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Reviewing phosphorus and nitrogen

targets for the SSSI meres

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CONFIDENTIALITY STATEMENT

EXECUTIVE SUMMARY

1. The meres in the North-West Midlands of England are a regional cluster of lakes of high conservation importance, yet impacted by high nutrient concentrations from surrounding land-use and population settlements. Despite their long-history of being in a eutrophic state, the most rapid enrichment and consequent changes to aquatic flora have occurred over the last 50-100 years. In many lowland temperate lakes, these changes have largely resulted from phosphorus enrichment and national legislation has set target concentrations for this element to prevent or reduce nutrient enrichment. However other nutrients, such as nitrogen, can also limit or co-limit productivity and is probably of more widespread importance than generally recognised, but currently no target concentrations exist for this nutrient.

2. The purpose of this review, therefore, was to:
    *   review existing phosphorus target concentrations for 26 meres with SSSI status
    *   assess the applicability of nitrogen target concentrations for these meres
    *   recommend P and N target concentrations for the 26 SSSI meres
    *   recommend further research to address data gaps and improve understanding and management of the meres.

3. The review considered key published and unpublished literature and recent work in setting P and chlorophyll standards for the Water Framework Directive. It also analysed data on current concentrations of nitrogen & phosphorus provided by the Environment Agency and macrophyte species provided by Natural England.

4. There is not a single way to assess nutrient-limitation so eight approaches were used: i) N:P ratios, ii) comparison of Chla: total phosphorus (TP) versus European average response, iii) comparison of Chla: total nitrogen (TN) versus European average response, iv) Chla:TP ratios, v) Chla:TN ratios, vi) seasonal minima of phosphate and nitrate, vii) modelling using a stoichiometric model 'Metabolake and viii) direct bioassays.

5. Although nitrogen-limitation is becoming recognised as being more widespread then hitherto thought, in the case of the meres, the frequently high concentrations of TP caused by input from glacial deposits, low rates of TP loss caused by low flushing rates or lack of a distinct outflow coupled with potential loss of nitrogen to the atmosphere via denitrification will tend to favour nitrogen-limitation and this was reflected in the analysis.

6. The analyses indicated that at the 22 sites where data were available, 7 sites were mainly phosphorus-limited (32%), 8 sites were mainly nitrogen-limited (36%) and 7 sites were either mainly co-limited or not limited by nutrients (32%). Direct bioassay data showed that nutrient-limitation can vary over a year.

7. Nutrient targets are needed to manage water quality or achieve conservation objectives. They are not something essential of themselves.

8. Macrophyte diversity, a possible conservation objective, does not appear to relate to nutrient availability in the meres, possibly because most of the meres have relatively high nutrient concentrations and possibly because the macrophyte populations have adapted to these concentrations over many decades. Total number of species vs nitrate in the meres is not markedly different from the UK data-set used to establish the relationship between macrophyte diversity and nitrogen so this is unlikely to be the cause of the lack of a relationship.

9. In terms of setting targets, many of the meres have high alkalinities so high-baseline targets for TP would be expected. Site-specific Water Framework Directive TP targets for the meres at the High/ Good boundary range from 14 µg L^{-1} for Oak Mere (low alkalinity) to 46 µg L^{-1} for Quoisley Little Mere. The Good/ Moderate boundary targets range from 21 to 57 µg L^{-1}. These concentrations are generally below the inferred TP concentrations from around 1850 which range between 31 and 50 µg L^{-1} at the five sites where cores have been analysed. Consequently, even Good/ Moderate Water Framework Directive targets may not be achievable.

10. The presence of nitrogen limitation or co-limitation in the meres means that nitrogen targets are also appropriate at some of the sites. Total nitrogen targets were derived from European datasets relating concentrations of chlorophyll *a* to total nitrogen for different types of lakes. In turn, the chlorophyll *a* target was derived from Water Framework Directive standards for different lake types. The Good/ Moderate total nitrogen target varied between 0.4 mg to 1.4 mg L^{-1}.

11. Where possible, mere-specific targets are preferable to general targets, but these require better data to implement. A range of different future projects addressing data gaps and uncertainty over the functioning of the meres are suggested. In particular, the role of trophic-interactions, for example grazing of phytoplankton by zooplankton and control of zooplankton by fish, in moderating water quality needs to be assessed and managed.

