

# Horsey Mere Dossier

Part of the review of lake restoration practices and their performance in the Broads National Park, 1980-2013

Produced by the Broads Authority January 2016



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# Site by site case histories: Horsey Mere

# **1** Basic site characteristics

Horsey Mere is a shallow brackish coastal lake, which together with Hickling Broad and Heigham Sound forms part of the complex of broads on the Upper Thurne system. The Upper Thurne Broads have a physical tide of 5-10cm that is caused by the confluence of the River Thurne with the tidal section of the River Bure at Thurne Mouth. Horsey Mere is the least influenced by tidal action as it lies the furthest from Thurne Mouth at the head of a narrow channel, Meadow Dyke. The broad also receives a large volume of water from two land drainage pumps, Brogave Mill Pump and Horsey Mill Pump which drain an area of land to the North and East close to the coast. The land draining to the Brogave Mill pump has been progressively converted to arable and improved drainage has penetrated the saline water table resulting in a progressive increase in salinity of Horsey Mere since the 1960s.

Horsey Mere (UK Lake WBID) 35645	TG449222
Location	(Easting 644940, Northing 322212)
Water body area (Ha)	32.75
Mean depth (m)	1.5
Mean alkalinity (mEq/l)	2.89
River system	River Thurne
Connectivity	Riverine
Navigation	Yes
Water Framework Directive water body GB30535645	Phosphorus boundary values High/Good: 44 µgl <sup>-1</sup> Good/Moderate 62 µgl <sup>-1</sup> Moderate/Poor 123µgl <sup>-1</sup> Poor/Bad 246µgl-1 Chlorophyll boundary values High/Good 9 µgl <sup>-1</sup> Good/Moderate 20 µgl <sup>-1</sup> Moderate/Poor 39 µgl-1 Poor/Bad 118 µgl-1
Water Framework Directive Status (2012)	Moderate Ecological Potential Phytoplankton: Moderate Macrophytes: Moderate Phytobenthos: not classified Invertebrates: not classified Fish: N/A Phosphorus: Good Ammonia: not assessed

#### Table 1 Basic site characteristics for Horsey Mere



Figure 1 Geographical context of Horsey Mere showing

# 2 Palaeolimnology

No data are currently available

# 3 Chronology of management activities and key events

Date	Description
	No significant management interventions during period of data

Table 2 Chronology of management activities and key events for Horsey Mere

# 4 Water quality

Data prior to 1980 from UEA studies is available, but has not been collated for this work due to lack of resource. It will be made available in subsequent updates of the dossier.

# 4.1 Total Phosphorus

There has been no significant trend in the total phosphorus concentration of Horsey Mere either over the period of monitoring from 1979 to 2012 (Mann Kendall tau = 0.202, p=0.108), or in the last decade (Mann Kendall tau = 0.357, p=0.265). Total phosphorus is relatively low (median annual mean last decade of 48  $\mu$ gl<sup>-1</sup>) resulting in a current WFD classification of Good status Figure 2. Concentrations have fluctuated over the period of monitoring with highest values occurring at the same time as higher concentrations of total phosphorus in the discharges from the Brograve and Horsey Mill land drainage pumps (Figure 3). The concentration of total phosphorus discharged from Brograve Mill has declined significantly (Mann Kendall tau = -0.495, p<0.001), while that from Horsey Mill pump has increased significantly (Mann Kendall tau = 0.37, p=0.003).

Total phosphorus concentration in Horsey Mere is highest in the late summer (Figure 3b) and there is some evidence that this summer peak is getting longer (Bivariate GAM model which includes an interaction with year was significantly better than mixed gam model), extending from May to October in 2012, while it was from July to October at the start of the monitoring period (Figure 3c). As a result, there has been a just significant (Mann Kendall tau = 0.276, p=0.019) increasing trend of the ratio of summer/winter TP (Figure 4). While this might be interpreted as indicative of an increasing impact of sediment released phosphorus it is more likely an effect of

a changing balance of phosphorus inputs from the land drainage pumps and potentially a changed influence of tidal mixing from Heigham Sound.

