Improvement Programme for England’s Natura 2000 Sites (IPENS) – Planning for the Future IPENS032

An Investigation into the Nutrient Levels of Breckland Fluctuating Meres

Breckland Special Area of Conservation (SAC) and Special Protection Area (SPA)

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Foreword

The **Improvement Programme for England's Natura 2000 sites (IPENS)**, supported by European Union LIFE+ funding, is a new strategic approach to managing England's Natura 2000 sites. It is enabling Natural England, the Environment Agency, and other key partners to plan what, how, where and when they will target their efforts on Natura 2000 sites and areas surrounding them.

As part of the IPENS programme, we are identifying gaps in our knowledge and, where possible, addressing these through a range of evidence projects. The project findings are being used to help develop our Theme Plans and Site Improvement Plans. This report is one of the evidence project studies we commissioned.

Aquifer-fed naturally fluctuating water bodies, such as the Breckland Fluctuating Meres, are a rare and threatened habitat under the EU Habitats Directive and the UK Biodiversity Action Plan. These water bodies are also listed in Water Framework Directive River Basin Management Plans, which require water dependent features within EU Habitats Directive protected areas to be brought into favourable conservation status.

Following aquatic and terrestrial surveys in 2011 elevated nutrient levels were detected in some of the Breckland meres. Nutrient enrichment is widely acknowledged to be the most significant pressure affecting lakes in England.

This study was commissioned to assess the scale of the nutrient problem and possible causes, and to put forward management options for resolving the issue. As variations in nutrient levels within the meres may simply form part of the natural cycle, a further outcome from the study was to gain a better understanding of how the system functions.

A desk study was carried out to collate and review existing data and fieldwork. Water sampling and a sediments assessment was undertaken to identify the key nutrient inputs to the site. A detailed nitrogen and phosphorus budget has been produced for each individual mere.

The resulting report increases our knowledge of the fluctuating meres and will inform and influence future monitoring and conservation management strategies. Issues covered in this report are incorporated into the Breckland Site Improvement Plan.

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An Investigation into the Nutrient Levels of Breckland Fluctuating Meres - Phase 2

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1. Introduction

1.1 Site description

The Breckland Fluctuating Meres are aquifer-fed, naturally fluctuating water bodies located near Thetford, Norfolk. This habitat type is defined by the UK Biodiversity Action Plan as having ‘an intrinsic regime of extreme fluctuation in water level, with periods of complete or almost complete drying out as part of the natural cycle. They have no inflow or outflow streams at the surface, except at times of very high water level, when temporary out-flows may develop. Instead, they are directly connected to the underlying groundwater system and periodically empty and are recharged via swallow holes or smaller openings in their beds’ (Maddock 2008). Groundwater is therefore the main source and sink for their water (Binnie and partners 1973, Jefferies 1992). Fluctuating meres are defined as a rare and threatened habitat under the EU Habitats Directive.

The meres lie within the Breckland biogeographical region, which is characterised by freely-draining, sandy soils, and a drier, more continental climate than the rest of the UK (Dolman *et al.,* 2010). Two sites in the region have been designated as SSSIs (Figure 1.1), namely Stanford Training Area SSSI, which contains Home Mere, Devil’s Punch Bowl and Fowl Mere, and East Wretham Heath SSSI, which contains Langmere and Ringmere (Figure 1.2). The location of the meres within the SSSIs is shown in Figure 1.1. All of the meres fall within a Nitrate Vulnerable Zone (NVZ), as well as being within the Breckland Special Area of Conservation and Special Protection Area (data from www.magic.co.uk, accessed January 2015).

1.2 Background to the project

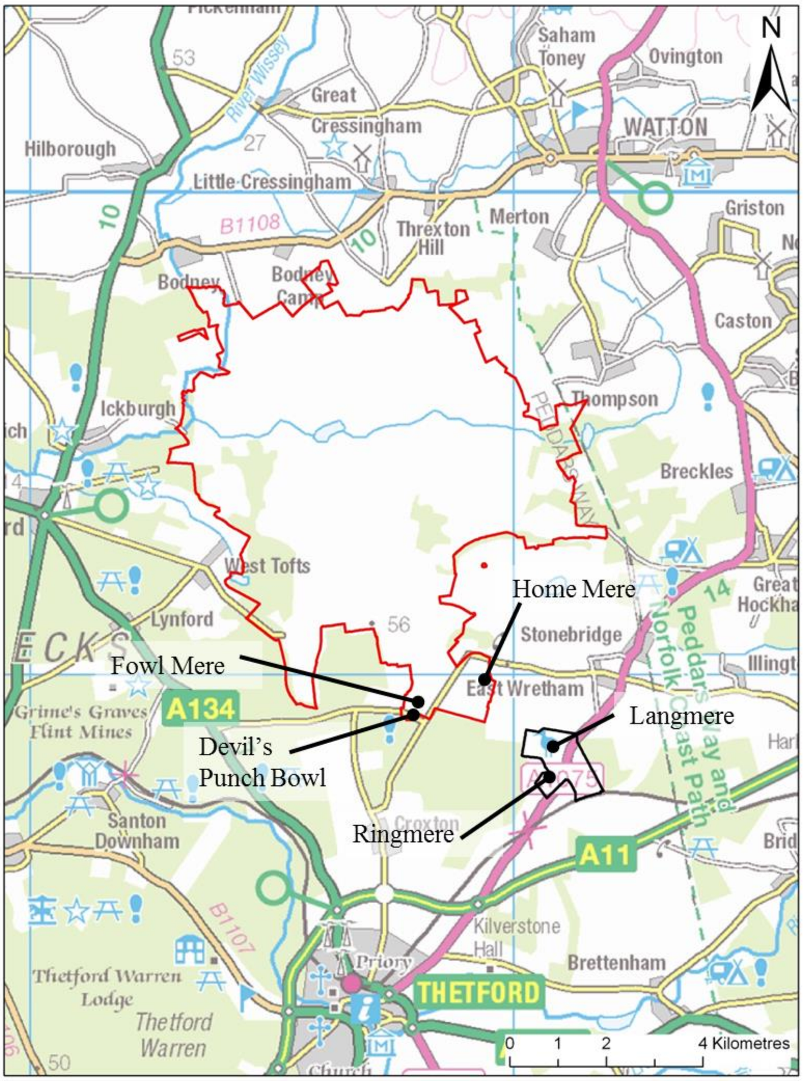
This work constitutes Phase 2 of a project which aims to provide a detailed understanding of the meres in order to inform effective management decisions.

Phase 1 (APEM 2013) carried out an initial investigation of the three fluctuating meres on Stanford Training Area SSSI (Home Mere, Fowl Mere and Devil’s Punch Bowl), and the two meres on East Wretham Heath SSSI (Langmere and Ringmere). A desk study and six month water quality data collection was carried out, following which a draft nutrient budget was created. This had various limitations, of which the key ones were that data collected in spring and summer were not available and that water level fluctuations were estimated from occasional sites visits rather than continuous measurement.

Phase 2 aimed to overcome these limitations by collecting data over an entire year and by precise monitoring of water levels. The range of data collected was also extended, to cover atmospheric inputs and local borehole water quality. Phase 2 was restricted to a study of Ringmere and Langmere, which were chosen for the detailed study for the following reasons:

- Evidence from vegetation surveys that the sites were possibly suffering from nutrient enrichment (Stewart 2012);
- Uncertainties regarding nutrient loads in the preliminary nutrient budgets developed for these sites during Phase 1;

- The proximity of both sites to existing groundwater boreholes;
- The availability of bird count data for the sites;
- The greater likelihood that the sites would contain water during the study as they dry less frequently than the other sites;
- The sites' proximity to each other, ensuring that resources could be invested wisely.



Stanford Training Area SSSI (red) and East Wretham Heath SSSI (black)

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Figure 1.1 Map showing location of Stanford Training Area SSSI (containing Home Mere, Devil's Punch Bowl and Fowl Mere) and East Wretham Heath SSSI (containing Langmere and Ringmere)

Figure 1.2 Satellite view of Langmere and Ringmere showing their relative location.
In this image Langmere is almost dry. Image from GoogleEarth (Imagery ©2015 DigitalGlobe, Getmapping plc, Infoterra Ltd and Bluesky), image copied January 2015.

1.3 Aim and objectives

The aim of Phase 2 of this work was to describe nutrient dynamics within the two fluctuating meres under study. In comparison with Phase 1, the intention was to reduce uncertainty in the apportionment of N and P budgets to the two meres through the increased quantification of nutrient sources and internal mobilisation mechanisms.

The objectives of Phase 2 were:

- to provide a detailed understanding of water level fluctuations within the meres over an annual cycle;
- to determine seasonal fluctuations in water nutrient concentrations;
- to determine the nutrient input and load apportioned from groundwater;
- to determine sediment nutrient concentrations and to estimate nutrient release rates from the sediment;
- to determine the contribution of precipitation and airborne (particulate and aerosol) nutrient deposition to the overall nutrient budget within two meres;
- to record the seasonal (spring and autumn) occurrence, abundance and species richness of macrophytes and shore line plants, with particular reference to those that indicate high nitrogen concentrations;

- to calculate a nutrient budget and source apportionment for each mere;
- to produce a series of recommendations to inform and guide management on how to sustain and enhance the ecology of the meres for the future.

Recent work by Lambert and Davy (2011) showed that atmospheric ammonia concentrations on East Wretham Heath, assumed to be derived from agricultural sources, had a mean of 5.03 µg m^{-3} and a peak of 11.80 µg m^{-3}, above the critical level for vegetation of 3 µg m^{-3} (APIS 2014). As this suggested an important impact of agricultural activity on nitrogen loadings onto the meres and surrounding vegetation, atmospheric NO_x concentrations were also assessed as part of this project.

2. Methods

Most sample and data collection was carried out during approximately bimonthly site visits (see Table 2-1 for dates) and the interval between each is referred to as the monitoring period.

Table 2-1 Sample and survey dates

Site visit dates	Time (days) since previous site visit date
24 October 2013	-
19 December 2013	56
24 February 2014	67
24 April 2014	59
18 June 2014	55
26 August 2014	69
01 October 2014	36

2.1 Water level fluctuations

A depth data logger was installed at the deepest point in each mere. A third data logger was installed c. 2 m above the highest recorded water level for each mere to provide the atmospheric pressure readings necessary to correct the depth pressure readings so that they accurately record water depth. Loggers were programmed to record barometric pressure every 30 minutes.

During each site visit stored data were downloaded. Recorded values were combined to create a daily mean pressure and used to calculate an accurate water depth for each mere. These were checked against actual depth readings taken on each sampling date to ensure accuracy. Depth data were then used to estimate mere surface area and water volume fluctuations using the bathymetric survey data gathered during Phase 1.

2.2 Lake water sampling

Water quality in each of the meres was sampled during each site visit (Table 2-1). At least three samples were taken along a transect from the shore to the deepest point of each mere. These samples were then combined to form one integrated sample, which was thoroughly mixed before being subsampled for analysis, thus giving an overall representation of water chemistry at the time of sampling.

The water samples were transferred to a UKAS accredited laboratory for water quality analysis. Concentrations of the following components were analysed: nitrite, nitrate, total nitrogen (TN), sulphate (SO_4), calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), sodium (Na), soluble reactive phosphorus (SRP), total unfiltered phosphorus (TP), orthophosphate (OP), total alkalinity (at pH 4.5) and chlorophyll-a (Chl-a).

Field instrument readings including dissolved oxygen (DO), pH, temperature and conductivity were recorded using hand held meters during site visits. Such instrument readings were taken at 50 cm intervals from the lake surface to the deepest point to determine depth-dependent variation.

2.3 Groundwater sampling

A single borehole was identified as usable for this study, located immediately south east of Ringmere (Borehole TL98/029 - Ringmere WHMP - (TL 91029 87808)). On each site visit (Table 2-1) a 100 ml water sample from the borehole was collected and transferred to a UKAS accredited laboratory for water quality analysis. Concentrations of the following components were analysed: nitrite, nitrate, TN, SO_4, Ca, Fe, Mg, Mn, Na, SRP, TP, and total alkalinity. In addition recordings of pH and total conductivity were taken at source.

A second borehole, close to Langmere, was identified but details and permission to include it were not provided until May 2014 and so it was not used.

2.4 Sediment sampling and nutrient release

Three sediment samples were taken from the top 10 cm of sediment within each mere on a single occasion on 19th June 2014. Coring was not considered feasible due to the high density of detritus, including roots, and so samples of approximately 1kg were taken using a trowel at equidistant points along a transect from the margin to the deepest point of each mere. Efforts were made to include as little vegetative matter as possible in the samples. APEM field scientists conducted a visual inspection of the grab samples to assess their silt, sand and clay content. The samples were then transferred into plastic bags and placed in cool storage prior to transportation to a UKAS-accredited laboratory, where concentrations of the following components were determined: TP, TN, Fe, Mn, Na, total organic carbon (TOC), elemental sulphur (S), soil organic matter, dry solids and loss on ignition (LOI).

Three further sediment samples were taken from each site and were kept in cool storage before transportation to the laboratory. Following the method in Nowlin et al, (2005), each sample was incubated for five days at 21°C under lake water from the mere from which it was collected, in order to estimate the nutrient release rates at summer water temperatures. Samples of water overlying the sediments were analysed before (day 0) and after (day 5) incubation for TN, nitrate, nitrite, TP and SRP, in order to estimate nutrient release rates from the sediment.

Further details relating to sediment nutrient release are provided in Appendix 1.

2.5 Atmospheric nitrogen concentration

Two nitrogen diffusion tubes (Gradko International RTU) were installed following the method in Lambert and Davy (2011), one adjacent to each mere, for passive monitoring of gaseous nitrogenous molecules. These tubes were set at a height of 1 m on a sampling post (Figure 2.1) and consisted of a 35.5mm length x 11.0 mm internal diameter thermoplastic tube fitted with two thermoplastic rubber caps, a yellow cap containing the absorbent and a white cap fitted with a one-micron porosity filter to prevent the ingress of airborne particulates. The tubes were set on each of the first six site visits, then collected after approximately one month's exposure (Table 2-2) and posted to the analytical laboratory. The concentrations of mono-nitrogen oxides (NO_x) were determined with reference to a calibration curve derived from the analysis of a series of standard N solutions by Ion Chromatography. The analyses were carried out by Gradko International (Winchester UK), an accredited laboratory.

Figure 2.1 Nitrogen diffusion Tubes attached to a sample post 1 m above ground level (from Lambert and Davy 2011).

Table 2-2 Nitrogen diffusion tubes: dates of setting and retrieval.

Diffusion tube set date	Diffusion tube collection date	Exposure time (hours)
24 October 2013	15 November 2013	505
19 December 2013	10 January 2014	505
24 February 2014	17 Marc h2014	502
24 April 2014	15 May 2014	505
18 June 2014	15 July 2014	648
26 August 2014	18 September 2014	552

2.6 Rainfall and dry deposition

One combined rainfall and dust deposition trap was installed at each mere to determine nutrient deposition (Figure 2.2). This followed the method of Allen et al. (1968), which combines dry (particulate and gaseous) and wet (precipitation) deposition. The sampler comprised a 25 cm diameter foam particulate filter at the top of the tripod and a rainwater collector (bottle with red lid on Figure 2.2) at the base of tripod. On each site visit, rainwater volume was recorded and the foam filter thoroughly rinsed with the collected rainwater sample before being sub-sampled and filtered for analysis. This allowed total local rainfall for each monitoring period to be estimated (assuming little loss to evaporation), together with quantification of the nutrient loads associated with particulate aerial deposition. The traps were reset on each site visit other than the final one with a fresh filter and rainwater collector. The rainwater was analysed for TN, TP and filterable TN and TP; particulate content was estimated by subtracting the filterable concentration from the total concentration.

These traps are subject to contamination, e.g. by insects, wind-blown leaf litter and bird droppings. Most such contamination is clearly visible if still present on the collection date; little was observed, but this is acknowledged as a potential source of error.

Figure 2.2 Rainfall and dust deposition trap.

2.7 Vegetation survey

Two vegetation surveys were carried out at each mere according to the methods outlined in Stewart (2012). The original aim was to survey both aquatic macrophytes and terrestrial vegetation in September 2013 and spring 2014. However delays in beginning the project meant that the first survey was not carried out until October 2013. The early autumn was mild in 2013 so a late terrestrial vegetation survey was possible, but aquatic macrophytes could no longer be surveyed. Similarly, the spring survey only covered terrestrial vegetation and was extended over several weeks in May-June 2014 to avoid disturbing ground-nesting birds.

In the absence of new macrophyte data, analysis was restricted to indications of nutrient status that could be derived from terrestrial plant assemblages growing at the sites. Ellenberg indicator values for soil fertility, a proxy for soil nitrogen content, were determined for each species recorded and used to assess overall fertility for the different plant assemblages recorded. These were taken from two sources: Hill el al. (1999) for vascular plants and Hill et al. (2007) for bryophytes.

Once the Ellenberg value for each species had been determined, the scores were totalled for each quadrat, and then the total was divided by the number of species present to arrive at a mean score for each quadrat. This was then compared against tables to determine its vegetation community type (as defined by Stewart 2012) to look for possible relationships between vegetation type and nitrogen.

Further details of the vegetation survey method are provided in Appendix 2.

