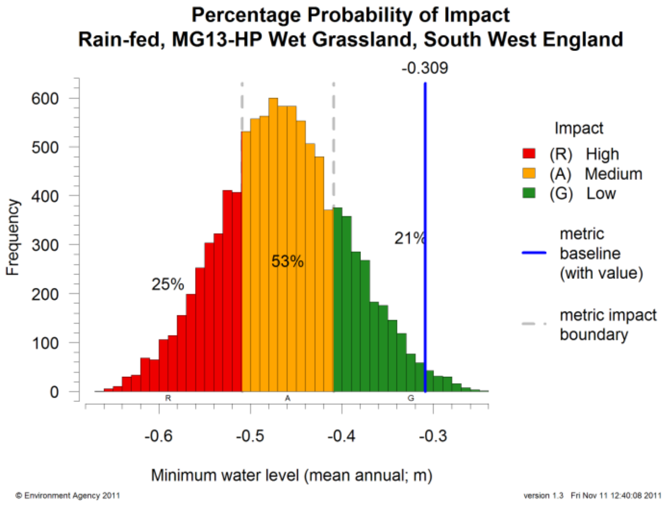

Figure 17. Example display of results from the wetland climate change tool for mean annual minimum water level for rain-fed MG13 wet grassland in South West England.

The UKCP09 project provided 10,000 different realisations of future climate for each future time-slice and emissions scenario, each of which is equally likely (or unlikely) to occur. Consequently, results cannot be given as single values but are presented in terms as the percentage chance that impacts would be slight (green), moderate (amber) or severe (red).

Display outputs from the tool can be either a simple bar depicting the percentages or as a histogram showing the distribution of the 10,000 realisations (Figure 17). It can be seen in Figure 17 that for MG13 there is a 21% chance that mean annual minimum water levels will about the same as the baseline (1961-1990), a 53% chance that they will decrease moderately and a 25% that they will decrease severely. It is noteworthy that the estimated mean of minimum annual water levels is 0.309 m below the surface, which is will reduce to -0.45 (mean value, with a potential range from -0.7 to -0.25. The green/amber boundary is -0.41 m and the amber/red boundary is -0.51 m.

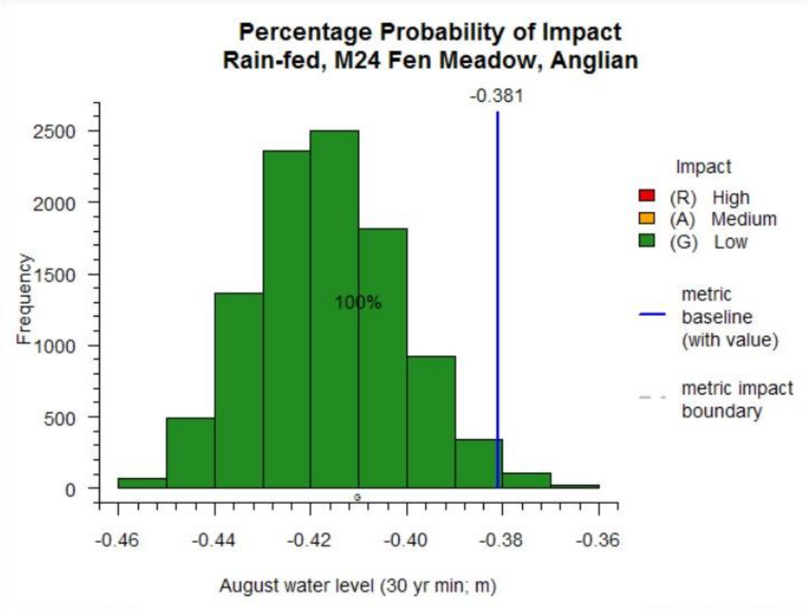

Figure 18. Projection for impacts of climate change by 2050s on rain-fed M24 fen meadow wetlands in Anglian region as indexed by the 30-year minimum August water table level.

The wetland climate change tool was applied to Woodwalton Fen. Various options were selected including rain-fed and river-fed, fen, reeds and wet grasslands, water balance and eco-related hydrology. All results were consistent in projecting that summer conditions would become drier, with some increase in drought stress. However, in all cases the degree of change by 2050s represented low risk of impact of the Fen. For example, Figure 18 shows the histogram of projections for fen meadow wetlands in Anglian region. It can be seen that the 30-year minimum August water table level reduces from -0381 to a mean value of around -0.415, but the range is -0.46 to -0.36 (a slight increase). However, all 10,000 realisations are within the green zone of low likely impact.

Water quality

Fens can occur along a nutrient gradient from highly eutrophic through to oligotrophic (Natural England, 2015). However, altering the nutrient status from natural can seriously degrade ecological character. The water quality within Woodwalton Fen is influenced by a range of factors including the quality of the abstracted influent from Great Raveley Drain, the legacy of phosphorus accumulation within the internal network of ditches and watercourses and the rate of turnover within the system.

Water quality information has been downloaded for the Great Raveley Drain Woodwalton Fen Sluice Sampling station (TL235847) for the period from January 2018 to February 2024. Whilst the data are not complete, they provide an indication of the prevailing nutrient levels in the Drain over the past seven years. The long-term data area shown in Figure 19 and Figure 20.

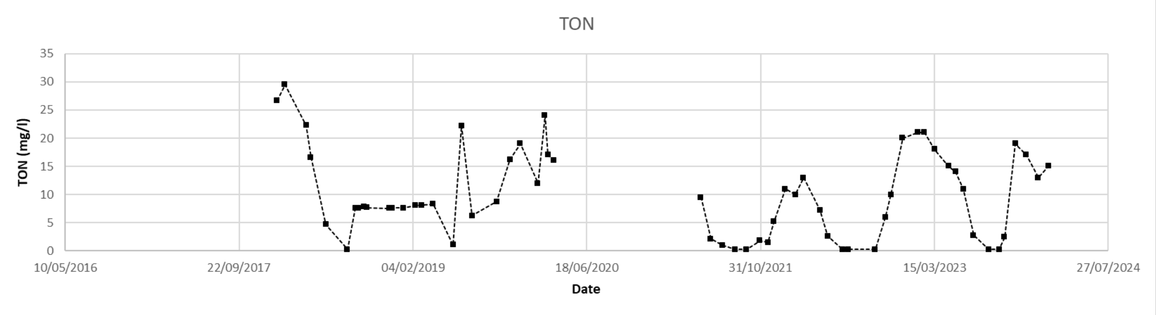

Figure 19. Total Oxidised Nitrogen values at Great Raveley Drain sampling station, 2018-2024. (Source: https://environment.data.gov.uk/water-quality/view/sampling-point/AN-53M46?_all=true).

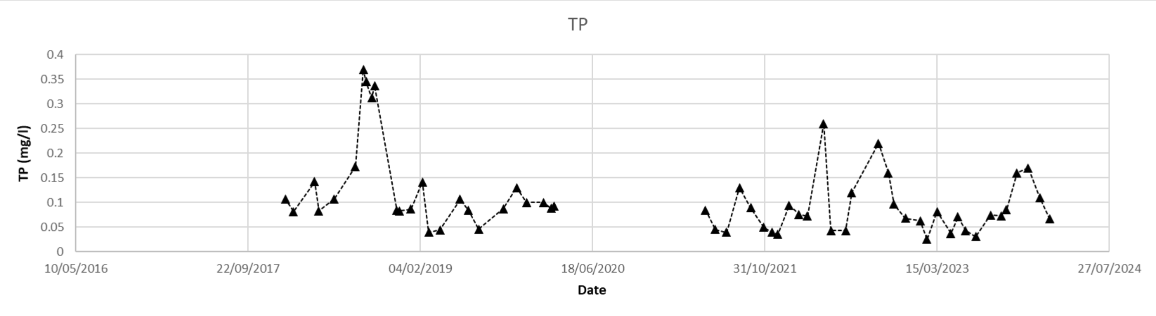

Figure 20. Total Phosphorus values at Great Raveley Drain sampling station, 2018-2024. (Source: https://environment.data.gov.uk/water-quality/view/sampling-point/AN-53M46?_all=true).