Without data on volume of water pumped into Horsey Mere it is impossible to determine the relative importance of each of the pumps. Total phosphorus concentration in Brograve pump has no significant seasonality, while that of Horsey Mill pump has the lowest concentration in late spring and the highest in later summer (Figure 5). Prior to 1995 the concentration of total phosphorus in these two pumps were similar, but since 2001 the concentration in Brograve was significantly lower (Figure 6). The reason for this change is not known, but the net effect on Horsey appears to have been no significant overall change in annual mean concentration, but higher values in the summer, perhaps from inputs from Horsey Mill pump. Comparing the smoothed long-term trends of total phosphorus in Horsey Mere with those in Brograve and Horsey Mill pumps confirms that Horsey Mill pump has the greatest similarity with peaks at the same time (Figure 7a & b). These peaks occur shortly after periods of lower river flow (Figure 7c), itself an index of effective rainfall buffered by ground water inputs. Using a generalized linear model (with an autoregressive correlation structure to minimise temporal autocorrelation) to relate the smoothers for TP in the pumps with that in Horsey Mere demonstrates that the total phosphorus concentration in Horsey Mill pump is the most important predictor of total phosphorus in Horsey Mere and that river discharge is also a significant predictor (Table 3). It is important not to pay too much attention to the significance levels of these relationships as the data are smooths and not individual data points, but they suggest that it is phosphorus inputs from Horsey Mill pump and the influence of effective rainfall that are important in determining the total phosphorus of Horsey Mere. This is a slightly surprising conclusion as it has always been assumed that as Brograve pumps a larger volume than Horsey Mill it is more likely to be the most significant influence on the broad. Given the lack of data on pumped volumes it is important to treat this conclusion as tentative and further analysis would be appropriate if longterm reliable records of pumping rates can be collated.



Figure 2 Trend in annual mean TP µgl<sup>-1</sup> for Horsey Mere (solid black line), compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers. Horizontal lines mark WFD boundary values.



Figure 3 Changes in TP (µgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend (Julian Days); c) contour plot showing changes in seasonality with time. (Trends extracted using GAM model, contour plot using a bi-variate GAM model)





Figure 4 Trend in ratio of summer/winter mean TP (µgl<sup>-1</sup>) for Horsey Mere, horizontal line marks 1:1 ratio

Figure 5 Changes in TP (µgl<sup>-1</sup>) for: a) Brograve Mill Pump, Long term trend (Annual); b) Brograve Mill Pump, Seasonal trend, c) Horesy Mill Pump, Long term trend (Annual) and d) Horsey Mill Pump, Seasonal trend. Trends extracted using GAMM models from monthly data



Total P Horsey Mill Pump µg/I

Figure 6 Relationship between annual mean total phosphorus (µgl<sup>-1</sup>) in Brograve and Horsey Mill Pump discharges (1987-1996 & 2001-2012). Red dotted line shows 1:1 relationship.



Figure 7 Comparison of long term GAM smooth trends of TP (µgl<sup>-1</sup>) for Horsey Mere (black line) with a) trend for TP in Horsey Mill Pump (dotted red line), b) trend for TP in Brograve Mill Pump and c) River Ant discharge (m<sup>3</sup>s<sup>-1</sup>). Trends extracted using GAM models on monthly data. (All values centred on long-term mean value)