2.8 Data analysis

Recorded lake variables – TP, TN, OP, Nitrite, Nitrate, TON, DO, Chl-a and depth profiles – were compared by use of independent-samples Mann-Whitney U test for non-parametric data due to small sample sizes and the non-parametric distribution of the collected data.

Relationships between concentrations of nutrients in lake water and inputs from rainwater were compared using linear regression.

2.9 Calculating a water budget

Area and volume estimates were made incorporating the bathymetric data collected during the Phase 1 study. Neither Ringmere nor Langmere have surface inflows or outflows, so water inputs were assumed to derive from direct precipitation and groundwater inflow, and water loss from evaporation and groundwater outflow.

Inputs to the meres were estimated for six periods throughout the study period, each beginning and ending on a site visit and normally therefore lasting approximately two months (Table 2-1).

Water inputs to each mere were estimated by determining daily changes in volume. Negative changes represent net water loss and were ignored. Positive changes represent net water gain and were summed for each period. Total inputs for the period were estimated by adding the actual increase in volume with the estimated loss through evaporation during the period.

Rainfall inputs were estimated using daily water surface area and daily rainfall. Only rain falling directly onto the water surface was considered; direct runoff from the immediate catchment was assumed to be minimal with water falling on the ground being incorporated first into subsurface flow. Evaporation volumes were calculated using water surface area, mean daily water temperature derived from dataloggers and mean daily humidity and windspeed, derived from weather records at RAF Lakenheath (18 km south west of the sites).

Groundwater inputs were estimated by measuring changes in volume of the meres, taking into account inputs from precipitation and losses from evaporation. The groundwater recharge estimates from Phase 1 have been improved upon by including estimates of both direct rainfall inputs and of evaporation rates. Where net change in water volume between months was positive, it was assumed that the difference was due to the groundwater recharge volume. If the change in volume between months was negative, it was assumed that there had been a net loss of water from the system.

Ringmere is a relatively regular shape, making estimates of volume and surface area straightforward (Figure 2.3a). Langmere in contrast, while also fairly regular, combines with two other adjacent basins as its water level rises (Figure 2.3b). These two basins have not currently been included in estimates of surface area and volume of Langmere; the volumetric data are available to enable this, but it is considered unlikely that this would alter nutrient budgets appreciably, as they are subject to the same inputs and outputs as the main mere.

Additional detail on the methods for calculating the water budget are provided in Appendix 3.

2.10 Calculating total nutrient load and source apportionment

Nutrient loads from the various sources (groundwater, rainfall, aerial deposition, birds etc.) were calculated individually. These individual loads were then combined to determine the TN and TP loads to the individual meres. A similar approach to that used in Phase 1 of this project was used to estimate loads from individual sources (APEM 2013).

2.10.1 Groundwater

The mean groundwater concentration of TN and TP was estimated by calculating the mean of the concentration recorded at the beginning and end of each monitoring period. This was multiplied by the total estimated net groundwater input volume to give a loading.

2.10.2 Rainfall

The rainwater collectors were assumed to have minimal loss through evaporation, and so the nutrient concentration from the sample collected on each end date was assumed to represent the mean concentration throughout each monitoring period. TN and TP concentrations were determined for each rainfall trap after every site visit, thereby providing a mean for the previous monitoring period.

Rainwater concentrations were multiplied by the estimated direct rainfall volume (the actual rainfall volume collected at each site multiplied by the mean lake surface area recorded over the monitoring period) to give an estimated nutrient load per area.

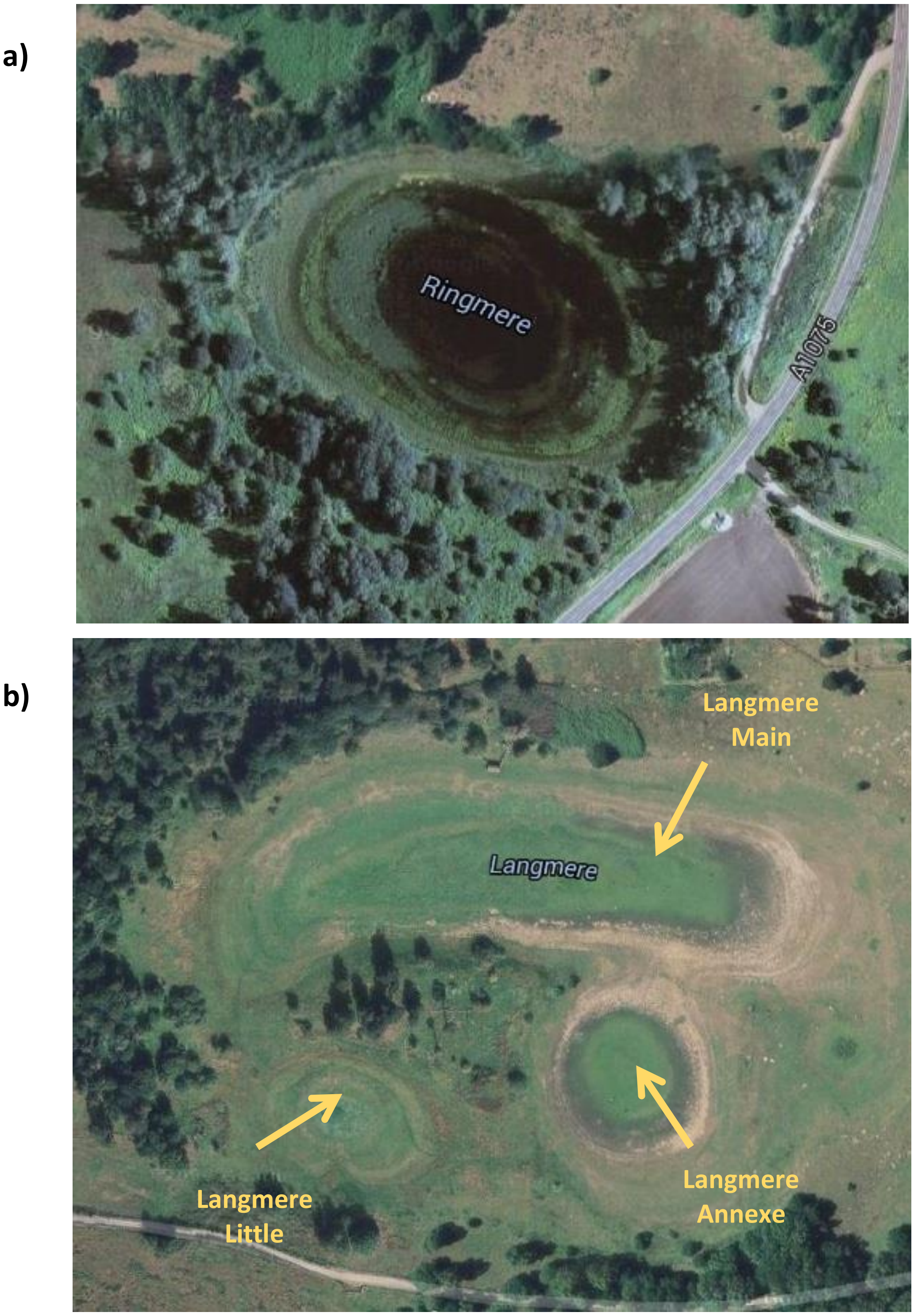

Figure 2.3 Detailed satellite image of a) Ringmere; b) Langmere, showing shape of each mere basin. The three separate components of the Langmere basin are highlighted.
Image from GoogleEarth (Imagery ©2015 DigitalGlobe, Getmapping plc, Infoterra Ltd and Bluesky), image copied January 2015.

2.10.3 Birds

To calculate the nutrient load from a bird population, the most up-to-date WeBS (Wetland Bird Survey, British Trust for Ornithology) data for Langmere and Ringmere were obtained and analysed. The most recent period of WeBS data available was from August 2012 to April 2013. These data were combined with the WeBS data used in the Phase 1 study (2002-2009) and an APEM survey from August 2013 (M. Dobson, personal observation) to calculate the nutrient load from birds.

Published species-specific nutrient excretion coefficients were used to estimate the nutrient loads from the bird population both seasonally and annually (Chaichana et al., 2010; Don and Donavan, 2002; Stoianov et al., 2000; Post et al., 1998; Manny et al., 1994).

The method used combines published daily nutrient loads from birds with published estimates of the time each species spends on the water, or close enough to the water for its excrement to enter the water body. This means that birds that spend a high proportion of their time on the water are considered to be contributing relatively more than species that spend less time on the water. However those that are on the water for extended periods of time will probably be feeding there and so will be recycling nutrients within the system rather than contributing to a net addition of nutrients. Accounting for this accurately is not possible in the absence of direct information on movements and feeding habits of the birds present, but was addressed by using a sensitivity analysis (see Appendix 4 for more details).

2.10.4 Sediments

Nutrient inputs from mere sediments were determined by subtraction: inputs from other sources were calculated and any nutrient concentration not accounted for from these sources was assumed to derive from internal loading, either from sediment release or decomposing vegetation. Potential nutrient inputs from mere sediments were estimated by scaling up from the five day laboratory incubation experiment to the area of the individual meres to provide an estimate of maximum potential sediment-water exchange of nutrients.

Where mere water nutrient concentrations were lower than those estimated from other inputs, the sediment was assumed to be acting as a nutrient sink.

3. Results

3.1 Water level

Changes in water depth in Langmere and Ringmere showed a similar pattern but a markedly different degree of fluctuation (Figure 3.1). Water levels were at their minimum in the winter (December to January) and maximum in summer (June). The most marked fluctuations were recorded in Langmere, where there was a c.1.6 m seasonal change in water levels and the mere almost completely dried up in December 2013.

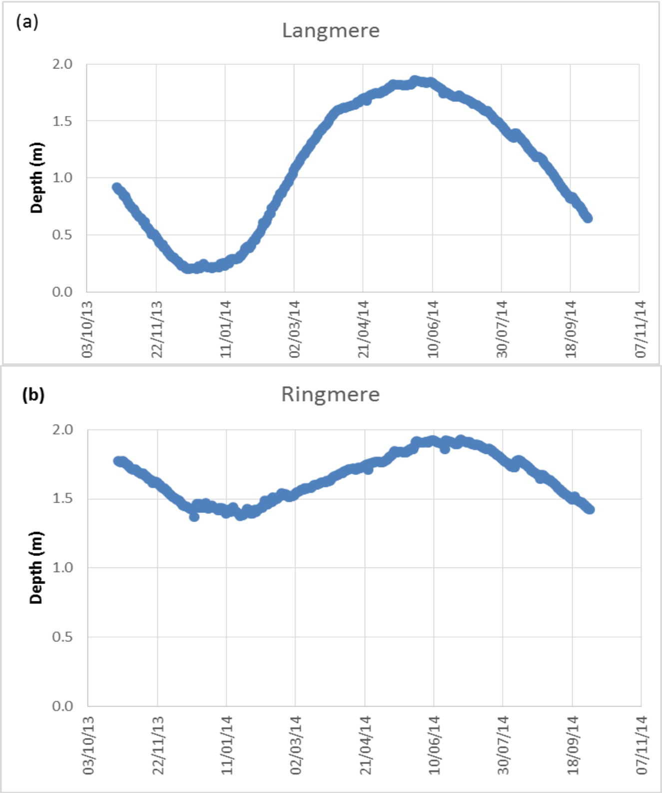

Figure 3.1 Maximum water depth over the study period in a) Langmere; and b) Ringmere.

There was no relationship between rainfall (Figure 3.2) and water level in either of the meres. Rainfall declined in autumn 2013, as the meres were drying, but then was very low over March and April, as the meres were refilling.

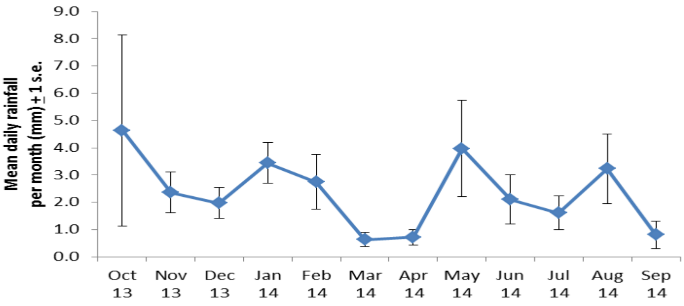

Figure 3.2 Daily rainfall over the study period.
The plot shows mean daily rainfall per month.

3.2 Lake water quality

Only key water quality components are considered here. Details of other measured components in lake water are provided in Appendix 5 - Lake water quality readings.

3.2.1 Dissolved Oxygen

Surface dissolved oxygen (DO) concentrations were low in October 2013 but then rose over the autumn and winter (Figure 3.3a), remaining close to or above saturation on all but the first reading (Figure 3.3b). There was no apparent annual cycle, as percent saturation was lowest in October 2013 but highest in October 2014.

The depth profiles of DO concentrations indicate that they were well-mixed for most of the year, but that there was a decrease in DO with depth as water levels dropped during October 2013 and again in August and October 2014 (Table 3.1).

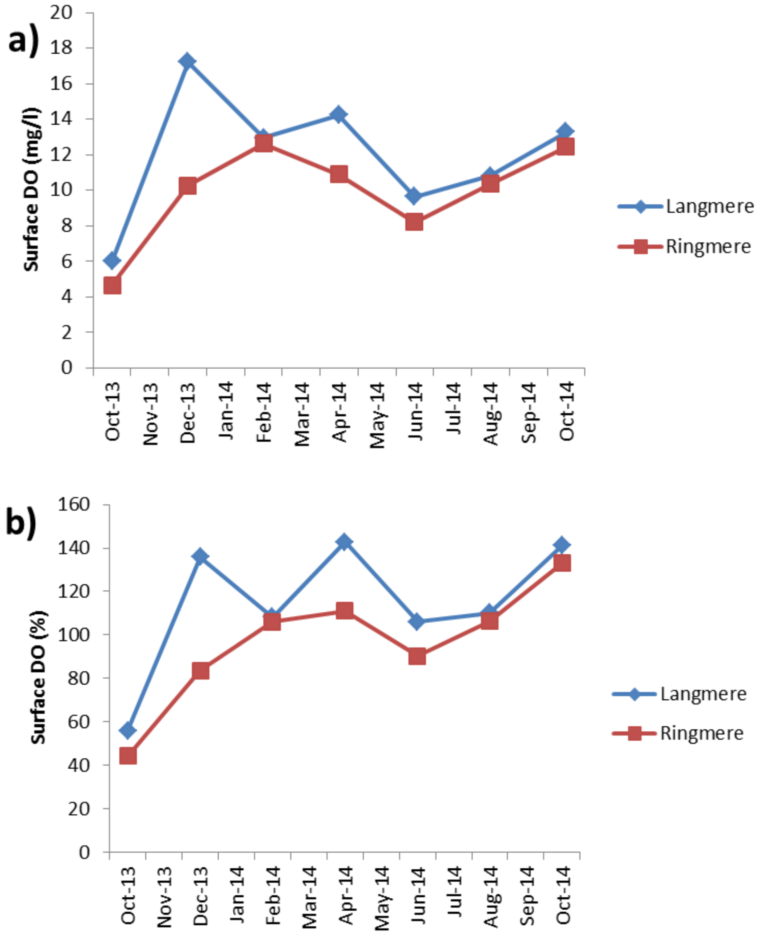

Figure 3.3 Surface concentrations of dissolved oxygen (DO) in Langmere (blue) and Ringmere (red): a) DO concentration (mg/l); b) percentage saturation.

Table 3-1 Dissolved oxygen (DO) profiles for a) Langmere, b) Ringmere.

a) Langmere

Date	Max Depth (m)	DO concentration (mg/l)			
		0 m	0.5 m	1.0 m	1.5 m
24/10/2013	0.96	6.01	5.93		
19/12/2013	0.21	17.21			
24/02/2014	0.89	12.95	13.08		
24/04/2014	1.70	14.25	14.16	14.68	
18/06/2014	1.75	9.64	10.15	10.20	8.52
26/08/2014	1.10	10.81	6.10		
01/10/2014	0.65	13.29	6.96		

b) Ringmere

Date	Max Depth (m)	DO concentration (mg/l)			
		0 m	0.5 m	1.0 m	1.5 m
24/10/2013	1.75	4.66	4.61	3.37	2.71
19/12/2013	1.40	10.27	9.56	9.62	
24/02/2014	1.50	12.64	12.55	12.30	
24/04/2014	1.75	10.90	10.82	10.34	9.28
18/06/2014	1.85	8.21	8.30	8.36	7.92
26/08/2014	1.66	10.36	10.70	11.17	10.90
01/10/2014	1.39	12.44	10.82	4.57	

3.2.2 Nitrogen

Total nitrogen (TN) concentrations were similar in both meres apart from a peak in Langmere in December 2013, coinciding with the mere being almost dry. Mean concentration in Langmere was 2.76 mg/l, whilst in Ringmere it was 1.85 mg/l. While concentrations (apart from the Langmere December peak) were relatively consistent, there was a small reduction in spring-summer compared with winter (Figure 3.4).