TABLE OF CONTENTS

Page number

1. INTRODUCTION

1.1 Purpose of the review

Over the last 100 years or so, human activity has caused many lakes to have become enriched with nutrients. This has resulted in a range of symptoms associated with eutrophication including increased algal biomass, deoxygenation at depth during stratification, changed species composition and loss of submerged macrophytes. In many deep, lowland, temperate lakes, recent changes have largely resulted from phosphorus enrichment and national legislation has set target concentrations for this element to prevent or reduce nutrient enrichment. However other nutrients, such as nitrogen, can also limit or co-limit productivity and is probably of more widespread importance than generally recognised. Currently however, no target concentrations exist for this nutrient. The meres in the North-West Midlands of Britain are systems where there is evidence that nitrogen may be the key nutrient limiting productivity at some sites. The purpose of this review, therefore, is to:

undertake a detailed review of the existing phosphorus target concentrations for twenty-three plus associated meres, giving a total of twenty-six, with SSSI status in the context of paleolimnological evidence of change:

- assess the applicability of nitrogen target concentrations for some or all of the meres,
- recommend P and N target concentrations for the twenty-six SSSI meres,
- recommend future work that is needed to improve understanding and management of the meres.

1.2 Data sources for the review

Data were compiled from the published literature and unpublished reports and from data and reports provided by Natural England and the Environment Agency. In total about 1100 files in different formats were received to inform the report. Dr Geneveive Madgwick (NE) and Dr Sian Davies (EA) provided additional information on macrophyte species composition and recent water quality respectively.

2.   BACKGROUND ON THE FUNCTIONING OF LAKES

2.1   Lake connectivity and global biogeochemical cycles

The gravitational flow of water falling as precipitation on land makes most lakes highly connected to their catchment. Dissolved and particulate material from the vegetation, soil and rock within the catchment are transported to a lake where it can be used as a resource by the biota of the lake, sedimented at the bottom of the lake, exchanged with the atmosphere as a gas, often after biological transformation of the original material, or washed out downstream, ultimately to the sea. Consequently, lakes, although comprising only about 3% of the global land surface area (Downing et al. 2006), are important in the global biogeochemical cycling of elements, particularly carbon (Cole et al. 2007; Downing et al. 2008; Downing 2009). It follows, therefore, that lakes are strongly influenced by changes in the supply of resources, such as nutrients, from within the catchment. However, they are also influenced by the atmosphere at local (such as weather), regional (such as atmospheric deposition) or global (such as climate change) scales. As a result, lakes are extremely sensitive to environmental perturbation and no lakes in the UK have been unaffected by Man's activities.

Lakes are part of the global water cycle and receive water as direct precipitation on the lake surface, inflow of surface water from the catchment and inflow of water from groundwater, which potentially derives from a greater area than the catchment alone. Lakes lose water by the same routes: evapo-transpiration to the atmosphere, surface water outflow via streams and recharge of groundwater. The rate of water exchange is highly variable with time as precipitation varies, but as a long-term average the rate of exchange can be as short as a few days for lakes with a small volume relative to the supply of water to over a thousand years for very large lakes with relatively low rates of inflow such as Lake Titicaca in South America or Lake Tanganyika in Africa. The retention time is important in controlling the input and loss of resources such as nutrients but also the loss of biological material, such as phytoplankton, produced within a lake.

2.2   Supply of resources for primary production

Nutrients in lake water derive from dissolved and particulate material brought in by inflowing water, deposited on the lake surface from the atmosphere, exchanged with the atmosphere or recycled within the water or sediment within the lake. Especially in lakes with retention times of less than around a year, external nutrient sources, of which inflowing nutrients is usually the main component, provide the major source of nutrients. These inflowing nutrients can be conveniently separated into 'diffuse sources' that enter the freshwater system over a large area of the catchment and 'point sources' where the input to the freshwater system is localised to one or a few places. Typically, diffuse sources can be natural (e.g. input of material eroded from the catchment) or man-made (e.g. inflowing of nutrients applied as fertilizer to fields) while point sources are usually man-made (e.g. input of material from a wastewater treatment works or a factory).

Resources needed by biota within a lake

Although many lakes receive a subsidy of energy and materials from organic carbon fixed within the terrestrial catchments as inflowing dissolved and particulate material (and a minor component from riparian vegetation and animals falling directly into the water), photoautotrophs: the phytoplankton, the phytobenthos and macrophytes, form the base of the food chain in most lakes. These organisms require light energy (photosynthetically active radiation, PAR, 400 to 700 nm) for photosynthesis and elements such as (in rough descending order of requirement): C, N, P, Si (mainly for diatoms), K, Ca, Mg, S, Fe, Mn, Cu, Zn, Cl, Mo and Co (Raven & Maberly 2005). In addition, H and O are required but derive directly from water and so are never a resource-constraint. During balanced growth, a typical algal molar ratio (the Redfield ratio, Redfield 1958) for the three major elements, C, N and P is 106C:16N:1P.