Table 3 Model fit for Generalized least squares model (with AR(1) correlation structure) for relationship between long term trend smooths for TP in Horsey Mere, TP in Brograve and Horsey Mill pump discharges and discharge of River Ant.

```
AIC
         BIC logLik
 183.9374 192.5413 -85.96871
Correlation Structure: AR(1)
 Formula: ~1
 Parameter estimate(s):
   Phi
0.7928827
Coefficients:
        Value Std.Error t-value p-value
(Intercept) -1.76967 3.173415 -0.557653 0.5817
s.TP_Hor_p. 0.40705 0.060490 6.729112 0.0000
s.TP_Brog_p. 0.01761 0.084906 0.207425 0.8372
s.Disch_Hon. -65.27397 24.733715 -2.639069 0.0136
 Correlation:
       (Intr) s.TP_H s.TP_B
s.TP_Hor_p. 0.011
s.TP_Brog_p. -0.019 -0.432
s.Disch Hon. 0.011 -0.424 0.223
Standardized residuals:
   Min
           01
                Med
                         Q3
                                Мах
-2.0824925 -0.7062014 0.2669386 0.7382338 2.3542643
Residual standard error: 6.256308
Degrees of freedom: 31 total; 27 residual
```

#### 4.2 Soluble Reactive Phosphorus

Soluble reactive phosphorus is extremely low in Horsey Mere (Figure 8) with no significant trend (Mann Kendall tau = 0.037 p=0.392). There is no clear seasonal variation of soluble phosphorus in Horsey Mere and no evidence of summer peaks, unlike most other broads (Figure 9b & c).

In contrast to the Broad there is a significant increase in soluble phosphorus in Horning Pump (Mann Kendall tau = 0.232, p=0.037) but no trend for soluble phosphorus in Brogave Pump, where concentrations are extremely low.



Figure 8 Trend in annual mean SRP (µgl<sup>-1</sup>) for Horsey Mere compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers.



Figure 9 Changes in SRP (µgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend (Julian Days); c) contour plot showing changes in seasonality with time. (Trends extracted using GAM model, contour plot using GAM model)

# 4.3 Total Oxidised Nitrogen (TON)

As for other broads there has been a slight but significant decline in annual total oxidised nitrogen in Horsey Mere since 1980 (Mann Kendall tau = -0.32, p=0.008) (Figure 10). Unlike other broads and in particular Hickling Broad there has not been a similar decline in winter total oxidised nitrogen, which is relatively high with a median concentration of 1.36 mgNl<sup>-1</sup> over the last decade. The changes in winter total oxidised nitrogen in Horsey Mere are similar to those seen in Hickling and are likely to be influenced by rainfall, with peaks occurring when river discharge and thus rainfall were high. In general, the trend in Horsey Mere is reflected in the trends for Brograve and Horsey Mill pumps, with higher concentrations in Brograve pump.

Seasonality of total oxidised nitrogen is typical of most broads, with maximum values in February which decline to reach a minimum in June (Figure 12b). This decline is slower than in Hickling Broad where minimum values occur by May. Similarly, autumn levels increase slightly earlier in Horsey than in Hickling, reflecting the importance of the direct pumped inputs from Brograve and Horsey Mill pumps.

As soluble reactive phosphorus in Horsey Mere has remained unchanged the ratio of summer TON/SRP has declined slightly (Mann Kendall tau = -0.266, p=0.017) although it has generally remained above 20 with a median value over the last decade of 38 (Figure 13) which is typical of other riverine broads. There is thus no evidence for nitrogen limitation of the phytoplankton in Horsey Mere (Figure 14).



Figure 10 Trend in annual mean TON (mgNl<sup>-1</sup>) for Horsey Mere (solid black line) compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers.



Figure 11 Trend in winter (Nov-Feb) mean TON (mgNI<sup>-1</sup>) for Horsey Mere (solid black line), showing GAM smoother



Figure 12 Changes in TON (mgNl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend (Julian Days). (Trends extracted using GAM model); c) contour plot showing changes in seasonality with time.



Figure 13 Trend in ratio of summer mean TON/SRP in Horsey Mere. Horizontal line marks Redfield ratio.