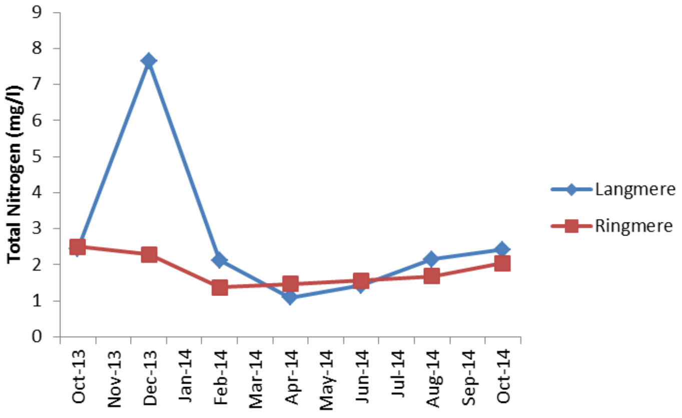

Figure 3.4 Total nitrogen concentrations in Langmere (blue) and Ringmere (red).

Almost all total oxidised nitrogen (TON) recorded was nitrate. Concentrations were high over winter and early spring but declined close to zero during summer and autumn in both sites (Figure 3.5). In Langmere, mean nitrate concentration was 0.40 mg/l, while in Ringmere it was 0.25 mg/l.

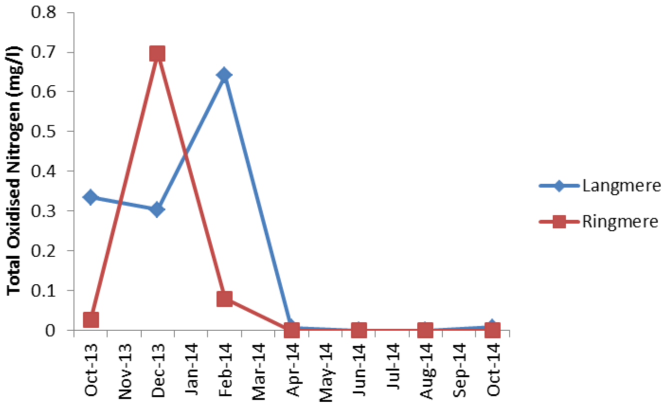

Figure 3.5 Total oxidized nitrogen concentrations in Langmere (blue) and Ringmere (red). Note values shown as zero denote concentrations below the limit of detection (<0.005 mg/l).

3.2.3 Phosphorus

Total phosphorus (TP) concentrations followed a similar pattern to TN in Langmere, peaking when the mere was almost dry in December 2013, then following a cycle of reduction over the spring and early summer and rising again from late summer. The mean concentration was 0.193 mg/l. In Ringmere, TP concentrations followed a different pattern, reaching their lowest values in winter and then rising to peak over the summer; the mean concentration was 0.125 mg/l (Figure 3.6).

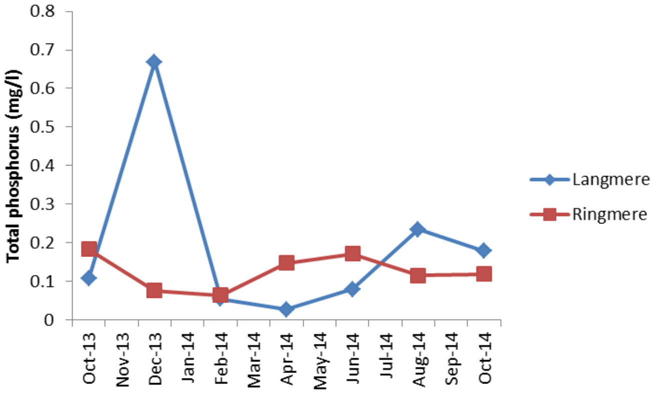

Figure 3.6 Total phosphorus concentrations in Langmere (blue) and Ringmere (red).

In Langmere, orthophosphate concentrations averaged 0.047 mg/l, but varied throughout the year dropping to their minimum in late winter before rising again throughout the remainder of the study period. Orthophosphate concentrations in Ringmere were generally higher, with a mean of 0.070 mg/l; they also reached their lowest value in late winter but then rose more rapidly than in Langmere before beginning to drop during later summer – autumn (Figure 3.7).

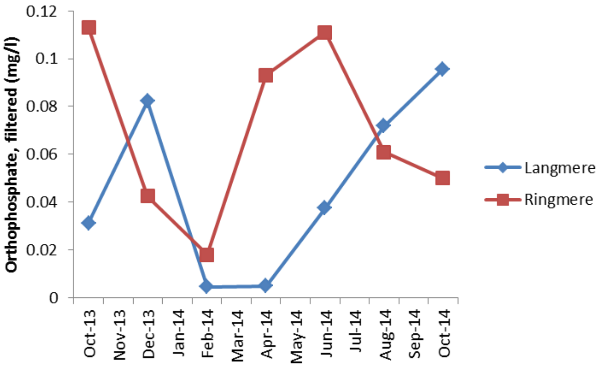

Figure 3.7 Orthophosphate (filtered) concentrations in Langmere (blue) and Ringmere (red).

3.2.4 *Chlorophyll-a*

Chlorophyll-a concentrations in Langmere were generally below 20 µg/l, but with a very high peak in December 2013 giving a mean concentration of 148.1 µg/l. This peak coincided with minimum lake level, when algal density was clearly visible in the field as being very high. In Ringmere, chlorophyll-a concentrations were typically lower, ranging from 2.3-19.6 µg/l with a mean of 6.8 µg/, and with no evidence of a rise in December 2013. The extreme peak in Langmere corresponded with large peaks in total nitrogen and total phosphorus concentrations as the lake volume fell to a minimum (Figure 3.8).

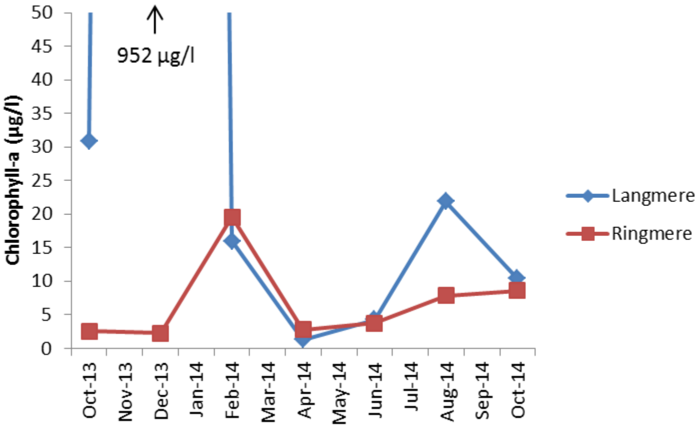

Figure 3.8 Chlorophyll-a concentrations in Langmere (blue) and Ringmere (red).

3.2.5 *Comparison between meres*

Comparing water chemistry readings across the study period shows that alkalinity was significantly higher in Ringmere (mean 157.65 mgl^{-1}, SE 15.70) than Langmere (mean 86.75 mgl^{-1}, SE 10.60), whereas calcium concentration was higher in Langmere (mean 44.57 mgl^{-1}, SE 6.40) than in Ringmere (mean 10.70 mgl^{-1}, SE 0.46). Sodium concentrations were higher in Ringmere (mean 20.65 mgl^{-1}, SE 0.76) than Langmere (mean 10.24, SE 0.16 mgl^{-1}). Other lake water chemistry parameters showed no difference between sites.

At Ringmere there was a highly significant positive relationship (r^2= 0.986, $p < 0.001$), between the recorded TP in the lake water and the concentration of TN in the rainwater falling in the area. In Langmere, in contrast, there was no such relationship (r^2 = 0.093, p = 0.618).

3.3 Groundwater nutrient concentrations

Only key water quality components are considered here. Details of other measured components in groundwater are provided in Appendix 6 - Groundwater quality readings.

3.3.1 Nitrogen

TN concentrations in groundwater averaged 0.24 mg/l. There was a possible trend of declining concentration over winter and then rising in summer, although the concentration in October 2013 was considerably higher than in October 2014 (Figure 3.9a).

The mean concentration of TON in groundwater was 0.037 mg/l, and this was almost entirely in the form of nitrate. Nitrate concentrations in groundwater ranged from 0.007-0.150 mg/l with a mean concentration of 0.034 mg/l. Variation in TON followed that of TN, although with a much lower peak in autumn 2013 and a high recording in August (Figure 3.9b).

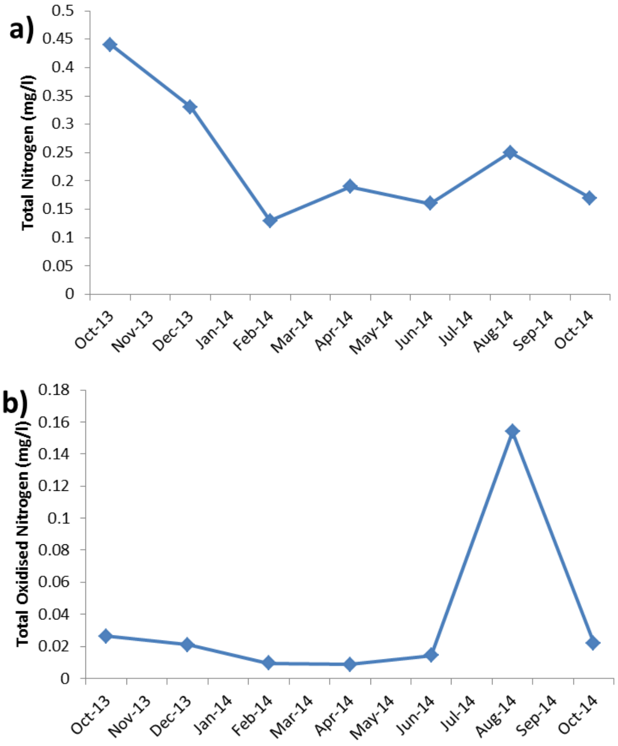

Figure 3.9 a) Total nitrogen (TN), and b) Total oxidised nitrogen (TON) concentrations in groundwater from Ringmere borehole.

3.3.2 Phosphorus

TP concentrations in groundwater from Ringmere borehole averaged 0.066 mg/l. There was a seasonal trend of high concentration in autumn, followed by a decline until later spring and a subsequent rise. The peak concentration was recorded in December, with the lowest concentrations (below the limit of detection) measured in April and June (Figure 3.10a). Orthophosphate (filtered) concentrations averaged 0.007 mg/l and followed a similar pattern to TP, although without the December 2013 peak (Figure 3.10b).

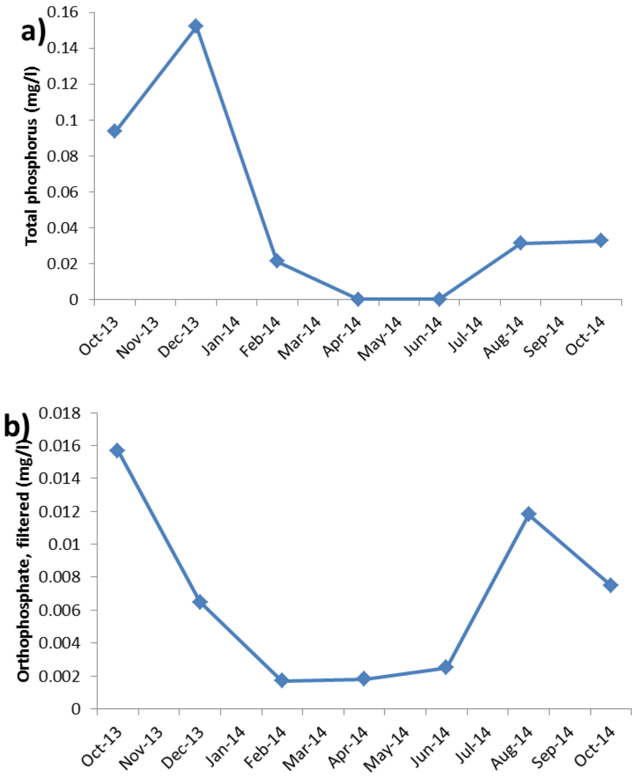

Figure 3.10 a) Total phosphorus (TP) and b) orthophosphate (OP) concentrations in groundwater from Ringmere borehole.

Note TP concentrations shown as zero are below the limit of detection (<0.02 mg/l).

3.4 Sediment nutrient concentrations

Middle and deep sediments from Langmere were reported as dark brown sand loamy sediment, while surface samples were described as medium brown clay sandy sediments with plant material. All sediment samples from Ringmere were reported as medium brown clay sandy sediment with plant material.

Only key water quality components are considered here. Details of other measured components in sediment are provided in Appendix 7 – Sediment nutrient readings.

3.4.1 Nitrogen

In both meres, sediment TN concentration increased with depth, particularly in Langmere, with concentrations in shallow sediments considerably lower than from other sites (Figure 3.11). Overall, TN concentrations were higher in Ringmere sediments than Langmere sediments, which correspond with the results from the Phase 1 sediment sampling.

However, while concentrations from comparative sampling locations in Langmere were similar between the two studies (mean Phase 1 – 10,208 mg/kg, Phase 2 - 9520 mg/kg), in Ringmere they were higher in Phase 2 (Phase 1 – 10,850 mg/kg, Phase 2 – 14,500 mg/kg).

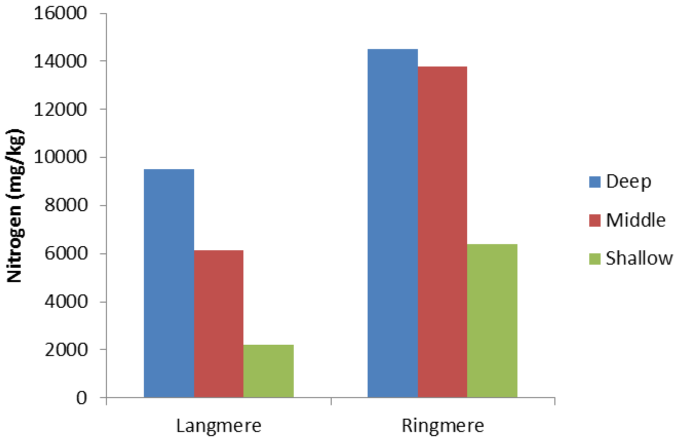

Figure 3.11 Nitrogen concentration (mg/kg) in sediments from Langmere and Ringmere (19 June 2014).

3.4.2 Phosphorus

Sediment TP concentrations were lowest in shallow sediments but those from middle and deep sediments were similar in both sites (Figure 3.12). Sediment TP concentrations were higher in Ringmere than Langmere, again corresponding with results from the Phase 1 sediment sampling. However, comparing Phase 1 samples with equivalent deep samples in Phase 2 with shows that concentrations were low compared with Phase 1, particularly at Ringmere (Langmere mean Phase 1 - 776 mg/kg, Phase 2 - 688 mg/kg; Ringmere mean Phase 1 - 1757 mg/kg, Phase 2 - 897 mg/kg).

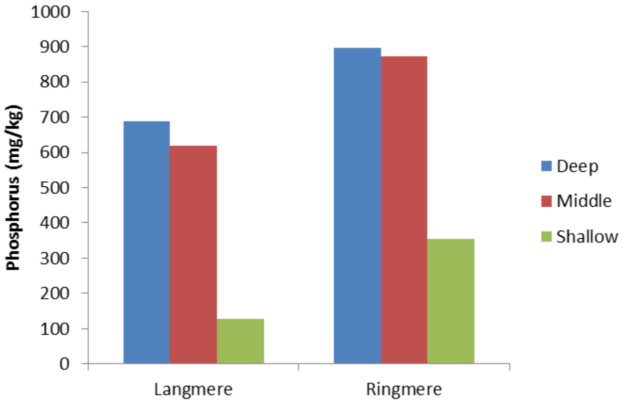

Figure 3.12 Phosphorus concentration (mg/kg) in sediments from Langmere and Ringmere (19 June 2014).

3.5 Sediment incubation results

Nutrient release rates from incubated sediment for TN did not follow a clear pattern with respect to depth of collection. However the TP release rate was considerably higher from shallow sediment than other depths in both meres (Figure 3.13). A mean release rate was calculated and used for source apportionment estimates (Table 3-2).

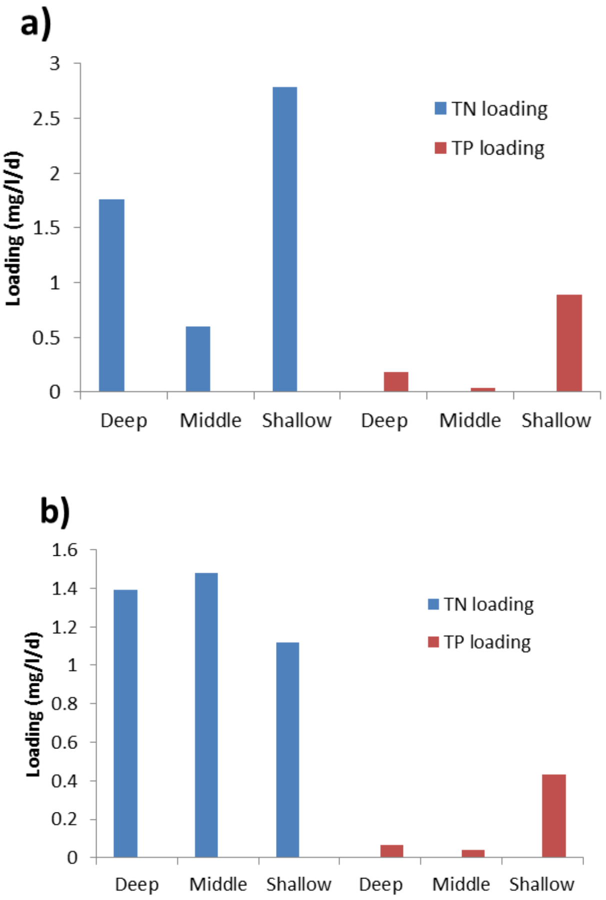

Figure 3.13 Daily nutrient release from incubated sediment samples: a) Langmere; b) Ringmere.