The total oxidised nitrogen (TON) values range between 0.2 and a peak of 29.5mgTON/l. The average value over the recording period was 10.02mgTON/l. The UK Government's Water Expert Advisory Group (WEAG) has emphasised that 1-5 to 2.0 mgN/l is the absolute baseline for good ecological status in surface waters (Defra, 2022). Therefore, the concentration of TON in the Great Raveley Drain is considerably above the baseline target for nitrogen in surface waters.

The total phosphorus (TP) values range between 0.03 and 0.37mgTP/l. The average value over the recording period was 0.107mgTP/l. The WEAG have estimated that the Technically Achievable Limit (TAL) for phosphorus reduction at sewage treatment works is 0.25mgTP/l (Defra, 2022; Environment Agency, 2022). With an exception over a short period in 2018, the concentration values for TP recorded in the Great Raveley Drain are consistently below this TAL.

The 2018 to 2024 water quality data have been summarised to produce monthly estimates of the range in concentration in Great Raveley. The derived monthly data have been plotted against the elevation of the water level in Great Raveley Drain (based on the average monthly stage board values between February 2021 and January 2024) (Figure 21). The TP data demonstrate a peak concentration value towards the end of the summer over August and September with a derived average value of 0.22mgTP/l. However, over the same late summer period the maximum derived value is in excess of 0.35mgTP/l. Spearman's rank correlation was computed to assess the relationship between average TP and water level in the Great Raveley Drain. There was no significant correlation observed between the minimum or maximum stage board elevation and the mean, maximum or minimum concentration of TP.

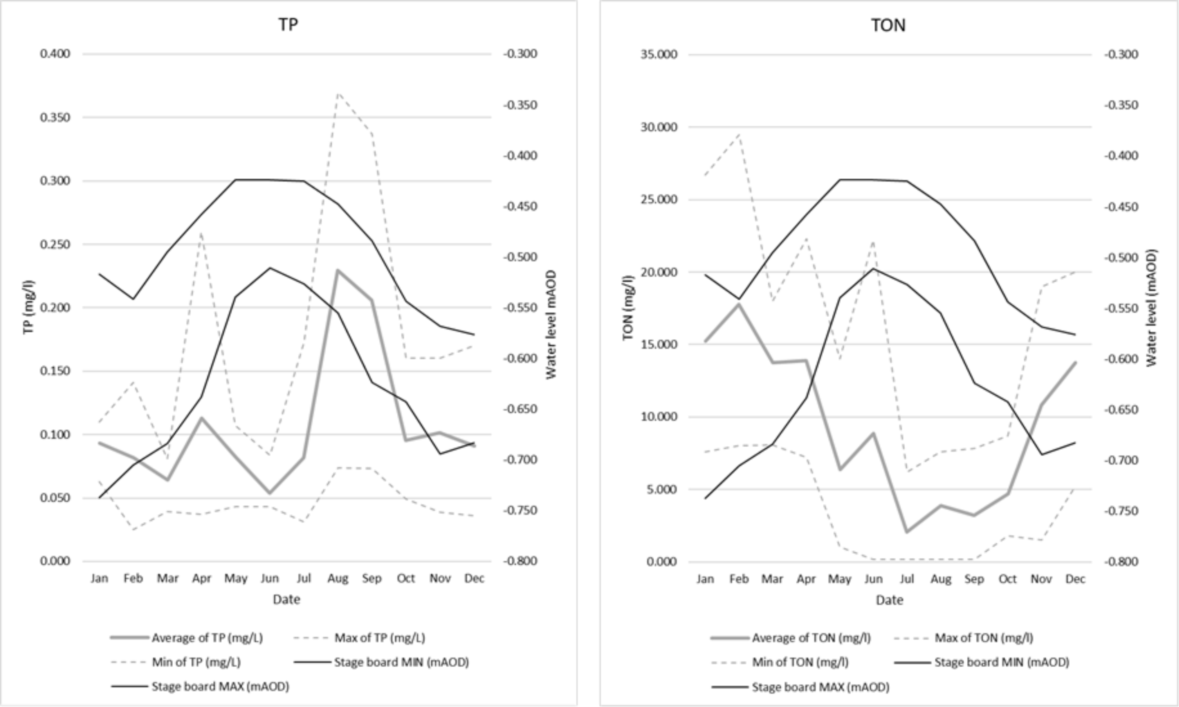

Figure 21. Derived monthly water quality data for Great Raveley Drain.

The TON data demonstrate a clear seasonality, with elevated concentrations in the winter months and lowest concentrations in July, August and September (Figure 21). Computation of Spearman's rank correlation also demonstrated that there was a negative correlation observed between the minimum stage board value and the average TON (r(10)=-.73, *p*=.009) and the stage board water elevation and the minimum TON value (r(10)=-.81, *p*=.002). This suggests that as water levels in the Great Raveley Drain decrease the TON values increase.

The hydrological system in the vicinity of Darlow's Farm and Woodwalton Fen is not natural and represents a heavily managed system. Consequently, the water quality in the Great Raveley Drain is subject to variations in the anthropogenic management of the system, both in terms of the quantity and quality of water. Potential land use changes across the Great Fen area, especially the on-going and desired conversion of arable land to wet grassland under conservation management will undoubtedly influence the future water quality in the Drain. However, as with elsewhere in England (Comber et al., 2023), the ditch network feeding Great Raveley Drain may be a significant reservoir of nutrients the legacy of which may influence water quality for many years after any changes in land management have been implemented.

2.6 Habitats and land use at Darlow's Farm

The land at Darlow's was formerly under arable production until its purchase in 2002. Arable farming ceased progressively across the land in Darlow's Farm from the early-2000s. Since this time, the management of the site has focussed on creating wet grassland through the raising of water levels in the ditches and grazing by cattle and, currently, horses.

A detailed botanical survey was conducted of Darlow's in February 2024 (Wild Frontier Ecology, 2024). The vegetation survey classified the fields within Darlow's using the UK Habitat Classification (UKHab Ltd., 2023). Compartments D1 and D2 were classified predominantly as 'modified grassland', with the exception of the northern part of D1 which supported an area of 'other neutral grassland'. Compartments D3 and D4 were classified as '*Holcus-Juncus* neutral grassland'. The area of former buildings between compartments D2 and D4 was classified as 'bramble scrub'.

The 2024 vegetation survey identified that the ditches were vegetated with common reed *Phragmites australis* and rushes *Juncus* spp. However, at the time of the survey the presence of Swamp stonecrop or New Zealand pigmyweed *Crassula helmsii* was not recorded in the ditches. However, during a site visit in March 2024, extensive stands of *Crassula helmsii* were observed in the ditch on the western boundary of D4 and also in the parallel ditches to the west of this ditch. Historically, *Crassula helmsii* has been recorded in the fields to the west of D4 in association with areas of relatively unvegetated ground with standing water.