Figure 14 Changes in SRP\_TON for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend (Julian Days). (Trends extracted using GAM model); c) contour plot showing changes in seasonality with time. (Trends extracted using GAM model, contour plot using GAM model)

#### 4.4 Chloride

In common with the other Thurne Broads, chloride levels in Horsey Mere are high giving rise to brackish conditions. Chloride concentrations in Horsey Mere have shown little long-term change since 1980, with a median annual value of 2600 mgL<sup>-1</sup>, the highest of all the monitored broads. These high concentrations reflect the saline influence on the drainage ditches in the catchments of both Brograve and Horsey Mill pumps. The highest concentrations are in the Brograve discharge (median annual mean 2843 mgL<sup>-1</sup>) with those from Horsey Mill being slightly lower (median annual mean 2089 mgL<sup>-1</sup>). There has been no significant trend in the concentration in the Brograve discharge (Mann Kendall tau = -0.145, p=0.16) but a just significant increase in the Horsey Mill discharge (Mann Kendall tau = 0.269, p=0.018).

As for other Thurne broads the highest concentrations occurred in the mid-1990s (Figure 16a). Surprisingly this is not clearly related to the long-term trends in chloride in the pump discharges (Figure 18a). Peaks in the long-term trend for chloride in Brograve and Horsey Mill pumps are clearly related to each other, with peaks occurring during years when river discharge was low (Figure 18b). However, the high chloride that occurred in the mid-1990s in Horsey Mere is only partially seen in the trends from the pumps.

The seasonal changes of chloride in Horsey Mere show a minimum in February with maxima in June and September (Figure 17). The general seasonal trend follows that of the pump discharges, particularly Brogave pump. In the winter Horsey has the lowest chloride levels, reflecting the dominance of the inputs from Brograve pump. During July and August chloride levels dip reflecting the reduced pump input and maximum influence of mixing with Hickling broad (Figure 17)



Figure 15 Trend in annual mean chloride (mgl<sup>-1</sup>) for Horsey Mere (solid black line) compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers



Figure 16 Changes in chloride (mgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend; c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)



Figure 17 Seasonal smoothers for chloride concentration (mgl<sup>-1</sup>) in Horsey Mere (black line), compared with Hickling Broad (broken black line), Brograve Pump (dotted red line) and Horsey Mere (dotted blue line). (Smooths extracted using mixed GAM model)



Figure 18 Comparison of long-term trends for a) chloride concentration (mgl<sup>-1</sup>) in Horsey Mere (solid black line), Brograve pump (dotted red line) and Horsey Mill pump (dotted blue line) compared with b) long-term trend for river discharge (m<sup>3</sup>s<sup>-1</sup>). (Trends extracted using GAM models, values centred on long-term average)

#### 4.5 Total Iron

Total iron in Horsey Mere is high (Figure 19), with a median annual mean value of 971  $\mu$ gl<sup>-1</sup> in comparison to 202  $\mu$ gl<sup>-1</sup> in Hickling. This is due to the very high concentration of total iron discharged from the Brograve pump, which has concentrations an order of magnitude higher than those measured in Horsey Mere. The difference is a result of settlement of much of particulate iron between the pump discharge and Horsey Mere in Waxham Cut. Since 1980 total iron levels have fluctuated in concentration, with lowest values in 1989 and 1990, a period of particularly low river discharge and rainfall. However, there has been a significant increasing trend of total iron in Horsey Mere (Mann Kendall tau = 0.353, p=0.007).

The seasonal pattern of total iron in Horsey Mere shows maximum values in the winter, when pumped discharge is highest (Figure 20b). A similar pattern occurs in both Brograve and Horsey

Mill pumps, almost certainly reflecting their pumping regimes (Figure 21 & Figure 22). Unfortunately, there is no recent data for total iron for theses drainage pumps, but it is very likely that the increase in total iron in Horsey Mere will be due to changes in the pumps. There is some evidence that the most recent increase is occurring during the summer period (Figure 20c) and this may reflect a change to pumping regimes. Given the potential importance of iron levels on macrophytes it is suggested that consideration is given to monitoring of total iron levels in the Thurne land drainage pump discharges.