Table 3-2 Mean potential daily loadings from sediment.

Site	Nutrient	Mean (mg/l/d)	SE (mg/l/d)
Langmere	TN	1.713	0.630
Langmere	TP	0.368	0.265
Ringmere	TN	1.330	0.108
Ringmere	TP	0.178	0.127

3.6 Rainwater nutrient concentrations

3.6.1 Nitrogen

TN in rainwater over both meres averaged 4.91 mg/l. There was a clear peak in April 2014, following which the concentration dropped before rising gradually between June and October 2014 (Figure 3.14a).

The proportion of TN in particulate form also peaked in April 2014, but otherwise showed a trend of increase from a low in February 2014 to a high in October 2014 (Figure 3.14b).

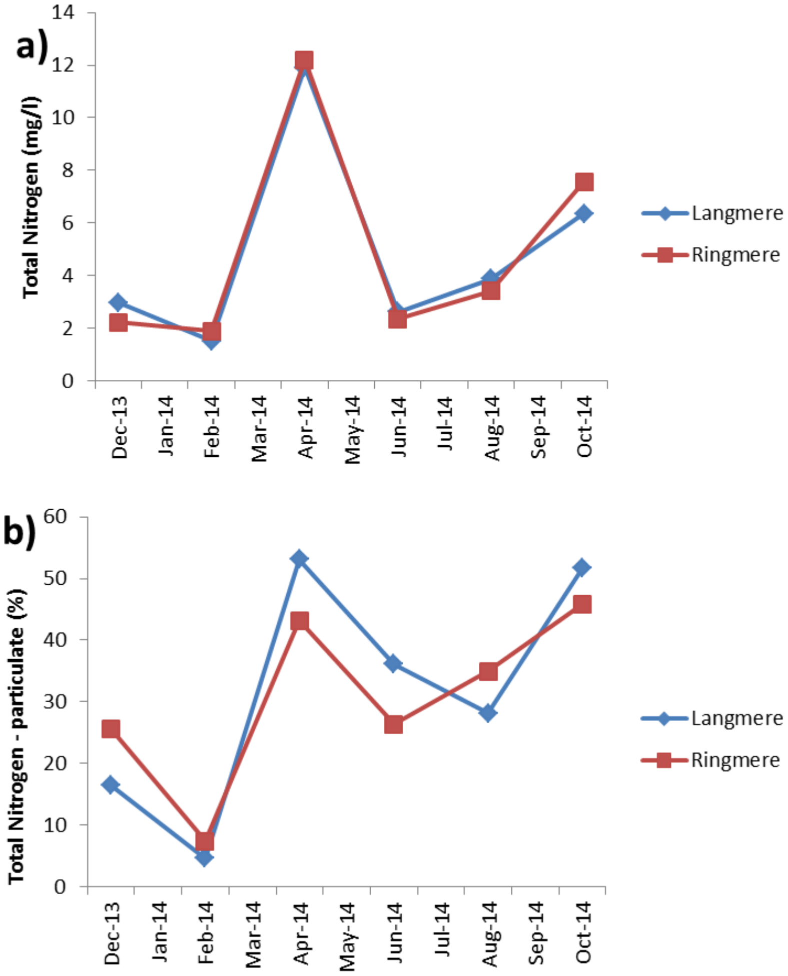

Figure 3.14 Nitrogen concentrations in rainfall samples from Langmere (blue) and Ringmere (red): a) total nitrogen (TN); b) percent of TN in particulate form.

3.6.2 Phosphorus

TP concentrations in rainwater averaged 1.77 mg/l, with a general decline across the sampling period, apart from a peak equivalent to that for TN during April 2014 (Figure 3.15a).

The proportion of TP in particulate form followed a similar pattern to TN, with a peak in April 2014, but continued to rise over summer until it reached over 70% in October 2014 (Figure 3.15b).

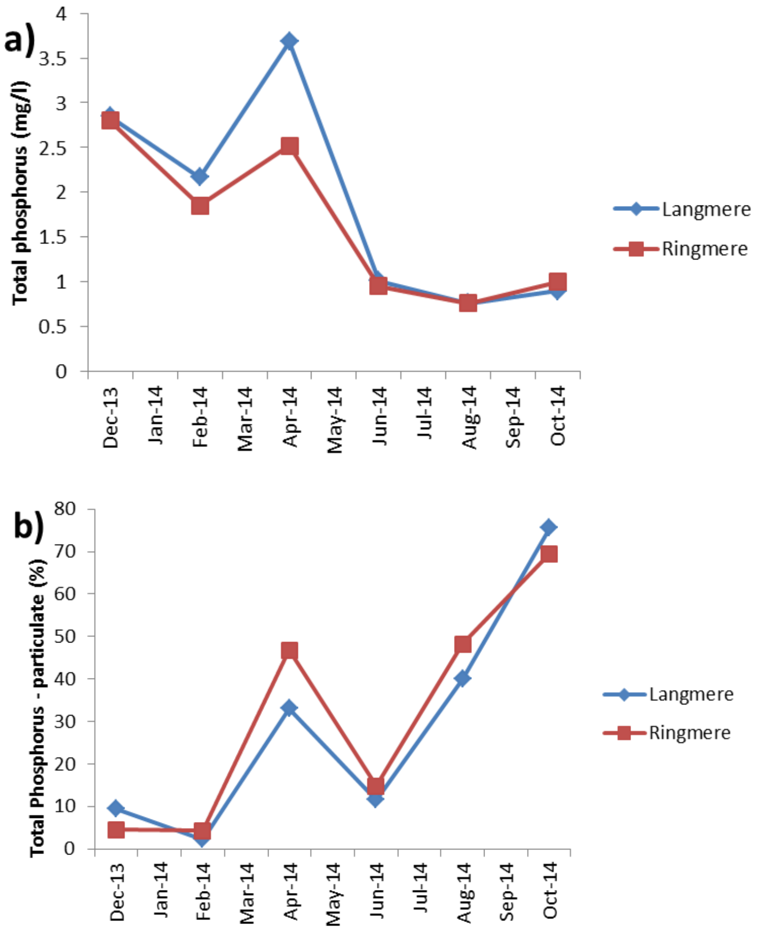

Figure 3.15 Total phosphorus concentrations in rainfall samples from Langmere (blue) and Ringmere (red): a) total phosphorus (TP); b) percent of TP in particulate form.

3.7 Atmospheric nitrogen concentration

3.7.1 Nitrogen

Atmospheric concentration of NO_x over the meres averaged 15.23 µg/m^3. NO_x concentrations were highest in the winter with maxima in November (Langmere) and January (Ringmere), and lowest concentrations in July on both meres (Figure 3.16). There was a slight difference in concentrations recorded between the two meres. The maximum values recorded were lower than the annual mean critical level for NO_x of 30 µg/m^3 (APIS 2014).

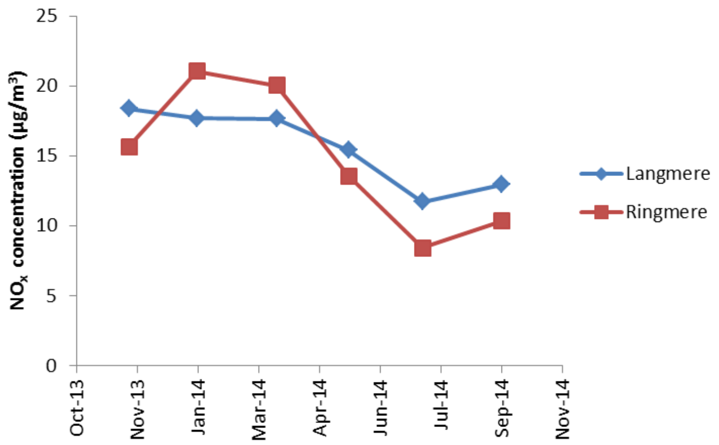

Figure 3.16 Atmospheric concentration of NO_x over Langmere (blue) and Ringmere (red).

3.8 Bird counts

From 2002-2013, the most abundant bird at both meres was mallard, with a mean count of 26.3 birds at Langmere and 10.6 birds at Ringmere. At Langmere, sizeable populations of black-headed gull, Canada goose, coot and moorhen were also recorded, while teal and coot were also present in high numbers at Ringmere. In general, fewer birds were counted at Ringmere than Langmere.

Tables summarising the monthly mean bird count data for Langmere and Ringmere are provided in Appendix 8 – Bird count and estimated bird nutrient input data.

3.9 Marginal vegetation

Five vegetation Types (Stewart 2012) were identified as present over the two sampling seasons (Table 3-3).

Table 3-3 Vegetation Types recorded from Langmere and Ringmere.

Type	Description	Number of occurrences	Ellenburg scores recorded
I	Reed canary grass and Orange foxtail	12	5.57 – 6.30
J	Recently exposed community	1	5.83
K	Damp inundation grassland	11	4.6 – 6.4
L1	Dry inundation grassland	4	4.56 – 5.9
L2	Dry inundation grassland	8	4.56 – 5.9

The range of Ellenberg N-scores for each vegetation type is shown in Table 3-3. Type I and K sites were classified as intermediate to rich fertility; L1 and L2 were lower to intermediate fertility and the type J site was intermediate fertility.

The most frequently occurring Types I and K were located between the shoreline and towards the upper limit of the recent inundation zone, while Types L1 and L2 were found either where grassland vegetation was well-established and had not been recently inundated, or at the upper limit of the inundation zone where the conditions had become slightly drier and the plant species had germinated and/or matured.

In 2013 Langmere Main quadrats were dominated by Type K which had developed into Type I and Type L1 by 2014. The established grasslands located beyond the regular inundation zone retained their Type L1/L2 character over the two sampling seasons. Similarly, the Langmere annex quadrats within the inundation zone were Type K in the autumn 2013 and in 2014 retained Type K vegetation towards the shoreline with the mature Type L2 further up the inundation zone. In 2013 Little Langmere showed a vegetation type sequence from Type I to Type K to Type L2 from shore line landwards. By 2014, when water levels had risen, the sequence had reduced to Type I close to the shoreline and Type L2 at the top end of the inundation zone.

In 2013 Ringmere had high water levels and a narrow inundation zone exposed. The vegetation samples were vegetation Type I, with one Type J around the perimeter of the mere between the shoreline and the upper inundation zone. By 2014, water levels had dropped slightly exposing more of the inundation zone. The samples closer to the shoreline retained their vegetation Type I, but those that had been exposed for longer had developed into drier grassland vegetation Types L1 and L2.

4. Source apportionment

4.1 Total nutrient loads

The largest inputs of TN into both meres were internal loadings from sediments and rainfall (Figure 4.1a, Figure 4.2a). In Langmere, sediment loading contributed 45% and rainfall added 36%, whereas in Ringmere sediment loading contributed 64% while rainfall added 27%. Other sources were small, although birds were more important in Langmere, where larger populations contributed 12%, than in Ringmere (4%). Groundwater was responsible for 7% of Langmere TN and 6% in Ringmere.

The main source of TP to both meres was rainfall, accounting 60% of inputs to Langmere and 78% to Ringmere (Figure 4.1b, Figure 4.2b). Birds were the second most important source, contributing 34% to Langmere and 13% to Ringmere. The remainder 6% in Langmere and 9% in Ringmere was derived from groundwater. The estimated contribution of these sources combined exceeded measured concentrations, suggesting that the sediment was acting as a net sink for TP.

Estimated total nutrient loadings are similar to those from Phase 1 with the exception of TN to Langmere, which is less than half the Phase 1 estimate (Table 4-1). However, source apportionments differed: the Phase 1 study, relying upon literature values for rainfall nutrient concentration, estimated this as less than 1%, compared to a contribution of up to 83% in this study (note that applying the literature values to Phase 2 data would give rainfall contributions of 8-11%). On the other hand, birds had a much higher contribution to the Phase 1 nutrient budgets (21-90%).

Table 4-1 Comparison of loading estimates from Phase 1 and Phase 2 studies.
Phase 1 estimates were derived from six months' data so have been doubled to provide an annual estimate.

	Phase 1 estimate (kg/year)	**Phase 2 estimate (kg/year)**
Total nitrogen (TN)		
• Langmere	183.0	71.4
• Ringmere	86.2	66.6
Total phosphorus (TP)		
• Langmere	16.4	14.4
• Ringmere	13.0	10.7

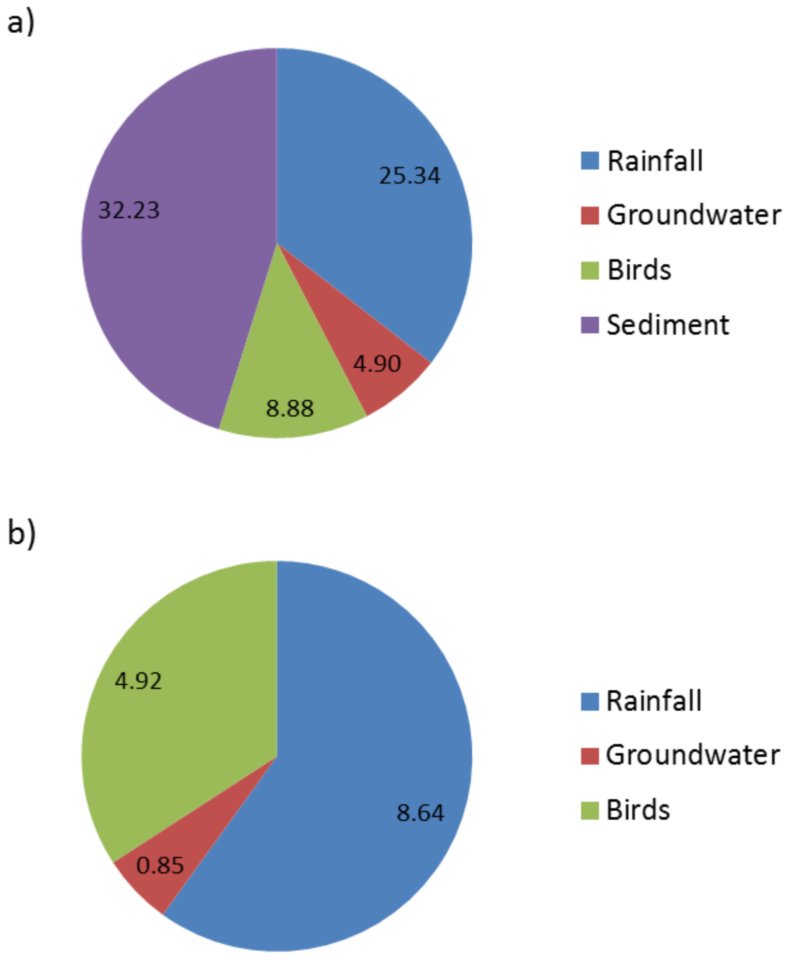

Figure 4.1 (a) Total Nitrogen and (b) Total Phosphorus loads (kg) to Langmere.

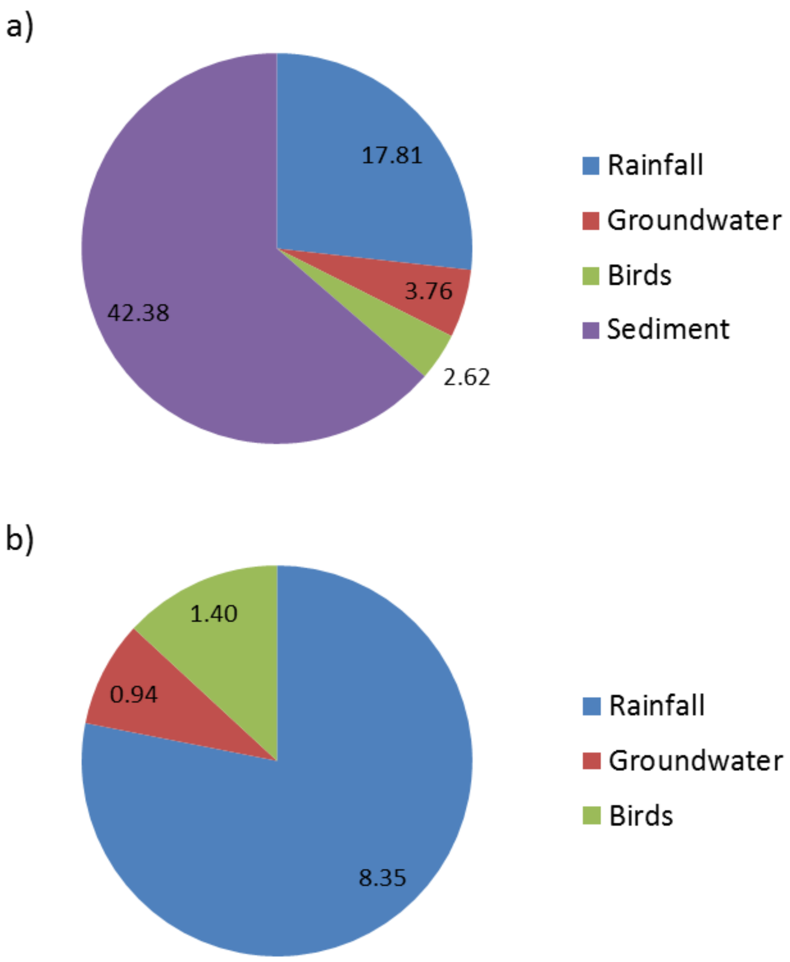

Figure 4.2 (a) Total Nitrogen and (b) Total Phosphorus loads (kg) to Ringmere.