Rates of net production and sustainable biomass on an area basis have an absolute upper limitation imposed by light-energy availability (Talling 1971) and light can limit productivity in lakes which are optically-deep because the high concentration of coloured dissolved organic carbon causes rapid light attenuation (Jones 1996; Karlsson et al. 2009). In many lakes, however, light never limits productivity because one of the other resources, such as phosphorus or nitrogen, becomes limiting first.

3

Carbon is an essential component of carbohydrates, proteins, lipids and nucleic acids and can form upto 45% of the ash-free dry weight of freshwater organisms. The total concentration of inorganic carbon in a lake is largely determined by the geology of the catchment. Soft-waters in catchments with little limestone or base-material have low alkalinity and low concentrations of inorganic carbon. Hard-waters in catchments with a lot of limestone or base-material have high alkalinity and high concentrations of inorganic carbon with an upper limit often set by the solubility product of calcium carbonate. Inorganic carbon can be temporally depleted from lake surface waters when rapid photosynthesis removes CO_2 and HCO_3^- faster than it can be resupplied from the atmosphere, inflows or the sediment, leading to elevated pH (Maberly 1996). Although this carbon depletion probably has consequences for species composition of phytoplankton and macrophytes, over a year most lakes have excess CO_2, relative to atmospheric equilibrium concentrations (Cole et al. 1994) and carbon availability probably rarely controls productivity.

Nitrogen is an essential component of proteins and nucleic acids and typically comprises about 1.5% of the ash-free dry weight during balanced growth. Available sources include dissolved inorganic ions such as nitrate and ammonium, organic nitrogen in the form of simple molecules such as amino acids and, for certain cyanobacteria that can convert dinitrogen gas into ionic forms of nitrogen via 'nitrogen-fixation', dissolved nitrogen gas. The dissolved inorganic nitrogen derives mainly from point and diffuse sources within the catchment but can also derive from atmospheric deposition directly on the lake surface or indirectly on the catchment (Bergstrom & Jansson 2006).

Phosphorus is an essential component of nucleic acids and many biochemical intermediates within a cell, including ATP, and typically comprises about 0.2% of the ash-free dry weight during balanced growth. Phosphorus is mainly available as dissolved orthophosphate although certain organisms can produce external phosphatase enzymes that cleave phosphate from phosphorus-containing molecules. Phosphorus mainly enters a lake from the catchment although there can be a small direct input as atmospheric deposition.

In-lake nutrient sources and in-lake processes
In some lakes, especially those with very long-retention times, or in productive lakes with dense microbial populations or anoxic sediments, the internal supply of nutrients can be

important in driving primary productivity. This results from a number of different processes. Firstly, nutrients can be effectively recycled by a 'microbial-loop' (Azam et al. 1983) whereby consumption of phytoplankton by protozoa, rotifers or crustacea, or decomposition by fungi, bacteria or viruses leads to regeneration of dissolved nutrients that can be utilized again by phytoplankton. Secondly, in shallow lakes mixing of surface sediments by wind and wave can release nutrients from the interstitial water in the sediment which is often enriched in nutrients because of decomposition processes. Thirdly, in productive lakes that stratify, restriction of oxygen supply to the sediment surface coupled with a high demand for oxygen by microbial decomposition of organic material can cause the sediment surface to become anoxic, leading to low (negative) redox potential. This causes ferric iron (Fe^{3+}) that can bind phosphate to be reduced to ferrous iron (Fe^{2+}) that does not bind phosphate, leading to release of phosphate to the overlying water (Mortimer 1941, 1942). Other nutrients such as ammonium and silica can also be released from the sediment to the water during anoxia.

Phytoplankton biomass is not-only controlled by rates of production but also by rates of loss. Firstly, hydraulic losses are especially important in rapidly-flushed lakes, approaching the retention time of a slow-moving river, and these can be great enough to prevent the build up a large phytoplankton populations (Reynolds & Lund 1988; Elliott et al. 2009). Secondly, loss of algae to the sediment can also be significant. Many phytoplankton perennate on the sediment as part of their life history (Karlsson-Elfgren & Brunberg 2004; Head et al. 1999) but for others the loss to the sediment results in reduction in population density. Because of Stoke's law, which relates rates of sinking to excess density and the size of a particle (Reynolds 1984), sinking rates, and hence losses, are greatest in diatoms because of their dense silica cell wall and in large non-vaculate colonies such as the cyanobacterium *Tychonema bourrelyi*. Thirdly, phytoplankton can be consumed by other organisms including viruses (Middleboe et al. 2008), chytrid fungi (Ibelings et al. 2004) and especially zooplankton. The latter, particularly the larger filter-feeding *Daphnia*, can remove a substantial amount of phytoplankton, especially the smaller species that are more readily filtered and processed.