Figure 19 Trend in annual mean total iron (µgl<sup>-1</sup>) for Horsey Mere (solid black line), compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers



Figure 20 Changes in total iron (µgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend (Julian Days); c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)







#### Figure 22 Changes in total iron for Horsey Mill pump: a) Long term trend (Annual); b) Seasonal trend (Julian Days); c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)

# 4.6 Suspended Solids

There is a slight, just significant decreasing trend of suspended solids in Horsey Mere (Mann Kenall tau = -0.29, p=0.031), however there were no monitoring for this suspended solids during the mid to late 1990s (Figure 19) and there have probably been several longer term fluctuations which are similar to Hickling Broad. The highest concentrations occur during the summer, particularly in the early 1990s (Figure 24c). This might be caused by phytoplankton, but there is no similar peak of chlorophyll during this period (Figure 28c) and there is a very poor relationship between suspended solids and chlorophyll a (Figure 45) so although phytoplankton are likely to be a contributory factor this is unlikely to be the full explanation.

Comparing the seasonal pattern of suspended solids in Brogave and Horsey Mill drainage pumps with that of Horsey Mere does not suggest that solid levels were particularly high during the summer period of the early 1990s, rather that in Brogave levels were highest in the winter, probably linked to high particulate iron (Figure 25 & Figure 26). Concentration of suspended solids in Brogave have however decreased substantially in the last decade, while those in Horsey Mill pump have increased, particularly during the summer. These changes are very similar to those for total phosphorus, although the cause is not known.



Figure 23 Trend in annual mean suspended solids (mgl<sup>-1</sup>) for Horsey Mere (solid black line), ) compared with trends in Brograve pump (broken blue line) and Horsey Mill pump (broken red line) showing GAM smoothers



Figure 24 Changes in suspended solids (mgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend; c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)



Figure 25 Changes in suspended solids (mgl<sup>-1</sup>) for Brograve Pump: a) Long term trend (Annual); b) Seasonal trend; c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)



#### Figure 26 Changes in suspended for Horsey Mill Pump: a) Long term trend (Annual); b) Seasonal trend; c) contour plot showing changes in seasonality with time. (Trends extracted using mixed GAM model, contour plot using GAM model)

# 4.7 Chlorophyll a

The chlorophyll a concentration in Horsey Mere is lower than Hickling Broad, but still relatively high with a median annual mean concentration for the last decade of  $24 \ \mu gl^{-1}$  placing the broad in moderate status for the WFD. Concentrations have fluctuated during the monitoring period (Figure 27) and are similar to those seen in Hickling Broad. However, unlike Hickling, where levels decreased significantly, there has been no significant long-term trend in Horsey Mere (Mann Kendall tau = -0.064, p=0.30) (Figure 28a).

The seasonal pattern of Chlorophyll in Horsey shows a bimodal pattern with peaks in April and the late autumn. The April peak is much lower and there is only a slight decrease in concentration before the summer/autumn peak (Figure 28b). This is a very different pattern to that seen in Hickling, where the spring peak is much higher and is probably caused by the high spring flushing rate of Horsey Mere due to the large drainage pump inputs. Using AIC to select the most appropriate GAM model suggests that the bivariate GAM model incorporating an interaction between Year and Month is not significantly better thus there is no strong evidence that the seasonal pattern has changed since 1980. However, a plot of mean chlorophyll for May to July (Figure 40b) does show an increasing trend which is just significant (Mann Kendall tau =

0.258, p = 0.018). Thus the chlorophyll levels in Horsey Mere show considerable inter-annual variation with an indication of a slight increase in the onset of the summer algal population.



Figure 27 Trend in annual mean chlorophyll a (µgl<sup>-1</sup>) for Horsey Mere (solid black line), showing GAM smoother.



Figure 28 Changes in Chlorophyll a (µgl<sup>-1</sup>) for Horsey Mere: a) Long term trend (Annual); b) Seasonal trend; c) contour plot showing changes in seasonality.

# 4.8 Chlorophyll a:Total Phosphorus ratio

The chlorophyll/TP ratio for Horsey Mere is relatively high with a median annual mean value of 0.49 over the last decade. The ratio shows no significant long-term trend (Mann Kendall tau = -0.085, p = 0.25) and is consistent with the brackish nature of Horsey Mere and the lack of any significant zooplankton grazing.