2.7 Other considerations

Protected species

The site is known to support several protected species and species of conservation interest. The area of scrub between compartments D2 and D4 supports a main badger *Meles meles* sett and badger foraging activity was noted in several of the compartments. Incidental observations also indicate that the four Darlow's compartments support a several species of breeding birds as well as other birds of conservation concern such as common crane *Grus grus*, snipe *Gallingo gallingo* and lapwing *Vanellus vanellus.* The ditches have the potential to support water vole *Arvicola amphibius* and Chinese water deer *Hydropotes intermis* was observed in the southern part of compartment D4.

Groundwater source protection zone

Groundwater source protection zones have been designated by the Environment Agency to protect groundwater sources used to supply drinking water. The area of Darlow's Farm has not been designated as a groundwater protection zone.

Nitrate Vulnerable Zone

Nitrate Vulnerable Zones (NVZs) are areas designated as being at risk from agricultural nitrate pollution. The designations are made in accordance with the Nitrate Pollution Prevention Regulations 2015. The entire area of Darlow's Farm is classified as an NVZ and the use of nitrogen fertilisers or the storing of organic manure would be subject to appropriate rules and guidance.

Flood risk

The entire area of Darlow's Farm is classified as being in Flood Zone 3. This means that the land in this area has a high probability of flooding from rivers (or the sea). Any planning application for development in this area would require a flood risk assessment to be undertaken.

Archaeology and heritage

The register of all nationally protected historic buildings and sites in England, including listed buildings, scheduled monuments, protected wrecks, registered parks and gardens, and battlefields, indicates that there are no such features in the area of Darlow's Farm. However, the peat deposits within the four compartments may contain significant archaeology and/or heritage value.

Rights of way and public access

There are no public footpaths or rights of way within, or along the boundaries of, the four Darlow's compartments. The nearest public footpath is to the west of site of the former Darlow's Farm buildings.

Birdstrike risk

The creation of wetlands has the potential to increase the risk of bird strike to aircraft. Civil Aviation Publication (CAP) 738 Safeguarding of Aerodromes details the requirement for relevant planning authorities to consult the relevant consultee before granting planning permission for any development within 13km of a certified aerodrome (referred to as the 'safeguarding area') which is likely to attract birds.

Two minor airfield are present within 13km of the four Darlow's compartments: one at Connington (TL193869) some 3.9km to the west-north-west and another at Upwood (TL271840) approximately 3.8km to the south east. Both of these sites have limited flying activities.

Historic landfill or contaminated ground

No historic landfill or contaminated ground is recorded as being present within the four Darlow's compartments.

Unexploded ordnance

There are no records of unexploded ordnance within the site.

Services and infrastructure

Whilst a full services search has not been conducted, site observations indicate that there are no overhead services. Buried services will include water pipes for the management of water levels in the ditches.

2.8 Summary of data review

A variety of data and information have been reviewed to ascertain whether it would be possible to restore an area of peatland and to create a dedicated 'treatment' wetland within the four compartments at Darlow's Farm and whether such a wetland could improve water quality entering the NNR.

The key factor in both restoring a peatland and creating a well-functioning 'treatment' wetland is the availability of water to maintain the wetland hydrology throughout the year and to prevent the area from drying out, and potentially allowing nutrients to be remobilised and further peat degradation and oxidation to persist. The ability to abstract water from the inlet sluice, and the availability of water throughout the year, is critical to meeting the modelled water demand both in the 'treatment' wetland and beyond in Woodwalton Fen and the adjacent fields. The calculations undertaken suggest that there is sufficient water available to create a 'treatment' wetland and to re-wet an area of degraded peatland both within Darlow's Farm and beyond. However, it is recommended that the flow rates estimated for the intake are checked and re-evaluated *in situ* to confirm the modelled outcomes.

The success of restoring peatland and creating a 'treatment' wetland depends on the need to abstract water from the Great Raveley Drain. The viability of this source relies on the future ability to retain the existing abstraction licencing arrangements. Any change in the licencing conditions could impact on the future viability of the desired outcomes.

The topography of Darlow's and Woodwalton Fen poses a water management challenge if the water quality benefits area to be delivered to the NNR. Water in a 'treatment' wetland would need to be lifted from Darlow's over the northern perimeter bank at Woodwalton Fen. This represents a head difference of in excess of 1.5m. This would require the installation of pumps. The recommendation would be to install solar or wind pumps (or a combination of the two) to ensure that water can be delivered sustainably to the NNR.

The presence of *Crassula helmsii* within the ditch network and fields at Darlow's Farm is a serious concern. Whilst it could be argued that the spread of *Crassula* into Woodwalton Fen is inevitable, the ecological risk associated with creating an extensive area of wetland, and by doing so providing the perfect habitat for its establishment and spread, is considered to be significant. As has been discovered elsewhere, the eradication of *Crassula helmsii* usually fails and can be very costly (van der Loop et al., 2022). The abstraction of water from an area (the 'treatment' wetland) that could become heavily infested with *Crassula helmsii* to supply a site holding multiple nature conservation designations may potentially constitute an illegal activity under the Wildlife and Countryside Act 1981 as it is illegal to plant or otherwise cause to grow in the wild any plant listed in Schedule 9 of the Act.

The creation of a 'treatment' wetland will require excavation of degraded peat to construct a series of wetland cells across the four compartments at Darlow's. The spoil generated from this activity could be used to bury the existing areas of *Crassula helmsii*. Burial is one of the few effective measures for the eradication of *Crassula helmsii*. This potential approach should be investigated further.

The soil analysis reveals that the peat is relatively intact at depths below approximately 0.5m. The Fe:P ratios suggest that the risk of significant release of phosphorus as a result of rewetting the peat soils is low across all four compartments at Darlow's. This risk could be reduced further through removal of topsoil or minimising the extent of surface water inundation.

The rewetting of the peat soils at Darlow's has the potential to reduce and mitigate the impacts of climate change. Whether on a global level or at a site scale, the challenges of managing net fluxes of greenhouse gasses remains the same with regards to long-term net radiative forcing (Günther et al., 2020). At the site level, a balance must be struck between the radiative forcing effects of CH_4 emissions as a result of restoration activities (which may represent a significant short-term impact) against the long-term and persistent CO_2 emissions from the on-going degradation of the peat soils at Darlow's. There remains a risk over the short-term, up to 10 years, that there may be an increase in CH_4 flux from flooding the existing soils (Zak and McInnes, 2022). However, the risk of increased CH_4 flux could be mitigated by slow rewetting through increasing the elevation of water levels within the soil profile or by the removal of topsoil.

The area of the four Darlow's compartments is known to support a main badger sett and there may well be other protected species, such as water vole and breeding birds, present within the site. Any works associated with creating a 'treatment' wetland would need to take into account the necessary measures to address any potential impacts to protected species.

The entire area is within Flood Zone 3 and therefore should be subjected to a specific flood risk assessment. The requirement for this would need to be addressed through liaison with the Lead Local Flood Authority.

The excavation of even degraded peat deposits may well require an archaeological watching brief to record potential finds and information of heritage value. Early discussions with the Local Planning Authority are recommended to further consider this issue.

Overall, the desk and field data review has not highlighted a physical constraint to the conversion of the land in the four compartments at Darlow's to a 'treatment' wetland which can provide Woodwalton Fen with a 'treated' water supply. Similarly, even if water was not delivered to the NNR, the potential to bring water in from Great Raveley Drain to restore an area of degraded peatland is considered feasible. However, the most significant limitation is the considerable ecological (and ethical) risk associated with the establishment of *Crassula helmsii* at the site and its subsequent potential conveyance from the 'treatment' wetland into the NNR.