Further details and tables of data are presented in Appendix 9 – Source apportionment figures.

4.2 Seasonal nutrient loads

Seasonal changes in the inputs are shown for Langmere (Figure 4.3) and Ringmere (Figure 4.4); data for these figures are provided in Appendix 10 – Seasonal nutrient loading estimates. Groundwater inputs comprised the highest proportion of the nutrient load in late winter and spring for both TN and TP in both meres, while birds were most important in autumn and winter, particularly for TP and in Langmere. The sediment was a net sink of TP throughout the year.

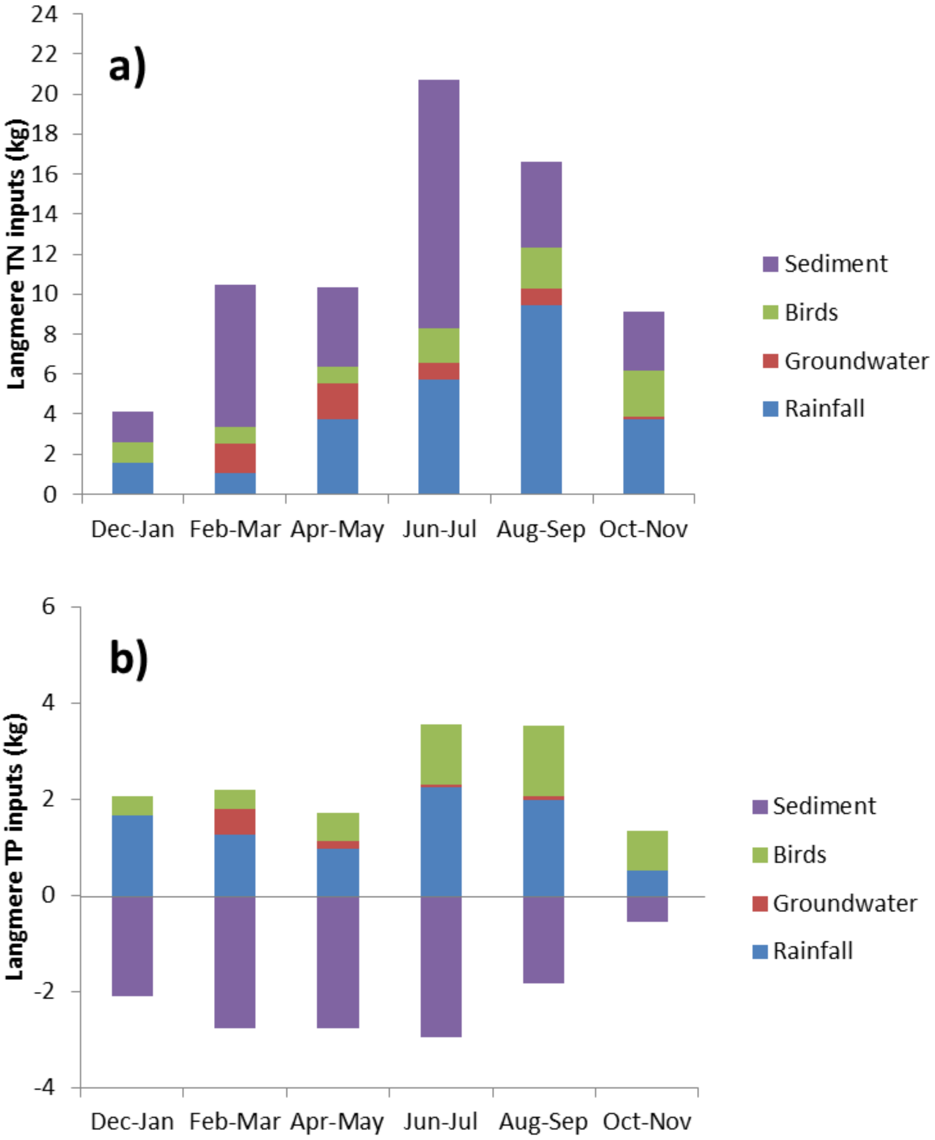

Figure 4.3 Seasonal variation in (a) total nitrogen and (b) total phosphorus loads (kg) to Langmere.

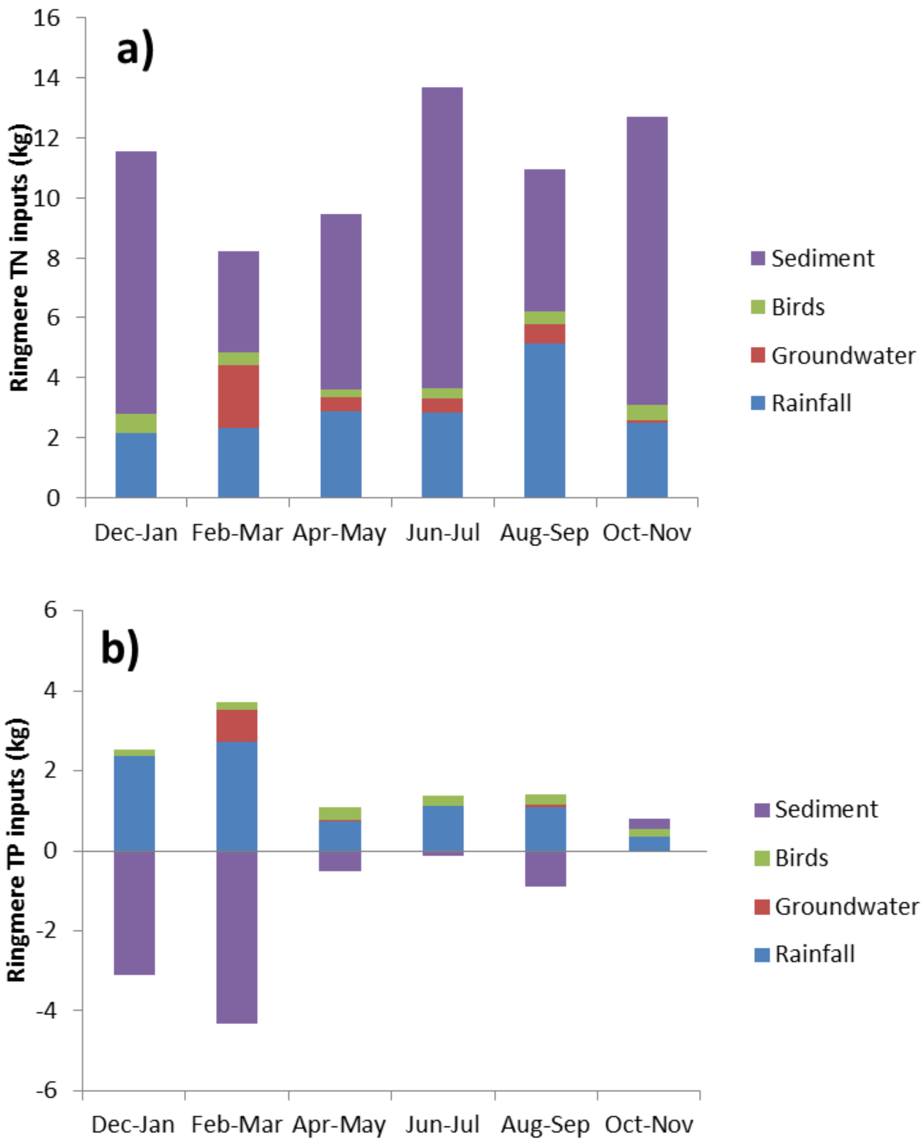

Figure 4.4 Seasonal variation in (a) total nitrogen and (b) total phosphorus loads (kg) to Ringmere.

5. Discussion

5.1 Comparison with Phase 1

Water depth fluctuations differed markedly from those observed during Phase 1, when each mere was dry in September 2012; Ringmere began to fill in October-November 2012, and recorded water depth ranged from 0 - 1 m, while Langmere remained dry until after mid December 2012 and its depth ranged from 0 - 1.4 m. During Phase 2, in contrast, the autumn was a drying period and the two meres showed very different degrees of fluctuation. This difference among the study periods provides valuable extra information on trends under different conditions, although as conditions have not been replicated it is essential that any extrapolation of the results to draw general conclusions is carried out with caution.

5.2 Current nutrient status of Langmere and Ringmere

Both Langmere and Ringmere are nutrient enriched and, while the mean TP concentration in Ringmere was considerably lower in Phase 2 than Phase 1, in both phases the water bodies would be classified as bad under WFD (UKTAG 2008) (Table 5-1).

Table 5-1 Summary of WFD quality standards and current Breckland Meres classifications, based on data from the two surveys.

WFD Class Boundary Mean TP (mg/l)		Mean TP concentration (mg/l) – Phase 1 study		Mean TP concentration (mg/l) – Phase 2 study	
		Langmere	Ringmere	Langmere	Ringmere
Bad	>0.196	0.470	1.030	0.400	0.250
Poor	0.099-0.196				
Moderate	0.050-0.098				
Good	0.036-0.049				
High	≤0.035				

No specific SAC or SSSI-related nutrient targets have been provided, but in the latest condition assessment it was noted that Ringmere has had long-term excessive levels of P (Natural England, 2011). This is consistent with the findings presented both in this report and in the Phase 1 report (APEM 2013), which demonstrate that mean and maximum TP concentrations appear to have increased significantly since the 1960s and 1970s in both meres.

The nutrient enriched status is supported by terrestrial vegetation that grows on the inundation zone. The vegetation types occurring on recently exposed mud or developing soon after exposure (I, J, K) contain plant species generally indicative of intermediate to richly fertile sites. The vegetation Types (L1 and L2) which had matured and/or not been recently inundated appeared to have species present which were indicative of less to intermediately fertile sites. Source apportionment data suggest that the sediments act as a nutrient sink during inundation; whilst this is apparently more relevant to TP than TN, enhanced TP concentrations may also influence vegetation growth during the dry phase.

A pattern identified during Phase 1 was for a sharp decrease in sediment TP between December and February, suggesting that TP may be released into the water column from sediment and decomposition of inundated vegetation once the meres are inundated. This was partially supported by water quality readings, which showed a large peak in TP concentration in Ringmere immediately following inundation, although this then dropped considerably (Figure 5.1a) even as more of the inundation zone was flooded, and the pattern appears to be one of dilution with increasing water volume rather than differential release (Figure 5.2a). If TP release from sediment or decomposing vegetation was a key determinant of water conditions, then the concentration would be expected to rise disproportionately during inundation and then to remain more constant even as the meres drained. In Ringmere there was no major change in volume during Phase 2, but in Langmere, which almost dried completely in December 2013, there was a peak TP concentration during the minimum volume period which dropped as soon as water volume increased (Figure 5.1b). There was, however, a much less clear relationship between TP and water depth in Langmere than Ringmere (Figure 5.2b).

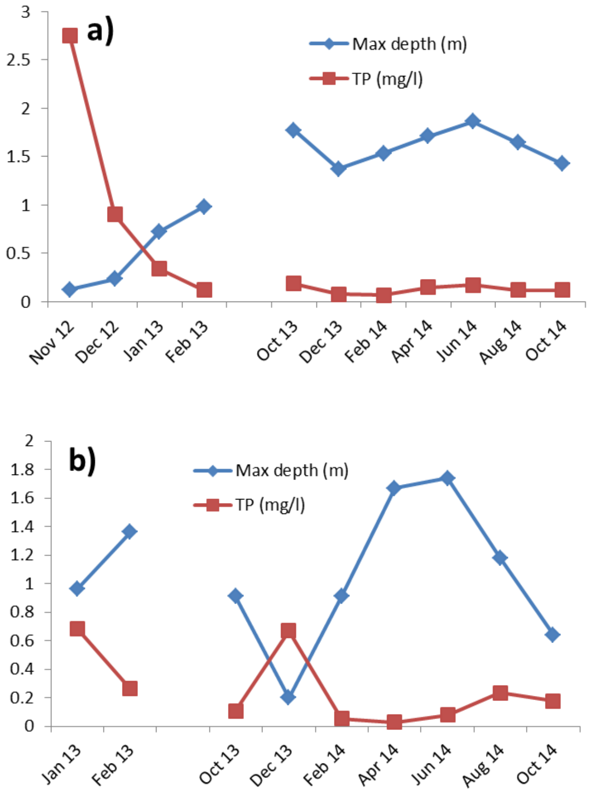

Figure 5.1 Trends in maximum depth and TP concentration in a) Ringmere, and b) Langmere (Phase 1 and Phase 2 data combined).

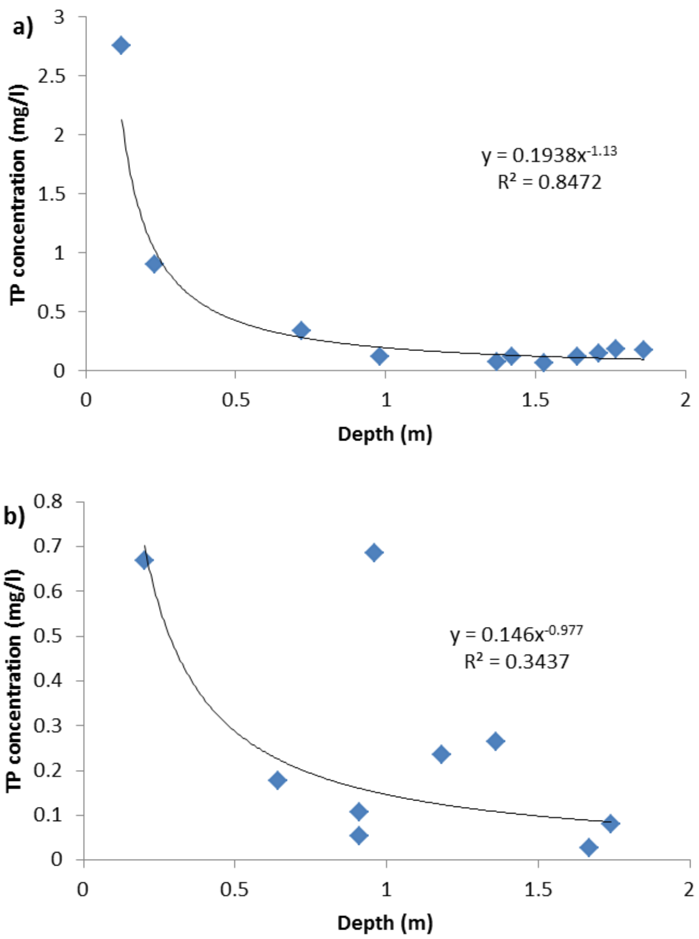

Figure 5.2 Relationship between TP concentration and depth in a) Ringmere, and b) Langmere.

A ratio of TN:TP below 10:1 can indicate N limitation, with a ratio above this potentially indicating P limitation (Philips et al. 2008). The Phase 1 study provisionally concluded that the meres were N limited (Table 5.2: Nov 12 – Feb 13). Further data collection now shows the situation to be more complex, with clear evidence for P limitation during some months, but a possible seasonal cycle with transition to P limitation in summer (Table 5.2: Oct 13 – Oct 14). The Phase 1 data do, however, suggest a period of N limitation following a dry phase, matching the observation from Phase 1 that TP and OP concentrations were both an order of magnitude higher than the concentrations measured in this study.

Table 5-2. Ratio of TN to TP for the meres

Values below 10, signifying probable N limitation, have been highlighted in orange. Values between 10 and 25, signifying a possible transitional phase between N and P limitation, are highlighted in yellow.

	Nov 12	Dec 12	Jan 13	Feb 13		Oct 13	Dec 13	Feb 14	Apr 14	Jun 14	Aug 14	Oct 14
Langmere	-	-	9.9	14.3		22.9	11.4	39.6	40.1	18.1	9.2	13.6
Ringmere	4.8	9.5	11.4	13.4		13.7	30.3	21.6	10.0	9.2	14.6	17.2

5.3 Nutrient dynamics in Langmere and Ringmere

Despite the absence of surface water inflows and outflows, the Breckland meres are very open systems. Rainfall and other atmospheric inputs, along with inputs from birds, appear to be major net sources of nutrient enrichment. However, despite the importance of these external inputs, there is potential for internal nutrient loading to be important in the meres. The shallow depths of the meres reduce the potential for anoxic conditions to develop that would facilitate nutrient release from the sediment. However, frequent drying and inundation provides alternative mechanisms for sediment nutrient release. The drying and refilling cycle allows growth of terrestrial vegetation which is then inundated. This vegetation is recycling nutrients that are already present in the system, but it is extracting them largely from the sediment and decomposition will result in nutrient release back into the water. This growth and decomposition cycle of vegetation is, however, a natural process in fluctuating lakes; much of the vegetation does not decompose fully and naturally fluctuating lakes are expected to have a high concentration of organic matter in their sediments (e.g. Kimberley and Waldren 2005). The sediments in Langmere and Ringmere have the potential to release nutrients, as demonstrated by the incubation study, but actual nutrient release is apparently relatively low and, in the case of TP, the sediments appear to be acting as a sink. May *et al.* (2008) commented that sediments with a concentration lower than 1 mg TP/g dry weight were unlikely to act as a source of phosphorus to the lake, and concentrations in the two meres are below this level and are relatively low compared with many other water bodies (Figure 5.3).