# Figure 29 Trend in annual mean chlorophyll a/TP ratio for Horsey Mere (solid black line) showing GAM smoothers

# 4.9 Sechhi Depth

Since 1978 Secchi depth measurements have fluctuated, but show a very slight decreasing long-term trend (Mann Kendall tau = -0.21, p=0.047) (Figure 30). These fluctuations, showing similar changes to those in Hickling Broad. In Horsey Mere water transparency is lower than might be expected from the general relationship between Secchi depth and chlorophyll for all broads (Figure 32) suggesting the importance of other sources of turbidity, such as suspended solids. There is a less convincing relationship between Secchi depth and suspended solids (Figure 32) than for chlorophyll but both can be show to be important in a multivariate model (Figure 33). The relationships are linear except at extremes and by standardising the variables prior to fitting a linear model the resulting regression coefficients can be used to show the relative importance of the variables (Table 4) The relationship is highly significant ( $R^2 = 0.58$  p<0.001) with both chlorophyll and suspended solids as significant predictors with suspended solids being the most important. Thus transparency in Horsey Mere is influenced by both biotic and abiotic factors.



Figure 30 Trend in annual mean Secchi depth for Horsey Mere showing GAM smother.



Figure 31 Relationship between water transparency (Secchi depth m) and chlorophyll a  $(\mu gl^{-1})$  in Horsey Mere. Lines show GAM smoothers for all broads (black) and for Horsey Mere (blue). (Data shown are only for samples where secchi depth is < water depth).



Figure 32 Relationship between water transparency (Secchi depth) and suspended solids (mgl<sup>-1</sup>) in Horsey Mere. Lines show GAM smoothers for all broads (black) and for Hickling (blue). (Data shown are only for samples where secchi depth is < water depth).



Figure 33 GAM model smooths showing prediction of Secchi Depth transparency by a) chlorophyll a and b) suspended solids for Horsey Mere. (Data shown are only for samples where secchi depth is < water depth).

Table 4 Linear Model predicting Secchi Depth from Chlorophyll and Total Suspended Solids using sample data where Secchi Depth is < water depth (variables scaled prior to fitting model).

```
Residuals:
      1Q Median
Min
                  3Q
                      Мах
-2.7887 -0.3153 -0.0370 0.2421 3.9271
Coefficients:
Estimate Std. Error t value Pr(>|t|)
(Intercept)
               0.17833 0.01233 14.47 <2e-16 ***
scale(log10(Chl)) -0.21055 0.01742 -12.09 <2e-16 ***
scale(log10(SS)) -0.64966 0.01678 -38.72 <2e-16 ***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.5827 on 2630 degrees of freedom
(8343 observations deleted due to missingness)
Multiple R-squared: 0.5808, Adjusted R-squared: 0.5805
F-statistic: 1822 on 2 and 2630 DF, p-value: < 2.2e-16
```

# 5 Macrophytes

### 5.10 Cover: macrophytes and algae

There has been a significant decline in cover (Mann Kendall tau = -0.569 p < 0.001), mostly in the "brackish" species, Myriophyllum spicatum and Potamogeton pectinatus (Figure 34, 35 & Figure 35) with the greatest change occurring since 2000 when macrophytes were also lost from Hickling Broad. There was a small increase in the cover of Charophyte taxa in Horsey Mere in 1999 which occurred at the same time as the very substantial increase in Chara in Hickling Broad.



Figure 34 Trend in cover of non-algal macrophytes for Horsey Mere (solid black line), showing GAM smoother.



Figure 35 Trend in macrophyte species in Horsey Mere.



Figure 36 Trend in algal macrophyte cover for Horsey Mere.

#### 5.11 Species richness

There are relatively few species in Horsey Mere and diversity has declined since 2004 (Figure 37)



Figure 37 Trend in macrophyte species richness for Horsey Mere (solid black line), showing GAM smoother.