3 Ecohydrological conceptualisation

3.1 Objectives

Assuming the legal, procedural and potential ethical constraints identified in Section 2 can be addressed adequately, it should be feasible to rewet the degraded peat soils and convert the four compartments at Darlow's into a 'treatment' wetland or to slowly rewet the area to restore the peat soils so as to meet the objectives of the NCPDGS of reducing emissions from peat, establishing a trajectory for peatland restoration and provide additional water quality benefits for a NNR. The primary focus of the 'treatment' wetland is on improving the quality of a source of water for Woodwalton Fen through reduction in the nutrient concentration and load. Whereas, the peatland restoration would extend across the four Darlow's fields through water being within a few decimetres of the ground surface or locally slightly above the ground surface in all four compartments.

3.2 Conceptual overview

Peatland restoration hydrology

There is sufficient water available from Great Raveley Drain to rewet the four compartments at Darlow's so as to catalyse peatland restoration. This is irrespective of whether the water from the four compartments is pumped into Woodwalton Fen or whether it entered into the wider field ditch drainage network to the west. Water would be abstracted from Great Raveley Drain via the existing penstock and offtake pipe. The water would be delivered to a sump on the existing ditch. From this point water would be diverted to the north into compartment D1 and subsequently flow under gravity into compartments D2, D4 and D3. Water would also be available to flow to the wider landscape to the west and into the Great Fen project area. Some minor earthworks would be required to create low-level bunds in certain locations to retain water within the compartments and prevent drainage to adjacent ditches. In some areas the water would be above the ground surface, to depths of possibly 0.4m, whereas in other areas the water level would be up to 0.3m below the ground surface. It is estimated that this approach could create some 19 hectares of rewetted peatland within the four Darlow's compartments and involve minor groundworks.

More extensive groundworks, including subtle reprofiling of the ground surface, could also be undertaken to both remove degraded peat soils and to allow more uniform, and relatively lower nutrient, conditions to be created over more extensive areas within Darlow's. Under this scenario, water level management would focus on creating the appropriate conditions for peat-forming vegetation to become established. The objective would be to create ground levels that would allow water to be kept at or near (within 100mm) the ground surface over as large an area as possible.

Peatland restoration communities

The success of the restoration of peat-forming communities will vary over both space and time, depending on the prevailing soil and hydrological conditions. If local groundworks or topsoil removal create a new soil surface this can present challenges for vegetation establishment as the bare peat will be susceptible to frost, wind and rain erosion. Furthermore, if the objective is to create a 'natural' peat community, there is no guarantee that the soil will contain a viable seed bank or that dispersal of seeds from nearby sites will occur sufficiently to allow colonisation and vegetation establishment. Therefore, seeding or planting may need to be considered to establish the vegetation community. The potential for iron toxicity, resulting from the transformation of Fe^{3+} to Fe^{2+} under anoxic conditions, may also limit the potential assemblage of plant species.

The restoration target should focus on establishing a 'fen' rather than 'bog' community due to the quality of the available water source from Great Raveley Drain. The restored peatland would take the form of a horizontal mire where water movements, following initial re-wetting and lifting of water levels, are largely across the surface, or through the peat, along a horizontal plane. The nutrient loading in the Drain will be limiting factor on the diversity of the vegetation community to be established as risk of long-term phosphorus release from the peat soils is considered to be low.

A range of techniques can be used to re-establish a peatland vegetation community. Harvested plant material, such as hay, from donor sites could be introduced to the bare peat surface. Seedlings could be grown in commercial nurseries and planted into the rewetted peat. If a suitable donor site can be found, the translocation of vegetated sods and turves could be considered. Alternatively, if paludiculture was the target outcome, the site would need to be planted with the appropriate crop species.

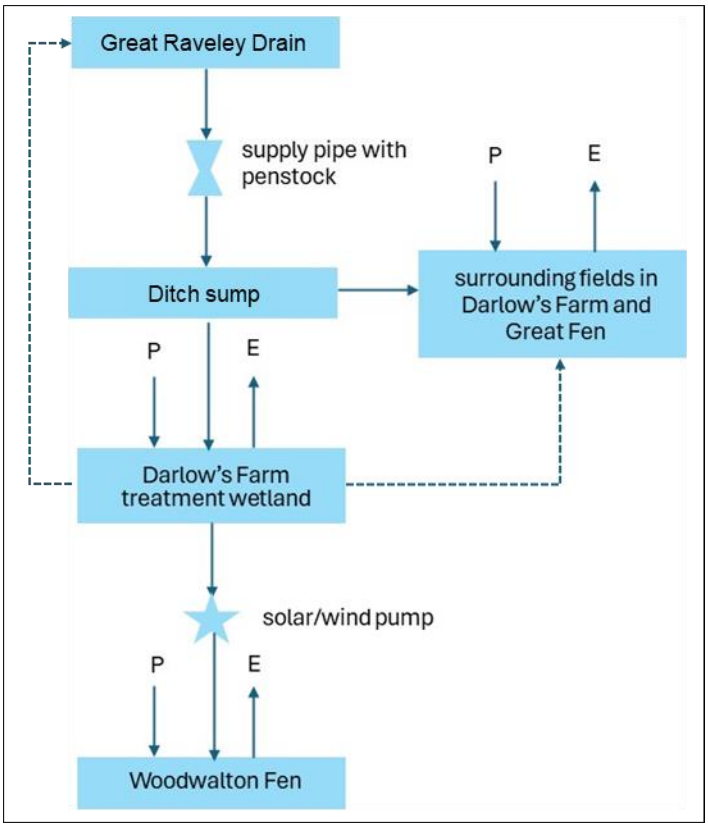

Figure 22. Revised conceptual proposal for the treatment wetland and associated hydrology.

Hydrological functioning of the 'treatment' wetland

The overall hydrological functioning of the 'treatment' wetland builds on the concept previously presented in Figure 13 and that required to rewet the peat area. Water would be abstracted from Great Raveley Drain via the existing penstock and offtake pipe. The water would be delivered to a sump on the existing ditch. From this point water would be diverted to the north into a wetland cell in D1 and subsequently flow under gravity into wetland cells created in D2, D4 and D3. Provision should also be made to allow some water to by-pass the wetland cells and continue along the existing drain from the sump towards the west to feed the other Darlow's fields and beyond into the Great Fen. Water passing through the four treatment wetland cells would arrive at a point in cell D3 from which it would be pumped into Woodwalton Fen by solar or wind pump. Provision should also be made to allow water to be returned to Great Raveley Drain or to be discharged to surrounding fields via the existing ditch network if it is not required within Woodwalton Fen. This revised concept is illustrated in Figure 22.