The build up of organic matter can have important implications for processes other than nutrient release: Langmere fluctuates in volume greatly because it is directly connected to the chalk aquifer, whereas Ringmere is partially separated from the same aquifer by a lining of organic matter (Acreman and Miller 2007); this presumably explains the higher calcium concentration in Langmere. Interestingly, data presented by Jones and Lewis (1941) imply that during the later 19th Century the levels of Ringmere fluctuated at least as much as Langmere, suggesting that the development of an organic lining is a relatively recent phenomenon.

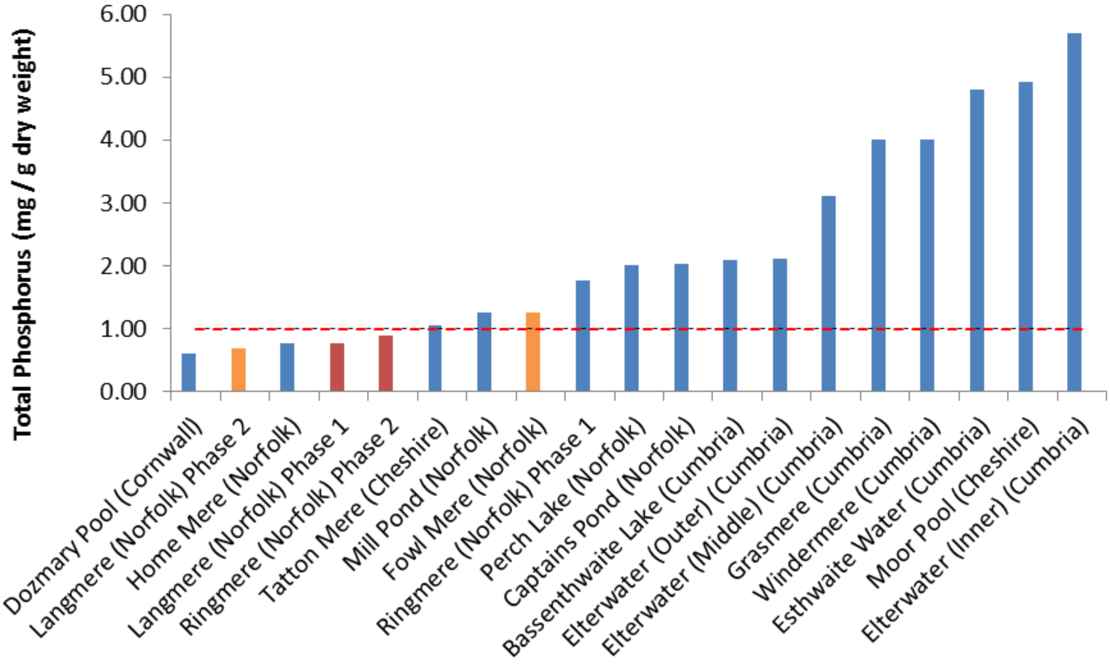

Figure 5.3 Comparison of sediment TP concentrations in Langmere and Ringmere (Phase 1 – red; Phase 2 – orange) with selected other lakes in England.

The dashed line marks the concentration below which net release from sediment is unlikely (May et al. 2008). Data from APEM and May et al. (2008).

Two important factors are of particular interest: the very high concentrations of nutrients in rainfall and the mass of TP that is apparently being incorporated into the sediment of both meres. The mean TP concentration in rainfall (1.77 mg/l) is 30 times the expected concentration quoted by Allen et al. (1968). There is the potential for this figure to have been artificially increased by localised contamination of the collecting vessels used in the field (for example via ingress by small invertebrates), but the generally close agreement in values between the two collecting devices (Figure 3.14, Figure 3.15) would suggest that this was not a significant factor. The rainfall measurements integrated dissolved inputs via rain with particulate dust that settled on the collecting devices. The percentage of the analysed concentration of TP that was not in dissolved form gives some indication of the importance of this dust deposition: it averaged 30% but reached a peak of 75.6% in Langmere and 69.5% in Ringmere. This leads to the possibility that some of the atmospheric inputs are not net input, but are dust created on exposed ground as the meres dry, which is then recycled into the meres as they refill. The spring peak in both particulate nitrogen (Figure 3.14b) and phosphorus (Figure 3.15b) in rainwater samples coincides with a period of low rainfall (Figure 3.2) during which, while the meres were increasing in volume, there was still an extensive surface area acting as a potential source of dust. Equally, however, this may have coincided with a period of ploughing and planting of agricultural land in the vicinity, which would also generate large volumes of dust under dry conditions. Dry and wet P and N deposition are independent processes and not significantly correlated (Ahn and James, 2001; Morales-Baquero et al., 2006), and particulate N is particularly associated with agricultural sources such as high concentrations of livestock and fertiliser application.

There are potentially important differences between the two meres. The stronger correlation in Ringmere between lake nutrient concentrations and rainwater concentrations suggests that Langmere nutrients are driven either by groundwater inputs or sediment release, while within Ringmere they are more closely related to rainfall. This would tally with the greater propensity for Langmere to empty and refill.

5.4 Other water quality variables

The high concentration of sodium in Ringmere relative to Langmere, while not relevant with respect to nutrient status, has potential management implications. Langmere sodium concentrations are close to those in groundwater, suggesting that this is the main source. In Ringmere, in contrast, they are twice as high. Sodium was not measured in rainwater, and this is a potential source, but the proximity of Ringmere to the road suggests that road salt may be a source. However, road salt is only applied during winter, and the concentration in Ringmere shows no seasonal variation, so it may instead be a natural concentration in the mere, which differs from that in Langmere because it drains and replenishes its water less freely.

6. Recommendations

6.1 Potential management options

Based on the work completed to date it is apparent that nutrient sources to the meres come from three general sources: rainfall, internal recycling and birds. This means that there are no straightforward approaches that can be taken, so the following are general recommendations, many of them statements of good practice or of options that are currently already being used.

6.1.1 Water level

There is currently no evidence to suggest that the meres are being detrimentally affected by abstraction and consequent changes to groundwater levels. It is important that this status is maintained and that the meres continue to fluctuate to a natural cycle. Excessive drawdown, particularly during a dry period, is to be avoided. It is recommended that the water table is carefully monitored with respect to abstractions and that Natural England and Norfolk Wildlife Trust are kept fully informed of trends and potential deviations from natural variability.

6.1.2 Internal loading

The two main contributors to internal loading are decomposing vegetation and input from the sediment. The vegetation survey showed that extensive growth of vegetation occurs during dry phases and, while these are simply recycling nutrients that are already present, they will create a cycle of uptake and release. Removal of vegetation by mowing is an option, although the sites are already closely grazed already by sheep, rabbits and wildfowl, and nutrient reduction would require removal of dead vegetation or grazer excrement from the site. On past occasions when nettles have grown on site these have been cut and removed prior to inundation; this removal is good practice and recommended for any terrestrial vegetation which is cut down within or adjacent to the meres. It not only reduces the potential for nutrient input during decomposition but is also a net export of nutrients from the site.

Sediment removal is widely used as a method for reducing internal loading. However, as there is no input of nutrient-enriched surface runoff, and extensive build-up of organic matter is a natural process in fluctuating lakes, this may not be appropriate for these sites. An exception may be localised removal of recent faecal inputs from birds if there are specific locations where these are at high density.

6.1.3 Terrestrial vegetation

While vegetation that grows in the inundation zone during dry periods contributes to internal recycling of nutrients, encroachment, particularly of trees, can result in net input of nutrients as organic matter is added. Therefore a herbaceous sward is preferred in the vicinity of the meres, and trees should be kept far enough away that direct inputs of leaf litter during autumn are minimised (whilst acknowledging that lateral movement of fallen leaves into the mere basins by the wind is inevitable). Close grazing of the sward will facilitate mobilisation of dust as the soil dries, and will also be attractive to waterfowl, and therefore if these are to be controlled a denser sward may be more beneficial. However, as this will lead to a potential conflict of interest with the terrestrial features of importance on the heath, a more appropriate approach would be to control numbers of grazing Canada geese (see below) and reduce trampling damage by restricting access by sheep during the early development of vegetation.

6.1.4 Birds

Birds are an important characteristic feature of the meres, mentioned both in the Biodiversity Action Plan for fluctuating meres, and in the SSSI designations for both areas. Therefore control or discouragement of birds in the meres is unlikely to be a feasible or desired option. Certain species such as Canada geese may be a disproportionate cause of the nutrient problem; reducing numbers of problem species (e.g. by shooting or trapping), is a potential and often effective short term solution, but is unlikely to lead to a permanently reduced local population if there is a large population in the region providing a reservoir for recolonisation, while control through scaring mechanisms would have a detrimental impact on species of conservation importance.

6.1.5 Groundwater

The Phase 1 survey expressed concern that groundwater inputs had been overestimated, and recommended that more site-specific groundwater nutrient data should be collected. Data were collected from the immediate vicinity of the meres during Phase 2 and have indeed suggested the reduced importance of groundwater as a nutrient source. However, there is always value in considering appropriate catchment-wide land management improvements to reduce the potential for groundwater inputs to become an issue.

6.1.6 Atmospheric inputs

The high proportion of inputs identified as being associated with rainfall makes this a priority to address. However, controlling atmospheric inputs is not straightforward. There are three approaches recommended.

a) Confirm that the rainfall nutrient concentrations recorded are genuine and not a consequence of contamination. This could be achieved by a process of targeted data collection over a short period of time (see ‘Further data collection’, below).

b) Determine the extent to which rainfall inputs are the result of local recycling rather than net inputs. While it is not realistic to determine precise origins of nutrients without using detailed tracing methods, some indication can be gained by placing rainfall collection devices along transects at different distances from the meres, and by relating nutrient concentrations to wind direction and adjacent land use activities (see ‘Further data collection’, below).

c) Control inputs from surrounding agricultural land. Effective land management to reduce dust blowing from agricultural fields would be of benefit to general air quality as well as reducing deposition in the surrounding area. While this is not a strategy that is of specific relevance to the Breckland Meres, it would be beneficial if the surrounding land is a net source of nutrients to the meres.

6.2 Further data collection

Three areas of further data collection are highlighted. It is emphasised that these are both targeted at developing a clearer understanding of nutrient dynamics within the system but that, at this stage, it is considered unlikely that they will identify further options for effective local management of nutrient inputs into the meres.

6.2.1 Vegetation inputs

A better understanding of internal loading and inputs from the immediate catchment would be derived from a study of vegetation decomposition dynamics on the sites. Leaf fall from surrounding trees can be quantified using vertical and lateral litter traps (e.g. Pretty et al. 2005), while their nutrient composition can be determined analytically and their decomposition rates in both terrestrial and aquatic environments can be measured using standard litter bag techniques (Graça et al. 2005).

In situ vegetation biomass can be quantified by harvesting measured areas and by nutrient composition analysis. Decomposition rates can be determined using the same litter bag techniques as for leaf fall inputs.

6.2.2 Atmospheric inputs

The very high atmospheric nutrient inputs recorded require further investigation, to determine whether these are a consequence of contamination; of very localised dust generation during drying and therefore of recycling nutrients derived from the meres; or of external inputs.

A confirmation of the accuracy of the rainfall nutrient concentrations would require nutrient analysis of rain collected within a few days of its falling. This would mean analysing small volumes, but this can be overcome through appropriate dilution.

More precise determination of the source of nutrients would be achieved by placing rainfall traps along transects at different distances from the meres, ideally in several different directions but at least along the line of the prevailing wind. A minimum of five rainfall traps along each transect, emptied at intervals of no more than one month, along with a visual assessment of human and agricultural activity in the surrounding area and analysis of wind direction, would enable a more precise indication of external versus internal loading of atmospheric dust and rainfall inputs.

A similar process using nitrogen diffusion tubes, and following the method of Lambert and Davy (2011) in placing tubes along a transect, will provide a better understanding of whether the high atmospheric nitrogen is derived from within or outside the immediate vicinity of the meres.

6.2.3 Bird inputs

While bird counts provide valuable information on their potential inputs to the meres, individuals that feed exclusively on the meres are simply recycling nutrients rather than being a net addition. Therefore, data on the proportion of time spent foraging elsewhere and thus importing nutrients would enable more precise estimates of their contribution to nutrient loading.

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8. Appendices

Appendix 1 – Supplementary detail on sediment nutrient release

Sediment samples were incubated for 96 hours in 3 litres of water at 21 °C. Conductivity was measured daily and used as a generic indicator of release of solutes from the sediment (Figure 8.1 and Figure 8.2).

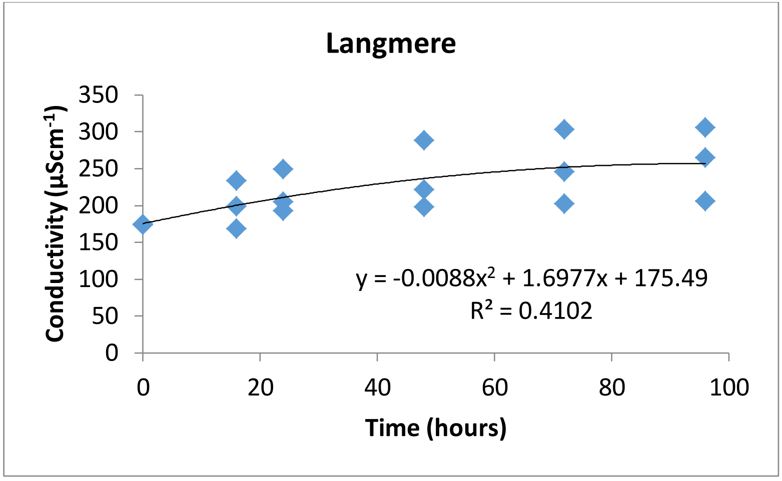

Figure 8.1 Langmere sediment conductivity over time.

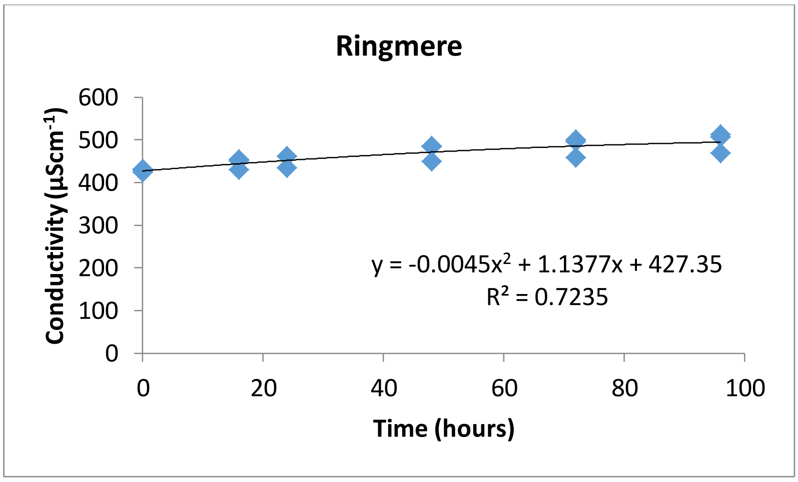

Figure 8.2 Ringmere sediment conductivity over time.

It was determined that conductivity was close to or at its peak in both meres after five days, and that nutrient release had therefore probably reached an equilibrium.

Therefore nutrient concentrations in water after 96 hours were considered to be indicative of release rates from the sediment in summer months. These were subtracted from mean concentration in control water to determine net input.

The concentration of nutrients in water with the incubated sediments was determined in mg/l. Nutrient inputs for the entire mere were therefore estimated by calculating the total volume of water up to a depth of 0.1 m over each five day period

Appendix 2 – Details of vegetation surveys

The autumn survey was carried out 15-16 October 2013. The spring surveys were carried out on 6th April, 5th May and 16th June 2014, the range of dates was due to the requirement to avoid disturbing nesting birds that were discovered during the sampling period.

In autumn the water level was low enough to create three separate water bodies within the Langmere complex and so each water body was surveyed; by spring/early summer 2014 water levels had risen sufficiently for Langmere Main and Langmere Annex to become connected. Ringmere was surveyed as one water body for both surveys. Each water body was walked to identify potential vegetation zones.

The shoreline of all the water bodies was walked for both surveys (2013 and 2014) and mapped using GPS (Garmin 62stc). For the Langmere group a second route was walked in 2013 just below a line of compact rush *Juncus conglomeratus* which appeared to mark the upper limit of the inundation zone. This was used to gauge the positioning of the quadrats for the autumn surveys, to be repeated in 2014.

Water levels were high in Ringmere in 2013, with only a narrow section of inundation zone present, so only the shoreline was marked in the field, with the approximate limit of inundated reed canary-grass *Phalaris arundinacea* beds also identified. A similar shoreline map was produced for 2014, although water levels had fallen slightly, exposing more of the inundation zone to terrestrial vegetation.

At Langmere, quadrats were recorded within three to four apparent sub-zones of the inundation zone to determine whether these constituted different vegetation types as set out in Stewart (2012). For Ringmere, the vegetation was only sampled to the landward side of the shoreline within the narrow, approximately 1 metre-wide zone, as the water levels were high in 2013, covering most of the potential inundation zone.