**5.12 Compositional change (Major growth forms; Change Index and LMNI)** There has been no significant change in the growth form or LMNI index of macrophytes in Horsey Mere (Figure 38 & Figure 39)



Figure 38 Trend in macrophyte Change Index for Horsey Mere.



Figure 39 Trend in lake macrophyte nutrient index (LMNI) for Horsey Mere (solid black line), showing GAM smoother.

#### 6 Summary of interactions

There has been a significant decline in macrophyte cover since the mid-1990s, mostly associated with the brackish species (M.spicatum, P.pectinatus, H. vulgaris). There have been slight increases in early summer chlorophyll a (May – July) and a more marked increase in total iron, particularly since 2006. The changes in total iron and chlorophyll occur at a similar time to the decline in macrophyte cover. There is no clear relationship between either rainfall or hours of sunshine and macrophyte cover (Figure 40).



Figure 40 Comparison of annual time series in Horsey Mere for a) cover of Charophytes + Najas (solid line) & M.spicatum + P.pectinatus + H.vulgaris (blue dotted line) b)mean May-July chlorophyll a ( $\mu$ g.l<sup>-1</sup>), c) annual mean total phosphorus ( $\mu$ gl<sup>-1</sup>), d) annual mean total iron ( $\mu$ g l<sup>-1</sup>), e) annual mean river discharge (m3.d<sup>-1</sup>) and f) 95<sup>th</sup> percentile of hours of sun

#### 6.13 Macrophytes and water quality

There are relatively weak relationships between non-algal macrophyte cover and chlorophyll and non-algal cover and total phosphorus in Horsey Mere (Figure 41 & Figure 42). However, there is a much stronger, approximately linear relationship with total iron (Figure 43), with macrophyte cover increasing as total iron reduces. A linear regression model illustrates this with a highly significant R<sup>2</sup> of 0.69 (p<0.001) when both total iron and chlorophyll a are included as predictors (Table 5). A slightly better model replaces chlorophyll with Secchi Depth transparency (R<sup>2</sup> = 0.75 p<0.001) (Table 6), but shows that suspended solids is not a significant predictor. Given that suspended solids and chlorophyll a were significant predictors of Secchi Depth it is not surprising that including transparency in the model directly improves the relationship. It is thus concluded that the decrease in cover of macrophytes in Horsey Mere is coincident with a decreased water transparency, and also that of total iron. Comparing the value of the coefficients using scaled data to fit the model suggests that both total iron and Secchi disc transparency are equally important, although the uncertainty associated with total iron is considerably less.



Figure 41 Relationship between non-algal macrophyte cover and mean chlorophyll a, showing trajectory of change in Horsey Mere. Grey points mark values for all other broads



Figure 42 Relationship between non-algal macrophyte cover and total phosphorus, showing trajectory of change in Horsey Mere. Grey points mark values for all other broads



Figure 43 Relationship between non-algal macrophyte cover and total iron, showing trajectory of change in Horsey Mere. Grey points mark values for all other broads

Table 5 Linear model predicting cover of non-algal macrophytes from Total Iron, Chlorophyll and Suspended Solids

```
Residuals:
 Min
       10 Median
                    3Q
                         Мах
-20.870 -11.528 -5.973 11.996 30.830
Coefficients:
          Estimate Std. Error t value Pr(>|t|)
                347.14 78.33 4.432 0.000677 ***
(Intercept)
                         17.84 -4.974 0.000254 ***
log10(Fe6051)
                -88.73
log10(Chl_AprSept) -50.31 23.27 -2.162 0.049833 *
                 34.49 43.12 0.800 0.438205
log10(ss_mgl)
_ _ _
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 16.23 on 13 degrees of freedom
 (11 observations deleted due to missingness)
Multiple R-squared: 0.7498, Adjusted R-squared: 0.6921
F-statistic: 12.99 on 3 and 13 DF, p-value: 0.0003299
```