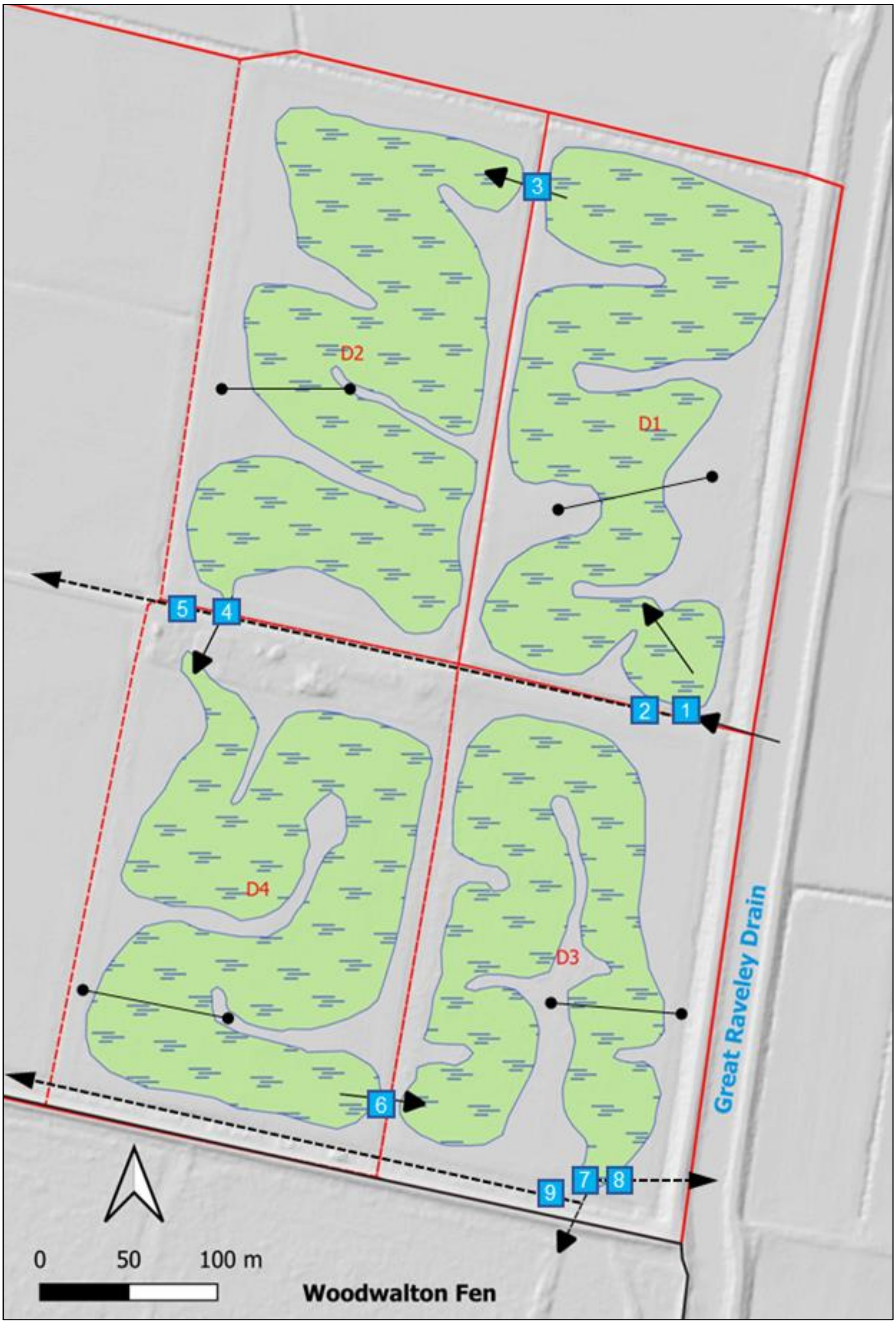

Figure 23. Concept design of a 'treatment' wetland. (Solid arrows indicate normal water movements; dashed arrows indicate possible flow paths if required; blue squares are possible locations of water control structures; black lines are cross-sections in Figure 24.)

Treatment wetland concept design

The concept design has focussed on the 'treatment' wetland as this has the potential to rewet a considerable area of peatland and provide the improved quality of water for the NNR. The concept design of the 'treatment' wetland is shown in Figure 23. Illustrative cross-sections are provided in Figure 24. The wetland cells would be excavated into the existing ground level to create a gradual gradient from cell D1 through cells D2, D4 and D3. The cells have a convoluted shape to minimise the risk of water short-circuiting across the system and to optimise the edge effect and diversity of habitats. The shape also responds to the local topography and attempts to minimise the amount of excavation and spoil disposal.

An attempt has been made to work with the existing topography as far as possible. However, there will still need to be a degree of excavation and removal of degraded peat as well as making up ground levels around the margins of the cells and field compartments (Figure 24). The objective is to create relatively level beds within the wetland cells and to manage water levels at or around a depth of 0.1m. In some locations the wetland cell will simply be excavated within the existing soil profile whilst in others a low bund may be required to retain water. It is recommended that the peat is compacted around the margins of the wetland cells to minimise lateral water losses. However, flooding the wetland cells will also elevate the water levels within the peat soils adjacent to the cells thus reducing the degree of oxidation and peat loss across the wider compartments. A summary of the proposed ground and water levels and the volumes of spoil to move is provided in Table 4.

Table 4. Summary of wetland cell information.

Compartment	Compartment area (m^2)	Wetland Cell	Area (m2)	Proposed ground level (mAOD)	Proposed normal water level (mAOD)	Volume above ground level (m^3)	Volume below ground level (m^3)	Volume to remove (m^3)
D1	53,359	D1	28,857	-1.2	-1.1	237.6	-4381.1	-4143.5
D2	54,456	D2	31,778	-1.4	-1.3	826.2	-2019.4	-1193.2
D4	54,102	D4	29,887	-1.6	-1.5	3229.5	-407.5	2822
D3	49,561	D3	23,080	-1.8	-1.7	4594.7	-24.6	4570.1
TOTAL	**211,478**		**113,602**			**8888.00**	**-6832.60**	**2055.40**

Water management infrastructure would be required to control water levels within the four cells and also to distribute water around the 'treatment' wetland and into the wider environment (Figure 23). Pipework would be required to manage the flow of water from cell to cell. Right angled adjustable pipe collars on 300mm pipes could be used to control water levels, or more complex or expensive options, such as integrated headwall with penstock could be considered at the detailed design stage. The following water control structures are proposed based on the initial concept design shown in Figure 23:

1. An adjustable structure to divert water from a sump in the existing ditch into wetland cell D1.
2. An adjustable structure to allow water to enter into the existing ditch system and to flow to the west.
3. An adjustable structure to allow water levels in wetland cell D1 to be controlled and to distribute water into wetland cell D2.

4. An adjustable structure to allow to allow water levels in wetland cell D2 to be controlled and to distribute water into wetland cell D4.
5. An adjustable structure to allow water to enter into the existing ditch system and to flow to the west.
6. An adjustable structure to allow water levels in wetland cell D4 to be controlled and to distribute water into wetland cell D3.
7. An adjustable structure to allow water levels in wetland cell D3 to be controlled and to distribute water into a sump which feeds a pump to distribute water into Woodwalton Fen.
8. An adjustable structure to allow water to be returned to Great Raveley Drain as required.
9. An adjustable structure to allow water to enter into the existing ditch system and to flow to the west.