The 2014 quadrat survey aimed to repeat the survey in the same areas as 2013 for comparison between the different seasons and to sample the inundation zone at different water levels. At Langmere, the water had risen from 2013 levels, which reduced the area of the inundation zone over which quadrats could be repeated in 2014. Therefore the number of quadrats which were sampled was reduced from 4 to 3.

In 2014, the water levels had fallen at Ringmere, exposing mud and therefore different vegetation communities appeared to be developing. Therefore, the number of quadrats was increased to sample the developing vegetation in the recently exposed inundation zone.

In both sampling seasons, a 1x1m quadrat was placed within potential vegetation zones (as set out in Stewart 2012), and the percentage cover of each species was recorded with the percentage of bare mud and open water, where present. In total 37 quadrats were sampled on the 2013 and 2014 surveys. Each quadrat was assessed for its Type using the TWINSPAN community types as set out in Stewart (2012).

A DAFOR rating was given to each species within the quadrat relating to percentage cover. Where the percentage cover was less than 4% a DOMIN value was determined as shown in Table 8-1.

Table 8-1 DAFOR and DOMIN scale used for vegetation assessment.

Percentage cover	DAFOR
100-91	Dominant
90-51	Abundant
50-26	Frequent
25-4	Occasional
<4 many individuals	3 (DOMIN scale)
<4 several individuals	2 (DOMIN scale)
<4 few individuals	1 (DOMIN scale)

Appendix 3 – Supplementary detail on water budget calculations

Calculation of mere depth

The estimated depths were compared with actual measurements made in the field on seven occasions. While depths estimated from the datalogger data were found to contain errors, there was a very close relationship between estimated and actual depth on these seven occasions (Figure 8.3 and Figure 8.4). These relationships were therefore used to correct the daily depth measurements.

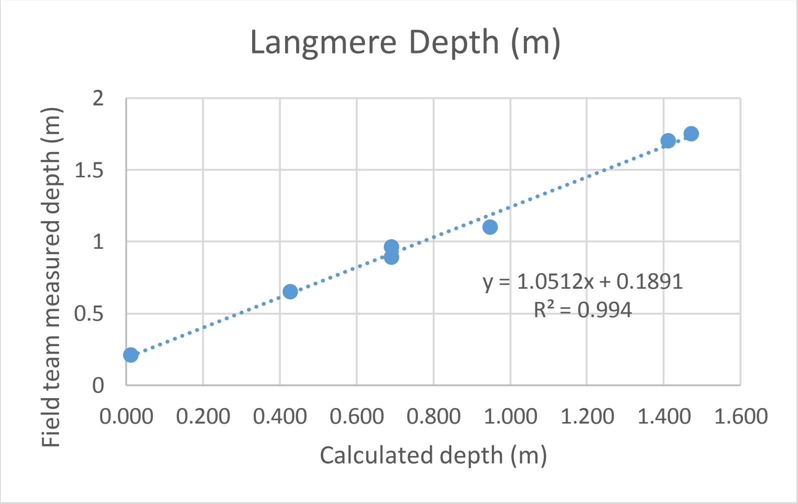

Figure 8.3 Relationship between depth measured in the field and calculated depth for Langmere.

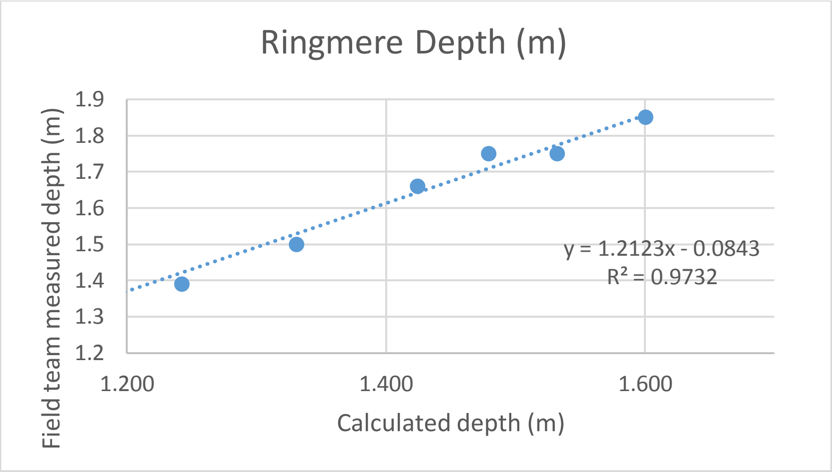

Figure 8.4 Relationship between depth measured in the field and calculated depth for Ringmere.

Calculation of mere surface area and volume

Mere basin structure was derived from bathymetric survey data calculated during Phase 1. Each mere is approximately triangular in shape and surface area at different depths was estimated by multiplying length by width and then subtracting 10% to account for the rounded edges of the lakes.

Each lake is a shallow bowl with a bed with little curvature. Therefore volume at any given depth could be estimated using simple trigonometry volume = 0.5(area*depth). Using the depth-area and depth-volume relationships derived from eight different depths, as determined from the bathymetric surveys, a relationship between each was established and applied to the daily depth estimates to estimate daily area and volume (Figure 8.5, Figure 8.6, Figure 8.7, Figure 8.8). Note that the depth-area plot for Ringmere closely atches that achieved by Jefferies (1992) at depths less than 1 m, but then increases more slowly at greater depths.

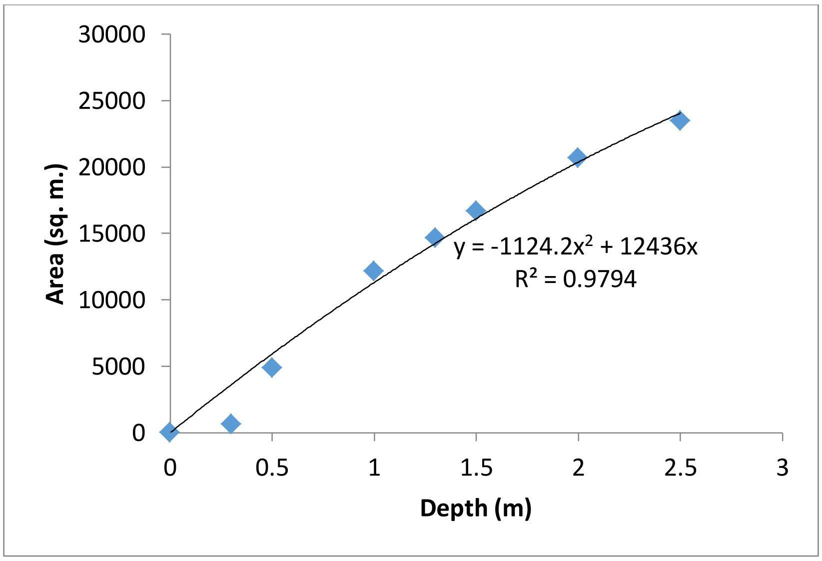

Figure 8.5 Depth and area relationship for Langmere.

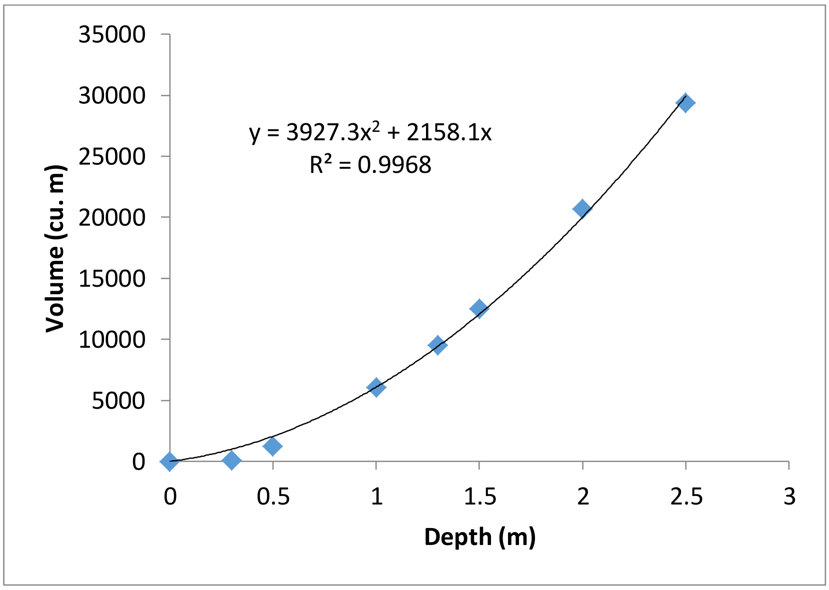

Figure 8.6 Depth and volume relationship for Langmere.

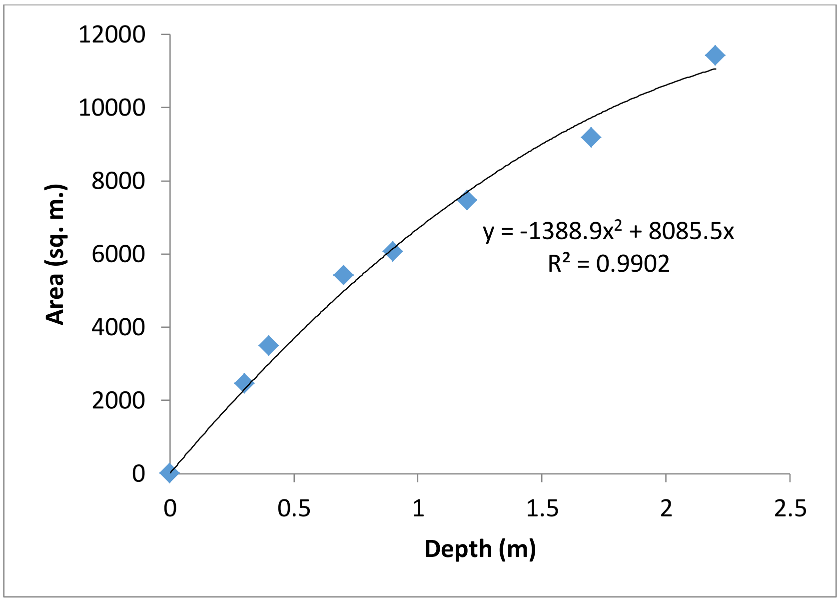

Figure 8.7 Depth and area relationship for Ringmere.

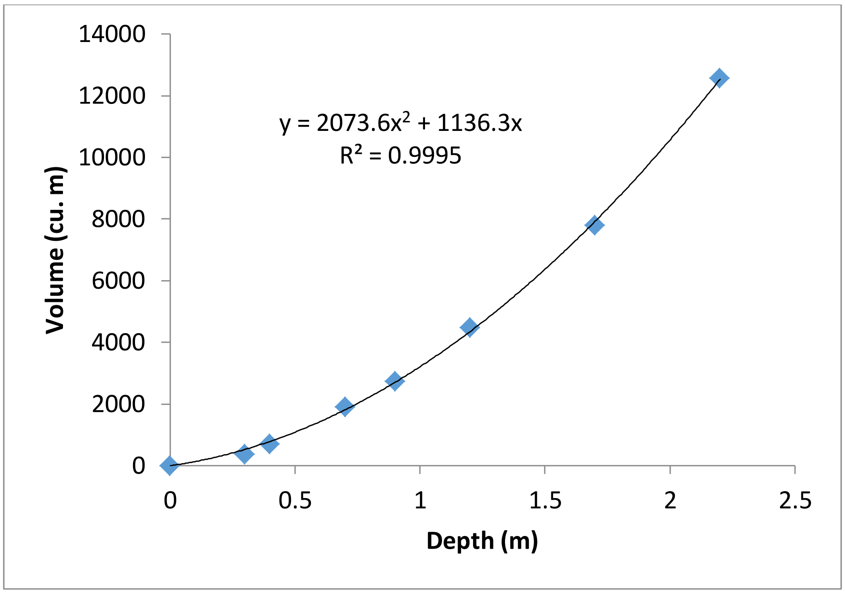

Figure 8.8 Depth and volume relationship for Ringmere.

Calculation of rainfall inputs

Rainfall data were derived from the daily record at RAF Lakenheath (52.41°N, 0.56°E), located west of Thetford and approximately 25 km southwest of the meres. The historic data were acquired through the Weather Underground website (http://www.wunderground.com/, Accessed: 24 October 2014). Rainfall was assumed to be the same at each of the lakes.

Direct inputs were estimated by comparing daily rainfall and daily surface area. 1 mm rainfall is equivalent to 1 L m^{-2} surface area, and so direct inputs can be calculated. This method did not account for any direct runoff during rainfall events from the immediate catchment, including rain that would fall in that part of the mere basin that was not flooded; this was all assumed to enter the groundwater. This may therefore introduce an underestimate in the contribution of direct rainfall.

Calculation of evaporation rate

Evaporation rate (kg/hour) was estimated using the following formula:

$$E = (25+19v) * A* (x_s-x)$$

Where:

v = air velocity (m/s)
A = surface area of the lake (m^2)
x_s = humidity ratio of fully saturated air at the ambient water temperature, determined using: $x_s = 0.0038e^{(0.0656*\text{water temperature})}$
x = actual humidity ratio, determined using: $x = X_s*(\text{mean humidity}/100)$, where mean humidity is expressed as a percentage

A daily estimate was derived, using daily surface area estimates and mean daily air velocity and relative humidity at RAF Lakenheath. Water temperature was the daily mean recorded by the dataloggers within each mere.

Note that estimating actual evaporation rates is notoriously difficult. The method used is adapted from one derived to estimate evaporation from open air swimming pools (www.engineeringtoolbox.com/evaporation-water-surface-d_690.html). It does not take into account changing air pressure and therefore may underestimate evaporation rates during periods of low pressure.

Appendix 4 – Supplementary detail on calculating inputs from birds

Published species-specific nutrient excretion coefficients were used to estimate the nutrient load from the bird population for each survey month. Total monthly bird nutrient load was then calculated using the following equation:

$$L_{av} = \sum_{n=x} n \cdot Ed$$

Where:

L_{av} = total avian nutrient load (g)
n = number of each aquatic bird species in one month
E = daily net nutrient content of excrement (g day^{-1} ind^{-1})
d = number of days in survey month

E is determined by using literature-derived estimates of daily nutrient production by different bird species, and then multiplying these by the estimated proportion of time each species spends on or adjacent to the water body, also derived from the literature. Where no data have been published for the species of interest, the species that is considered to be taxonomically and behaviourally most similar is used as a source of data.

As in the Phase 1 study, three scenarios are presented for 100%, 50% and 25% of the nutrient inputs from birds. This is a sensitivity analysis to account for the possibility of birds feeding at least in part within the meres themselves, reducing the net input of nutrients from beyond the catchments. Of these scenarios, the 50% of the maximum input has been applied for the purposes of source apportionment in each mere.

As with the Phase 1 bird loading estimates, there are two main limitations to the methods used in this study:

1) The coefficients used for bird mass and daily bird defecation rates were taken from literature and may be site-specific, and

2) It was assumed the entire nutrient load from bird excrement is bioavailable.