Table 6 Linear model predicting cover of non-algal macrophytes from Total Iron andSecchi Depth transparency

```
Residuals:
 Min
      1Q Median
                  3Q
                        Мах
-16.821 -12.376 -2.247 12.784 22.042
Coefficients:
      Estimate Std. Error t value Pr(>|t|)
                      64.84 3.175 0.00675 **
(Intercept)
             205.83
log10(Fe6051) -72.27
                       17.28 -4.183 0.00092 ***
                37.02 2.858 0.01265 *
SD
        105.80
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 14.51 on 14 degrees of freedom
(11 observations deleted due to missingness)
Multiple R-squared: 0.7847, Adjusted R-squared: 0.754
F-statistic: 25.52 on 2 and 14 DF, p-value: 2.142e-05
```

 Table 7 Linear model predicting cover of non-algal macrophytes from Total Iron and

 Secchi Depth transparency using scaled data to allow comparison of coefficients

```
Residuals:
  Min
         10 Median
                       3Q
                            Мах
-0.62459 -0.45954 -0.08342 0.47469 0.81847
Coefficients:
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)
                     -0.03793 0.13196 -0.287 0.77798
scale(log10(Fe6051)) -0.52116 0.12458 -4.183 0.00092 ***
scale(SD)
                      0.43637 0.15268 2.858 0.01265 *
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.5388 on 14 degrees of freedom
(11 observations deleted due to missingness)
Multiple R-squared: 0.7847, Adjusted R-squared: 0.754
F-statistic: 25.52 on 2 and 14 DF, p-value: 2.142e-05
```

#### 6.14 Chlorophyll v TP

Like Hickling Broad the yield of chlorophyll a per unit of TP is high, confirming that there is little evidence of grazing by zooplankton, which is not surprising given the high salinity of the broad (Figure 44).

There is no relationship between chlorophyll and total suspended solids (Figure 45) confirming that the suspended matter is not primarily caused by phytoplankton and is most likely the result of suspended iron hydroxides.



Figure 44 Relationship between annual mean chlorophyll a and total phosphorus, showing trajectory of change in Horsey Mere Grey points mark values for all other broads, horizontal and vertical dotted lines show WFD boundary values, diagonal dotted lines show relationship for European lakes (Phillips et al. 2008).



Figure 45 Relationship between annual mean chlorophyll a and suspended solids in Horsey Mere (blue points), grey points mark values for all other broads.

# 7 Evidence of overall system response to management

Although TP concentration and phytoplankton abundance in Horsey Mere are only moderate, significantly lower than in Hickling Broad the lake contains relatively few macrophytes. Their abundance has declined since 2000 and is associated with an increase in total iron, with both TP and chlorophyll concentrations remaining largely unchanged. There are fewer data available for total iron, but it is clear from regression models that macrophyte cover is significantly inversely related to total iron. Particulate iron, in the form of iron hydroxide (ochre) is the main factor controlling water clarity and probably macrophyte abundance in the broad.

The primary source of ochre are the land drainage pumps and it is unfortunate that no recent data are available to determine the concentrations that have been discharged to the broad in recent years. However, the general increase in rainfall is likely to have resulted in larger pumped volumes and consequently a greater input of ochre which may have been the most significant factor reducing macrophyte abundance

# 8 Future management options

Further work is needed to determine the importance of particulate iron inputs to Horsey Mere. Ochre has long been recognised as an issue (Holman and White 2008) in the Horsey catchment and action to reduce it is the most likely beneficial management action.

Given the potential importance of iron it is strongly recommended that existing monitoring of water quality of the land drainage pump discharges is extended to include total iron.

# 9 References

Holman, I. & S. White, 2008. Synthesis of the Upper Thurne Research and Recommendations for Management. Report to the Broads Authority. Cranfield University. available.

Phillips, G., O. P. Pietiläinen, L. Carvalho, A. Solimini, A. Lyche Solheim & A. Cardoso, 2008. Chlorophyll– nutrient relationships of different lake types using a large European dataset. Aquat Ecol 42(2):213-226.