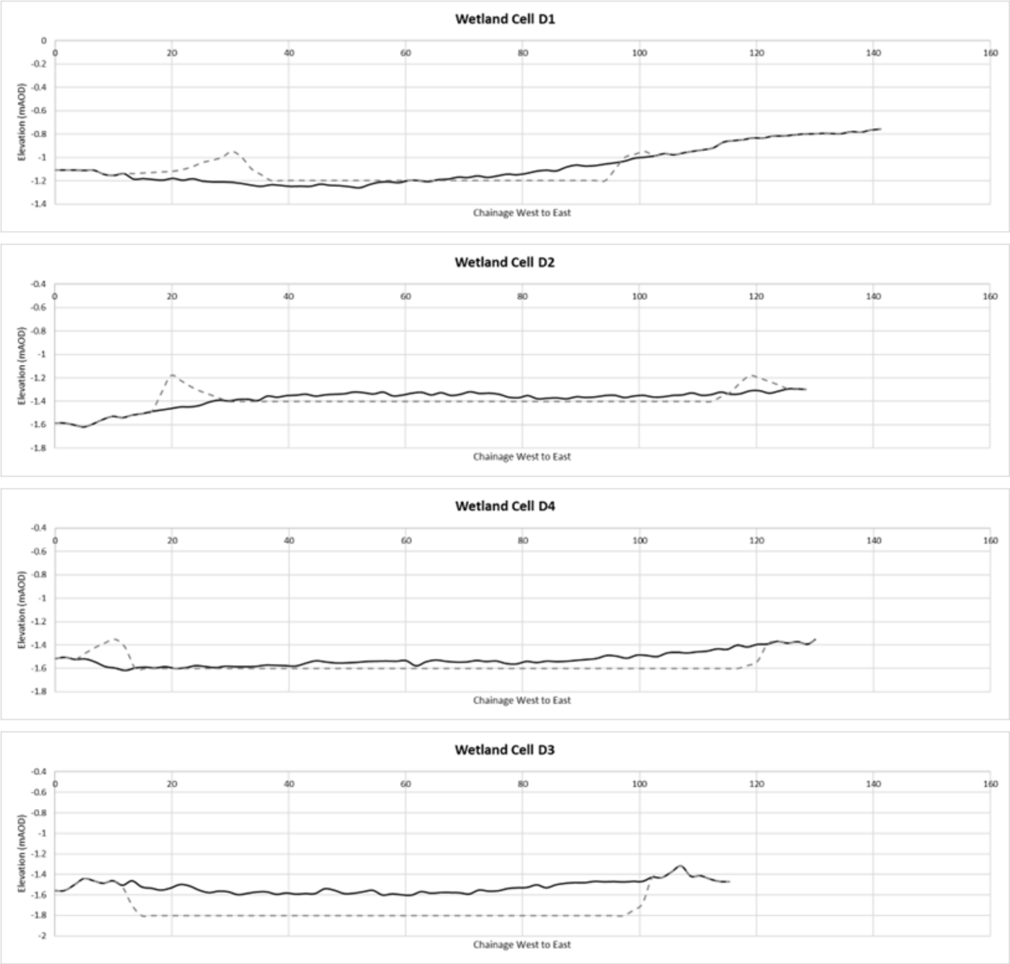

Figure 24. Illustrative cross-sections through the treatment wetland cells. (Note: vertical exaggeration x20; solid lines – current ground levels; dashed grey lines – proposed wetland cell ground levels.)

A solar or wind pump (or a combination thereof) would need to be installed at the southern end of cell D3 to pump the water up and over (or through) the existing perimeter bund. An exact location of the discharge point into the central portion of Woodwalton Fen would need to be identified as this will have implications on the pump design and specification. Similarly, the details of any pump would need to be appraised and specified based on the water demand values described above.

Treatment wetland habitat design

The wetlands would be designed to create an extensive and dense sward of emergent vegetation. The target vegetation community would have many of the characteristics of an S24 tall herb fen community, however without the main species Common reed *Phragmites australis* (Rodwell, 1995). The objective is to create very stable environment within the wetland cells that maintain a relatively constant redox profile through the water column and the substrate. This will provide the appropriate conditions for the biogeochemical transformations required to remove and trap nutrients. Common reed is highly efficient in transferring oxygen to root zone and potentially can disrupt the redox profile within the wetland cells. Therefore, a range of other plants characteristic of S24 communities, such as greater tussock sedge *Carex paniculata*, reed sweet grass *Glyceria maxima*, blunt flowered rush *Juncus subnodulosus*, yellow flag iris *Iris pseudacorus*, greater pond sedge *C. riparia* and common marsh bedstraw *Galium palustre*, should be considered.

However, an alternative planting specification could be developed based on establishing a paludiculture crop of bulrush *Typha latifolia*. This would entail creating a monoculture of bulrush. Whilst this might not create the habitat diversity and abundance of micro-niche habitats of a tall herb fen, it could provide the opportunity to harvest a commercial crop as well as delivering on the water treatment needs.

3.3 Water quality treatment

It is possible to use the hydrological, historical water quality and initial wetland concept design to gain an insight into the potential nutrient removal achievable.

As specified in Natural England (2022), the *P-k-C** model (Kadlec and Wallace, 2009) has been applied to estimate the impact that a ‘treatment’ wetland can have on reducing nutrient concentrations, and therefore loads, entering Woodwalton Fen. Application of the *P-k-C** model has assumed that water from the Great Raveley Drain would be treated by the wetland prior to discharging into Woodwalton Fen.

Dotro et al. (2017) have expressed the *P-k-C** model as:

$$\left(\frac{Co - C*}{Ci - C*}\right) = \frac{1}{\left(1+\frac{k_A}{Pq}\right)^P} = \frac{1}{\left(1+\frac{k_v t}{P}\right)^P} \qquad \text{(Equation 3)}$$

The information required calculating a rate coefficient using the *P-k-C** approach includes the physical attributes of the ‘treatment’ wetland (length, width, and effective depth of the treatment cell), operational data (flow rate(s), effluent water temperature, influent and effluent pollutant (nitrogen) concentrations). The hydraulic loading rate (HLR) (q) and hydraulic retention time (HRT) (t) are based on the inflow rate (Qi). The following parameters expressed are:

C_o	outlet concentration, mg/l
C_i	inlet concentration, mg/l
$C*$	background concentration, mg/l
k_A	modified first-order areal rate coefficient, m/d
k_V	modified first-order volumetric rate coefficient, 1/d
P	apparent number of tanks-in-series (TIS), dimensionless
q	hydraulic loading rate, m/d
t	hydraulic retention time, d

An initial assessment has been conducted based on the initial concept design of the ‘treatment’ wetland described above.

Analysis of the water quality data for Great Raveley Drain indicates that mean monthly TP values range between 0.54 and 0.23mgTP/l. Natural England (2022) suggests that ‘treatment’ wetlands may not be effective at reducing TP concentrations further at these relatively low levels. Therefore, improvements in water quality have focused on reducing the amount of nitrogen that could enter Woodwalton Fen.

Satisfying the peak water demand identified in Table 2 would require in excess of 2,200m^3/d to be abstracted from the Great Raveley Drain to ensure that water was available to be delivered to Woodwalton Fen at the time of maximum demand. Based on a target water level of 2.0.2m within the treatment wetland, this equates to a hydraulic residence time (HRT) within the wetland of in excess of ten days.

Using monthly TON mean values and a daily inflow from Great Raveley Drain through the ‘treatment’ wetland to Woodwalton Fen of 2,272m^3/d (equating to HRT=10), and using the *P-k-C** model, it is possible to provide an initial estimation of the reduction in concentration and load of TON in the water leaving the treatment wetland. The initial assessment suggests that it may be possible to reduce TON concentrations to below 3.00mgTON/l. This represents a reduction in concentration of approximately 80%. Based on an annual estimate, assuming that water is abstracted and passed through the treatment wetland for 365 days, the reduction in concentration equates to an approximate annual reduction in load of 74%, or some 5,800kgTON/yr.

Therefore, conceptually, the ‘treatment’ wetland should be able to deliver water with improved quality, and reduced nutrient concentrations, to Woodwalton Fen. The magnitude of the improvement in the water entering the NNR will depend on the duration flow and volume of water required as the water quality in the Great Raveley Drain varies over the year and therefore the maximum reductions in nitrogen load are generated over the winter period when TON concentrations are highest in the Drain.

3.4 Implications for Woodwalton Fen

Depending on the amount of water delivered via the ‘treatment’ wetland to Woodwalton Fen, and the time of year water is required, the incoming water should have an improved quality and reduced concentration of nutrients. Nitrogen loads should be reduced substantially and there may also be a slight reduction in the phosphorus loads but these might ultimately be negligible. However, whether the treatment of the water from the Great Raveley Drain prior to discharge into Woodwalton Fen will have a significant impact on the ecology of the NNR is beyond the purview of this report. Historical water quality data suggests that nutrients, and phosphorus in particular (APEM, 2017), may have accumulated within the system. Evaluating whether the benefits of improved water quality derived from a ‘treatment’ wetland will outweigh the impacts of the legacy of historic nutrient impacts is challenging. However, the implementation of a ‘treatment’ wetland will contribute to ensuring that future nutrient-driven impacts within the NNR are mitigated.