Appendix 5 - Lake water quality readings

Table 8-2 Langmere water quality readings

Analyte	*Units*	LOD	24/10/13	19/12/13	24/02/14	24/04/14	18/06/14	26/08/14	01/10/14
Nitrogen: Total as N	mg/l	0.1	2.45	7.64	2.13	1.09	1.43	2.16	2.42
Nitrate as N	mg/l	n/a*	0.276	0.283	0.630	<0.006	<0.005	<0.005	<0.008
Nitrite as N	mg/l	0.001	0.059	0.020	0.011	<0.001	<0.001	<0.001	<0.001
Nitrogen: Total Oxidised as N	mg/l	0.006	0.335	0.303	0.641	0.0062	<0.005	<0.005	0.0075
Phosphorus : Total as P	mg/l	0.02	0.107	0.669	0.054	0.027	0.0792	0.234	0.178
Orthophosphate Filtered as P	mg/l	0.001	0.0312	0.082	0.005	0.005	0.0375	0.0719	0.0956
Alkalinity pH 8.3	mg/l	5	<5	<5	<5	<5	<5	9.05	16.6
Alkalinity to pH 4.5 as $CaCO_3$	mg/l	5	84.7	55.2	117	116	62.3	80.2	85.3
Chlorophyll, Acetone Extract	ug/l	0.5	30.8	952	16	1.3	4.3	21.9	10.4
Calcium	mg/l	1	41.8	39.2	69.8	55.2	25.3	34.4	36.1
Iron	ug/l	30	1220	2870	341	195	355	992	1260
Magnesium	mg/l	0.3	2.31	1.93	2.53	2.69	2.25	1.69	1.65
Manganese	ug/l	10	30	78.3	32.1	10.3	14.5	22.7	35.6
Sodium	mg/l	2	9.29	7.66	6.96	8.86	8.94	8.16	9.81
Sulphate as SO_4	mg/l	10	20.5	42.4	63.1	28.1	<10	<10	<10

Table 8-3 Ringmere water quality readings

Analyte	*Units*	LOD	24/10/13	19/12/13	24/02/14	24/04/14	18/06/14	26/08/14	01/10/14
Nitrogen : Total as N	mg/l	0.1	2.5	2.29	1.38	1.47	1.57	1.68	2.05
Nitrate as N	mg/l	n/a*	0.015	0.667	0.074	<0.004	<0.005	<0.005	<0.005
Nitrite as N	mg/l	0.001	0.011	0.030	0.005	0.002	<0.001	<0.001	<0.001
Nitrogen : Total Oxidised as N	mg/l	0.006	0.0261	0.697	0.0789	<0.005	<0.005	<0.005	<0.005
Phosphorus : Total as P	mg/l	0.02	0.183	0.076	0.064	0.147	0.171	0.115	0.119
Orthophosphate, Filtered as P	mg/l	0.001	0.113	0.043	0.018	0.093	0.111	0.061	0.05
Alkalinity pH 8.3	mg/l	5	<5	<5	<5	<5	<5	12	31.7
Alkalinity to pH 4.5 as CaCO3	mg/l	5	180	158	145	188	173	119	86.9
Chlorophyll, Acetone Extract	ug/l	0.5	2.6	2.3	19.6	2.8	3.8	7.9	8.6
Calcium	mg/l	1	87.4	86.3	67.4	80.7	69.5	49.6	41.2
Iron	ug/l	30	626	360	90	304	371	340	756
Magnesium	mg/l	0.3	3.02	2.88	2.26	2.46	2.49	1.71	1.02
Manganese	ug/l	10	97.6	39.1	14.6	65.1	50.9	20.1	42
Sodium	mg/l	2	23.2	21.7	17.6	20.2	20	20	21
Sulphate as SO4	mg/l	10	37	39.2	29.9	13.9	<10	<10	<10

*Determined by calculation

Appendix 6 - Groundwater quality readings

Table 8-4 Ringmere borehole water quality readings

Analyte	*Units*	LOD	24/10/13	19/12/13	24/02/14	24/04/14	18/06/14	26/08/14	01/10/14
Nitrogen : Total as N	mg/l	0.1	0.44	0.33	0.13	0.19	0.16	0.25	0.17
Nitrate as N	mg/l	n/a*	0.025	0.016	0.006	0.0065	0.0073	0.153	0.0208
Nitrite as N	mg/l	0.001	0.001	0.005	0.003	0.002	0.0071	0.0011	0.0012
Nitrogen : Total Oxidised as N	mg/l	0.006	0.0263	0.0209	0.0095	0.0088	0.0144	0.154	0.022
Phosphorus : Total as P	mg/l	0.02	0.0937	0.152	0.021	<0.020	<0.020	0.0312	0.0328
Orthophosphate, Filtered as P	mg/l	0.001	0.0157	0.007	0.002	0.002	0.0025	0.0118	0.0075
Alkalinity pH 8.3	mg/l	5	<5	<5	<5	<5	<5	5.97	6.46
Alkalinity to pH 4.5 as $CaCO_3$	mg/l	5	37.4	35.7	36.6	36.2	43.3	39.1	37.8
Calcium	mg/l	1	10.8	10.1	10.4	12	12.1	8.66	9.22
Iron	ug/l	30	7790	16700	7350	7960	9770	12500	7090
Magnesium	mg/l	0.3	0.369	0.458	0.504	0.527	0.575	0.35	0.378
Manganese	ug/l	10	310	521	248	241	303	342	164
Sodium	mg/l	2	10.7	10.5	9.54	10.2	10.1	10.8	10.4
Sulphate as SO_4	mg/l	10	<10	<10	<10	<10	<10	<10	<10

*Determined by calculation

Appendix 7 – Sediment nutrient readings

Table 8-5 Sediment nutrient readings

Analyte	Units	LOD	Langmere			Ringmere		
			Deep	Middle	Shallow	Deep	Middle	Shallow
Nitrogen : Dry Wt as N	mg/kg	200	9520	6120	2230	14500	13800	6410
Carbon, Organic : Dry Wt as C	%	0.1	9.3	8.11	1.71	14	12.2	3.94
Iron : Dry Wt	mg/kg	200	9390	7050	1960	16100	14600	4320
Manganese : Dry Wt	mg/kg	2	62.4	65	11.1	230	186	63
Phosphorus : Dry Wt	mg/kg	10	688	619	128	897	872	355
Sodium : Dry Wt	mg/kg	10	64.7	60.6	12.6	129	136	55.8
Soil Organic Matter :- {SOM}	%	n/a*	5.39	4.7	0.992	8.12	7.08	2.29
Dry Solids @ 30°C	%	0.5	50.5	49.1	64.7	37.4	41.5	58.8
Dry Solids @ 105°C	%	0.5	47.5	51.2	54.3	35.9	38.4	56.8
Loss on Ignition @ 500°C	%	0.5	19.2	13.1	8.72	24.5	22.2	7.12
Sample description			Dark brown sandy loamy sediment	Dark brown sandy loamy sediment	Medium brown clay sandy sediment + plant material	Medium brown clay sandy sediment + plant material	Medium brown clay sandy sediment + plant material	Medium brown clay sandy sediment + plant material

*Determined by calculation

Appendix 8 – Bird count and estimated bird nutrient input data

Numbers are mean daily abundance, based on monthly visits. Derived from WeBS data from 2002-2009 and 2012-2013, plus August 2013 data from an APEM survey.

Table 8-6 Bird count data for Langmere.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bewick's Swan												0.4
Black Swan							0.2					
Black-headed Gull	29.9	3.9	75.4			0.7	4.8	1.1		0.3	8.7	19.1
Black-necked Grebe								0.1				
Black-tailed Godwit								0.1				
Canada Goose	2.0	1.0	1.1	0.6	2.3	15.3	28.5	53.9	30.4	64.7	0.5	
Common Sandpiper							0.3	0.1				
Coot	12.3	14.5	18.4	14.0	25.3	58.7	49.2	34.0	19.0	20.5	14.8	11.3
Egyptian Goose	0.5	1.3	0.3		1.3	2.0	2.5	2.8	1.9	3.2		0.8
Gadwall	4.9	5.0	7.6	4.4	3.6	5.7	2.8	2.2	3.0	3.2	7.0	2.4
Goldeneye												0.1
Great Crested Grebe					0.3	1.3						
Green Sandpiper	0.1	0.1	0.1				0.5	0.1				
Greenshank							0.2	0.3				
Grey Heron							0.2					
Greylag Goose	9.9	0.3	2.4		4.6		6.7	16.7	19.1	1.0	4.8	4.5
Greylag Goose (domestic)			0.1								0.2	
Hybrid goose											0.2	
Kestrel												
Lapwing		13.1	4.4	8.8	4.6	10.7	40.5	28.9	5.1	2.0		
Lesser Black-backed Gull	0.3		1.0	0.4	0.3		1.2	0.1	5.6	24.7	80.0	4.0

Table 8.6 (continued)

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Little Grebe	0.6	0.5	3.7	4.0	8.0	11.3	12.8	15.9	9.4	4.0	0.5	0.9
Little Ringed Plover					0.3							
Mallard	11.6	13.1	8.3	6.6	28.4	36.7	23.3	26.8	36.5	56.7	40.3	34.6
Mallard (domestic)										0.2	0.3	0.4
Moorhen	7.9	7.1	6.0	3.0	5.3	11.0	15.3	13.4	17.0	19.8	13.3	8.5
Mute Swan	0.1		0.1	0.6	1.3	1.0	0.8	0.6	0.4	0.3	0.2	0.1
Oystercatcher			1.0	0.6	0.9	0.7	0.3	0.2				
Pink-footed Goose										0.2		
Pochard	1.9	0.8	0.4	0.2	1.0	3.0	1.0	0.3		1.8	5.8	5.4
Redshank	0.1	0.1										0.3
Ruddy Duck			0.3	0.2	1.3	0.7	1.8	2.0	1.4		0.3	
Shelduck	4.4	3.9	8.3	7.8	5.7	1.0	1.3	0.2				
Shoveler	0.8	1.0	1.4	1.4			0.2	0.1	0.3	4.3	4.5	1.1
Snipe								0.1	0.3			
Teal	7.6	9.8	7.7	5.4		1.7	0.5	3.1	21.5	26.3	19.8	23.1
Tufted Duck	7.3	1.4	7.3	8.6	7.3	11.0	19.2	7.9	5.9	4.2	2.8	14.6
White-fronted Goose (European)								0.1				
Wigeon	0.5						0.2		0.3	6.8	1.0	

Table 8-7 Bird count data for Ringmere.

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bewick's Swan												
Black Swan												
Black-headed Gull								0.3				1.7
Black-necked Grebe												
Black-tailed Godwit												
Canada Goose							1.3	5.0				
Common Sandpiper												
Coot	5.0	5.8	7.3	7.7	6.7	5.3	6.3	7.3	7.5	5.5	9.0	5.1
Egyptian Goose				0.9								
Gadwall	5.0	3.3	2.1	1.1	0.9		2.0	1.3	4.3	0.8	5.8	2.9
Goldeneye												
Great Crested Grebe												
Green Sandpiper				0.1								0.8
Greenshank							0.3					
Grey Heron												
Greylag Goose			0.3	0.9	2.0		0.3					
Greylag Goose (domestic)												
Hybrid goose												
Kestrel												
Lapwing							0.5					
Lesser Black-backed Gull								1.7	14.9	13.3	15.0	
Little Grebe	0.1	0.5	3.3	3.9	5.1	3.3	3.5	2.7	3.5	1.5	0.5	0.1
Little Ringed Plover												
Mallard	25.0	10.1	6.1	4.9	6.0	9.3	6.7	9.7	6.9	6.0	14.5	17.3
Mallard (domestic)	0.3	0.1	0.1									

Table 8.7. Continued

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Moorhen	1.6	0.6	0.4	2.1	1.0	2.7	6.3	2.9	5.9	2.7	2.2	0.9
Mute Swan		0.3			0.4	0.3						
Oystercatcher				0.9			0.5					
Pink-footed Goose												
Pochard	2.4	1.9	1.6							0.3	3.2	
Redshank												
Ruddy Duck		0.1	0.1	0.4	0.3	0.7	1.0	0.6	0.9	1.0	0.8	0.1
Shelduck	0.6	0.9	1.7	0.7	0.3							
Shoveler	0.8	0.4	0.9	1.1						1.0	1.7	0.6
Snipe							0.2					
Teal	19.4	14.8	13.7	1.6	0.3		0.3	2.6	3.0	6.2	4.3	14.1
Tufted Duck	1.8	1.4	5.4	5.9	3.0	3.3	3.7	1.6	1.3	2.7	5.2	0.8
White-fronted Goose (European)												
Wigeon												

Appendix 9 – Source apportionment figures

Table 8-8 Estimated groundwater nutrient inputs to Langmere and Ringmere.

The volume is the estimated net change in volume during each period, once inputs from rainfall and outputs through evaporation have been taken into account, and is therefore considered to be an indication of the volume of water derived from groundwater.

Dates	Langmere			Ringmere		
	Vol (m^3)	TN (kg)	TP (kg)	Vol (m^3)	TN (kg)	TP (kg)
Oct-Dec	-101.37	-	-	-73.67	-	-
Dec-Feb	6,205.35	1.43	0.54	9,056.35	2.08	0.79
Feb-Apr	11,280.71	1.80	0.18	2,876.45	0.46	0.05
Apr-Jun	4,519.24	0.79	0.05	2,666.54	0.47	0.03
Jun-Aug	3,841.76	0.79	0.08	3,090.11	0.63	0.06
Aug-Oct	405.49	0.09	0.01	554.61	0.12	0.02
Total	26,151.19	4.90	0.85	18,170.38	3.76	0.94

Table 8-9 Atmospheric deposition of nitrogen to Langmere and Ringmere.

Sample Dates	NOx (µg/m^2)	Langmere		Ringmere	
		Mean Area (m^2)	TN (kg)	Mean Area (m^2)	TN (kg)
Oct-Nov	65.24	746.0	0.00005	1179.7	0.00008
Dec-Jan	74.71	1042.8	0.00008	1857.4	0.00014
Feb-Mar	72.08	774.2	0.00006	428.9	0.00003
Apr-May	56.30	2927.7	0.00016	1476.2	0.00008
Jun-Jul	49.98	2823.1	0.00014	1851.6	0.00009
Aug-Sep	48.40	270.3	0.00001	239.7	0.00001
Annual	-	-	0.00050	-	0.00043

Table 8-10 Summary of nutrient loads (kg) of Total Nitrogen (TN) and Total Phosphorus (TP) into Langmere and Ringmere.

Source	Langmere		Ringmere	
	TN (kg)	TP (kg)	TN (kg)	TP (kg)
Rainfall	25.34	8.64	17.81	8.35
Groundwater	4.90	0.85	3.76	0.94
Birds	8.88	4.92	2.62	1.40
Sediment	32.23	-12.93	42.38	-8.68
Lake Total	71.35	14.42	66.57	10.69

Table 8-11 Nutrient inputs from birds

Table 8.11a Langmere total phosphorus (TP) and total nitrogen (TN) loads from birds, assuming 100%, 50% and 25% scenarios.

Based upon monthly mean bird counts from WeBS data (2002-2009, 2012-2013) and an APEM survey in 2013 (MD).

Dates	100% Scenario		50% Scenario		25% Scenario	
	TP (kg)	TN (kg)	TP (kg)	TN (kg)	TP (kg)	TN (kg)
Oct-Nov	1.63	4.65	0.82	2.32	0.41	1.16
Dec-Jan	0.78	2.15	0.39	1.07	0.19	0.54
Feb-Mar	0.81	1.68	0.40	0.84	0.20	0.42
Apr-May	1.15	1.61	0.57	0.80	0.29	0.40
Jun-Jul	2.53	3.52	1.26	1.76	0.63	0.88
Aug-Sep	2.96	4.16	1.48	2.08	0.74	1.04
Annual	9.85	17.76	4.92	8.88	2.46	4.44

Table 8.11b Ringmere total phosphorus (TP) and total nitrogen (TN) loads from birds, assuming 100%, 50% and 25% scenarios.

Based upon monthly mean bird counts from WeBS data (2002-2009, 2012-2013) and an APEM survey in 2013 (MD).

Dates	100% Scenario		50% Scenario		25% Scenario	
	TP (kg)	TN (kg)	TP (kg)	TN (kg)	TP (kg)	TN (kg)
Oct-Nov	0.35	0.95	0.17	0.48	0.09	0.24
Dec-Jan	0.36	1.26	0.18	0.63	0.09	0.31
Feb-Mar	0.43	0.90	0.21	0.45	0.11	0.23
Apr-May	0.62	0.57	0.31	0.29	0.16	0.14
Jun-Jul	0.50	0.68	0.25	0.34	0.13	0.17
Aug-Sep	0.54	0.88	0.27	0.44	0.13	0.22
Annual	2.81	5.25	1.40	2.62	0.70	1.31

Table 8-12 Internal sediment loading of total nitrogen (TN) and total phosphorus (TP) to Langmere and Ringmere.

Dates	Langmere		Ringmere	
	TN (kg)	TP (kg)	TN (kg)	TP (kg)
Oct-Dec	1.49	-2.10	8.75	-3.10
Dec-Feb	7.14	-2.75	3.38	-4.31
Feb-Apr	3.98	-2.75	5.84	-0.51
Apr-Jun	12.42	-2.94	10.05	-0.14
Jun-Aug	4.27	-1.82	4.72	-0.88
Aug-Oct	2.92	-0.55	9.65	0.27
Total	32.23	-12.93	42.38	-8.68

Appendix 10 – Seasonal nutrient loading estimates

Table 8-13 Seasonal TN loads to Langmere

Total N (kg)	Dec-Jan	Feb-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Nov	Annual
Rainfall	1.54	1.08	3.75	5.74	9.47	3.77	25.35
Groundwater	0.00	1.43	1.80	0.79	0.79	0.09	4.90
Birds	1.07	0.84	0.80	1.76	2.08	2.32	8.88
Sediment	1.49	7.14	3.98	12.42	4.27	2.92	32.23
Total	4.11	10.49	10.34	20.71	16.61	9.10	71.36

Table 8-14 Seasonal TP loads to Langmere.

Total P (kg)	Dec-Jan	Feb-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Nov	Annual
Rainfall	1.67	1.26	0.97	2.26	1.98	0.51	8.65
Groundwater	0.00	0.54	0.18	0.05	0.08	0.01	0.85
Birds	0.39	0.40	0.57	1.26	1.48	0.82	4.92
Sediment	-2.10	-2.75	-2.75	-2.94	-1.82	-0.55	-12.93
Total	-0.04	-0.55	-1.03	0.63	1.72	0.78	1.50

Table 8-15 Seasonal TN loads to Ringmere.

Total N (kg)	Dec-Jan	Feb-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Nov	Annual
Rainfall	2.17	2.32	2.87	2.83	5.14	2.48	17.81
Groundwater	0.00	2.08	0.46	0.47	0.63	0.12	3.76
Birds	0.63	0.45	0.29	0.34	0.44	0.48	2.62
Sediment	8.75	3.38	5.84	10.05	4.72	9.65	42.38
Total	11.55	8.23	9.46	13.68	10.93	12.72	66.57

Table 8-16 Seasonal TP loads to Ringmere.

Total P (kg)	Dec-Jan	Feb-Mar	Apr-May	Jun-Jul	Aug-Sep	Oct-Nov	Annual
Rainfall	2.36	2.73	0.74	1.11	1.08	0.34	8.36
Groundwater	0.00	0.79	0.05	0.03	0.06	0.02	0.94
Birds	0.18	0.21	0.31	0.25	0.27	0.17	1.40
Sediment	-3.10	-4.31	-0.51	-0.14	-0.88	0.27	-8.68
Total	-0.56	-0.58	0.59	1.25	0.53	0.80	2.02