3.5 Additional considerations

Wider ecological benefits

The creation of an extensive ‘treatment’ wetland will also potentially provide both water quality and ecological benefits to the wider landscape of Darlow’s Farm and the Great Fen area. When water is not required to be discharged into Woodwalton Fen from the treatment wetland, the potential exists to divert this treated water into the ditch network and towards the neighbouring fields. The use of 'cleaned' water in the gradual restoration and enhancement of the wider landscape should also provide ecological benefits within the ditch network and even within rewetted fields.

Peat restoration

A key design principle is to ensure that the 'treatment' wetland retains approximately 0.2m of water above the ground surface. Under these stable waterlogged conditions further degradation of the existing peat soils should be abated. In time, as plant material dies and accumulates within the treatment wetland, the former peatland will gradually shift towards a form of restoration. However, to ensure that the treatment wetland remains functional, it will be necessary to maintain the surface water depth of 0.2m, therefore the successional shift towards a peat-forming system is unlikely to be achieved fully. Additionally, the water held within the wetland cells will contribute to the elevating water levels across the wider land within the four compartments at Darlow's, thus creating wider peatland restoration benefits.

An alternative approach, if the water quality treatment aspect was not considered important or necessary, would be to slowly raise the water levels across the four compartments of Darlow's Farm in order to keep water at or near (within 100mm) of the ground surface to re-establish the necessary conditions for the restoration of the peatland. This slow-wetting approach could also consider the removal of the degraded topsoil to minimise the risk of phosphorus release to the surface waters and to reduce the impact of CH_4 emissions.

Net radiative forcing

The creation of a 'treatment' wetland, with water flowing over the peat surface will potentially retard the net sink function of the site because of elevated CH_4 emissions. This situation could last for up to 50 years post inundation. The removal of the degraded topsoil would mitigate the risk of elevated CH_4 emissions and accelerate the achievement of an overall reduction in net radiative forcing, potentially in approximately 10 year. Alternatively, by targeting the slow rewetting of the peat soils, as opposed to the creation of a 'treatment' wetland, this will mitigate the generation of CH_4 emissions and will achieve a positive impact on net radiative forcing over a shorter timescale.

Spoil disposal

The concept design presented above has sought to create a 'treatment' wetland that can operate under gravity (with the exception of delivery to Woodwalton Fen) and to minimise the degree of excavation and hence spoil disposal. To satisfy a gravity flow through the four cells, the design will still generated spoil. This spoil could be used to create low-lying bunds around the cell margins to provide additional freeboard and water storage. This could be critical as detritus mud and necromass accumulate in the cells over time and the effective ground surface level raises. The spoil could also be used to partially infill over-deepened ditches elsewhere within the wider Great Fen, thus retaining organic, degraded peat material in a wet condition. An alternative proposal, as described above, would be to use spoil generated to bury areas of *Crassula helmsii* in an attempt to eradicate it from the area of Darlow's Farm.

4 Outstanding issues and recommendations

4.1 Outstanding issues

The analysis and assessment conducted to dates indicates that it would be feasible to bring water from Great Raveley Drain into the four fields at Darlow's Farm to create a restore the degraded peatland. There is also the potential to create a significant area of 'treatment' wetland at the four fields within Darlow's Farm and, by doing so, improve the water quality which could be used to meet the water demand in Woodwalton Fen. A range of issues remain outstanding that require further consideration by FEPP prior to proceeding to the development of detailed designs and costs. These issues include:

- **Peatland restoration or 'treatment' wetland**: The potential exists to achieve both peatland restoration, through surface flooding and lifting water levels across the four compartments, and the creation of a 'treatment' wetland which will restore and protect existing peat soils and provide a source of improved water quality for the NNR. Whilst not mutually exclusive, the final design will depend on resolution of these two elements and an agreement on the preferred outcome.
- ***Crassula helmsii***: The presence of *Crassula helmsii* in very close proximity to the proposed wetland treatment area poses a potentially significant, and potentially illegal, risk to the NNR. The earth works associated with the construction of the wetland treatment cells will create perfect conditions for the colonisation of *Crassula helmsii* across all the cells. The passage of water through the cells and subsequently into the NNR has a high likelihood of mobilising and transporting this plant into the NNR. However, the surplus excavated spoil from the creation of the wetland cells has the potential to be used to bury existing areas of *Crassula helmsii* and potentially stem its spread within the area.
- **Spoil disposal and flood risk**: The initial concept design presented will require a degree of earth moving and reprofiling of the current ground levels creating a surplus of spoil. The entire area of the four compartments of Darlow's Farm is in Flood Zone 3. Usually, the EA would require that any surplus material excavated to be removed into Flood Zone 1. This issue requires further consideration and dialogue with the EA.
- **Water quality improvements**: The calculations conducted in this report provide an indicative estimate of the potential water quality improvements. This estimate should be revisited as the design develops and also as a more precise estimate of the water demand in Woodwalton Fen is defined.
- **Influent location**: The concept design has been predicated on delivering water from the treatment wetland into an unspecified location within the reedbed compartment of Woodwalton Fen. The exact location of a discharge point needs to be identified and resolved prior to conducting a detailed design.
- **Habitat specification**: Options have been presented for the possible vegetation community proposed for the treatment wetland: a diverse tall herb fen community or a mono-specific *Typha* community as a paludiculture crop. Other vegetation communities may also be desirable or a mosaic of different communities could be considered under a peatland restoration scenario. Further consideration is needed by the FEPP regarding the desired vegetation communities.
- **Water supply to the Great Fen**: Access to a water supply from Great Raveley Drain benefits not just the restoration of the four compartments within Darlow's Farm but also provides a source for wider wetland restoration within the Great Fen project area. Whilst the extent and sustainability of this supply needs further investigation, the analysis conducted above demonstrates that there is sufficient water to meet the objectives in the four compartments at Darlow's Farm and to support wider wetland restoration.

- **Management**: The concept design has not considered in detail the management requirements for the treatment wetland. The availability of human and financial resources for managing a treatment wetland can influence design considerations. Further clarification is required on the potential management options prior to developing detailed designs.

4.2 SWOT analyses

Access to a water source from the Great Raveley Drain provides options for wetland creation and restoration. Notwithstanding the wider constraints identified, the availability of water to support wetland habitat creation and restoration presents an excellent opportunity. An analysis of the strengths, weaknesses, opportunities and threats (SWOT) has been conducted to try and provide further insights into the potential trade-offs between targeting peatland restoration and the creation of a treatment wetland through rewetting an area of peatland (Table 5).

The SWOT analysis highlights the positive and negative aspects of the different options. Some of the strengths and weaknesses will depend on the approach taken to implementation, such as target vegetation communities and the extent of groundworks. Some factors are beyond the immediate control of the project but could still influence the opportunities and threats. These will need to be considered as part of longer-term site management objectives. Overall, there is no clear preferred, or least-risk, option with both options providing the potential for positive outcomes.

4.3 Vegetation communities

Options remain, depending on the final approach pursued (peatland restoration or treatment wetland creation, and topsoil removal), regarding the desired vegetation communities to be established. Under both scenarios, there are the alternatives of trying to establish a ‘natural’ fen community or establishing a monoculture crop under paludiculture. The presence of *Crassula helmsii* is a potentially limiting risk factor if the area was left to recolonise from the remnant seed bank and seed dispersal from adjacent areas. Planting, translocation and spreading of harvested plant material are all techniques to be considered in the final design and implementation.

4.4 Alternative solutions and approaches

Whilst this study has indicated that it would be possible to restore an area of degrade peatland and create a ‘treatment’ wetland to tackle water quality issues arising from the transfer of water from Great Raveley Drain to the NNR, there may be other approaches which can contribute to the outcome of improved water quality supply.

A ‘treatment’ wetland represents, in its crudest description, an end of pipe solution. Often it may be more appropriate and sustainable to consider source control and changes to land use or agricultural practices to reduce the input of nutrients to the Drain. It is likely that this may already be occurring, as demonstrated by improved water quality over the longer term. However, distributed solutions, such as in ditch wetlands and riparian buffer zones spread across the wider catchment may contribute to similar water quality improvements and reductions in nutrient levels in the Drain. Longer-term, as land use changes in the Great Raveley Drain result from implementation of aspects of the Great Fen Project, the water quality in the Drain should improve. Consequently, the net benefits of the treatment wetland may be reduced as the water entering may be of a better quality.

A novel approach could be to consider creating floating wetlands within Great Raveley Drain or some of the major drains that feed into it. Whilst such an approach can be challenging, floating wetlands can provide water quality improvements and also increase habitat diversity (Appendix 1).

Table 5. SWOT analysis of options. (GRD – Great Raveley Drain; GHG – Greenhouse Gas; NNR – Woodwalton Fen NNR).

	Strengths (Internal or controlled factors / Helpful or positive aspects)	**Weaknesses** (Internal or controlled factors / Harmful or negative aspects)	**Opportunities** (External or uncontrolled factors / Helpful or positive aspects)	**Threats** (External or uncontrolled factors / Harmful or negative aspects)
Peatland restoration	• Water supply from GRD • Connectivity with NNR and wider habitat enhancements within the Great Fen area • Long-term reduction in GHG emissions from peat degradation • Flexibility in water management options to provide necessary conditions for peatland restoration • Restoration of peat-forming conditions	• Presence and potential spread of *Crassula helmsii* compromising habitat development • May require topsoil removal • Challenge of vegetation community establishment • Potential short-term increase in GHG emissions • Potential short-term release of nutrients from rewetted peat soils	• Provision of water supply to wider Great Fen project area • Connectivity with other habitat enhancements within the Great Fen project • Establishment of paludiculture	• Limits on water abstraction from GRD • Disposal of spoil • Climate change • Increased flood risk • No paludiculture market or infrastructure • Archaeological constraints
Treatment wetland	• Water supply from GRD • Connectivity with NNR and wider habitat enhancements within the Great Fen area • Long-term reduction in GHG emissions from peat degradation • Create new wetland habitats	• Presence and potential spread of *Crassula helmsii* • Risk of introducing *C. helmsii* to NNR • Limitations on provision of peat-forming conditions due to water quality management objectives • Need for planting to ensure vegetation establishment • Potential short-term increase in GHG emissions • Potential short-term release of nutrients from rewetted peat soils	• Provision of improved quality of water discharged to NNR • Provision of water supply to wider Great Fen project area • Connectivity with other habitat enhancements within the Great Fen project • Establishment of paludiculture	• Limits on water abstraction from GRD • Changes in water quality in GRD • Disposal of spoil • Climate change • Increased flood risk • Water quality compromised through paludiculture activities • No paludiculture market or infrastructure • Archaeological constraints

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Appendix 1 – Floating wetlands

Floating wetlands and their potential for removing nutrients from the Great Waverly Drain

Floating wetlands are increasingly being considered as a means of improving water quality in rivers particularly removal of nutrients. Floating wetlands, as the name suggests, consist of floating vegetation that has very limited contact with the bed of the river and therefore derive their nutrients and other elements from the water column alone. Floating wetlands occur naturally in many locations. Studies of the effectiveness has been mainly focused on created or highly managed floating wetlands in urban storm water ponds, mining and refinery plant wastewater, heavily polluted rivers and aquaculture ponds.

Acreman et al. (2023) found 53 scientific publications containing data on the effectiveness of floating wetlands, mainly from Asia (Bangladesh, China, India, Indonesia, Korea, Pakistan, Sri Lanka, Taiwan) but also from other countries worldwide (Australia, Belgium, Egypt, German, Italy, Netherlands, Portugal, UK, Costa Rica, Mexico, USA and Brazil). Most publications reported studies in which polluted water is introduced for treatment to a tank, lagoon or pond containing floating wetlands. In practice, treated water would then be released to a water course. In these studies, there is little flow or replenishment of polluted water; the plants remove pollutants from the same water over a period of time. Almost all the studies concluded that floating wetlands can remove significant amounts of pollutants from water, including heavy metals (*Fe, Mn, Zn, Cu & Pb*), nutrient pollution (N&P), Biological Oxygen Demand (BOD), chemicals (PFAS) and bacteria (*E Coli*). Effectiveness rate varied greatly; some tank studies reported 100% removal, others no removal.

Only three river studies reported data. In China, a wetland across the entire channel width removed 36.9% of total nitrogen, 44.8% of ammonia, 25.6% of nitrate and 43.3% of total phosphorus. A canal study in the USA, where the floating wetland covered only part of the channel, reported lowering of nitrate-as-nitrogen and phosphate by 6.9% and 6.0% respectively. A further study of floating wetland covering part of the channel in India reported a “slow flowing or almost stagnant river”; total nitrogen, ammonia and nitrate were reduced by 37.7%, 39.7% and 10.5% respectively but measurements were taken adjacent to the wetland, so not encompassing flow that would by-pass the facility.

Of the three river studies, the one with a floating wetland across the entire width of the channel showed greater pollutant removal than those that cover part of the channel. Plant species differ in their effectiveness to take-up pollutants. Species reported to be particularly effective at nutrient take-up were common reed (*Phramites Australis*), water hyacinth (*Eichhornia crassipes*), yellow flag iris (*Iris pseudacorus*), jointed rush (*Baumea articulata*) and broadleaf cattail (*Typha Latifolia*), although figures from different studies were inconsistent, perhaps reflecting the influence of other variables. Generally, the highest pollutant removal rates were amongst those plants with the highest biomass production and high transpiration rates. Floating wetlands containing a diversity of species were more effective than single species wetlands. The presence of microbes within a biofilm in the wetland enhanced pollutant removal significantly.

Continued pollutant removal efficiency can be enhanced by regular plant harvesting, which stimulates regrowth and prevents pollutants being re-mobilised back to the water. Whilst harvesting both roots and shoots could maximize nutrient removal, it can be difficult, time consuming, and costly; harvesting the plant shoots is the most practical and cost-effective option.

In addition to pollutant removal, floating wetlands can provide important habitat for birds, fish and invertebrates and plant harvesting produces raw materials for animal feed and biofuel production. However, maintaining these functions (*e.g*. avoiding harvesting during bird nesting) may not be consistent with management for optimum pollutant removal.

Installing and managing a floating wetland in the Great Raveley Drain could be effective for nutrient removal. However, there would be trade-offs. Designing the wetland so that plants can be harvested is difficult. Floating wetlands can restrict navigation and alter flood risk. Some floating wetlands are sources of greenhouse gases, such as nitrous oxide, but others reduce carbon dioxide emissions.

Plate 1. Floating wetlands a. on the Chicago River, USA (Cosier, 2022), b. in the River Kshipra, India (Billore & Sharma, 2009), c. in a eutrophic river in Jiaxing City, China (Zhao *et al*., 2012), d. canal, Chicago, USA (Peterson *et al*., 2021).

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