2.3   Relationships between nutrient availability and productivity

There are, perhaps, four main reasons why there has been a strong focus on phosphorus as the main limiting nutrient in freshwaters. Firstly, large-scale comparisons across temperate

lakes have found broad relationships between phytoplankton biomass (commonly expressed as the concentration of the ubiquitous photosynthetic pigment chlorophyll *a*) and phosphorus expressed as total phosphorus (e.g. Dillon & Rigler 1974; Vollenweider & Kerekes 1980; Vollenweider 1989, Phillips et al. 2008). Part of this association is correlative as phytoplankton will contribute both to chlorophyll *a* and to total phosphorus. Secondly, the history of eutrophication of lakes such as Lake Washington in the USA (e.g. Edmondsen & Lehman 1981); and in the UK lakes such as Windermere (Talling & Heaney 1988; Pickering 2001), Lough Neagh (Wood & Smith 1993) and Loch Leven (Carvalho & Kirika 2003) is related to an increase in the availability of phosphorus rather than nitrogen. Thirdly, the seminal whole-lake experiments on Canadian shield lakes (Schindler 1977; Schindler et al. 1978) demonstrated that in these lakes, phosphorus was the prime limiting nutrient. Fourthly, the management of P-loading is more practicable than that of N-loading, because much anthropogenic phosphorus loading arises as point source discharges (Reckhow & Simpson 1980). In contrast, nitrogen is highly mobile in the environment, transported to water bodies in surface or ground water, and even in precipitation and consequently its supply is more difficult to control than is phosphorus. Such powerful evidence has guided the management of eutrophication towards a focus on P control, through legislation acting on point sources and diffuse sources (Rast & Lee 1983; Janus & Vollenweider 1981).

Despite this evidence for the pre-eminence of phosphorus-limitation, from an early stage other nutrients were known to be limiting, including nitrogen (Sakamoto 1966), silicon (Reynolds 1984) or minor trace elements such as molybdenum, iron and cobalt (Goldman 1965). Nitrogen is the primary or co-limiting nutrient for phytoplankton production in some lakes in North America (Elser Marzolf & Goldman 1990), South America (Diaz & Pedrozo 1996), northern Sweden (Jansson et al. 1996), acidified lakes in central Sweden (Blomqvist et al. 1993) and some lowland German (Sommer 1989) and Dutch lakes (van der Molen et al. 1998). Nitrogen-limitation may be more widespread in tropical lakes (Vincent et al. 1984; Talling & Lemoalle 1998). Within the UK, nitrogen-limitation has been found in some Cheshire meres (Moss et al. 1992, 1994; James et al. 2003), other shallow eutrophic and mesotrophic lowland lakes around the UK (James et al. 2003) and upland UK lakes (Maberly et al. 2002). N-limitation does not appear to be confined to eutrophic lakes, and has been reported in mesotrophic lakes (Hough & Thompson 1996) and in oligotrophic lakes for periods during the late summer (Chang & Petersen 1995; Matthews et al. 2002) in North

America. Even where lakes are not predominately N-limited, the N-limitation of phytoplankton can occur even for short periods (Sommer 1989). For example, the phytoplankton of Lough Neagh is P-limited for much of the year but becomes N-limited in the late summer (DOE-DARD 2002). Periods of possibly limiting N concentrations have also been reported from Lough Erne and from a number of shallow lakes in the UK (DOE-DARD 2002; Maberly et al. 2002; Fisher 2003).

A recent meta-analysis of nutrient enrichment experiments from over 500 freshwater studies (Elser et al. 2007) showed that, on average, freshwater phytoplankton are as commonly nitrogen-limited as phosphorus-limited and addition of both nutrients typically produced the strongest response. A similar conclusion was reached by Lewis & Wurtsbaugh (2008) based on a review of the available literature. An intriguing possibility was raised by Bergstrom & Jansen (2006), namely that in the northern hemisphere atmospheric nitrogen deposition has driven some lakes from their natural N-limited state towards P-limitation: in other words, before Man's increase in N-supply via atmospheric deposition, most lakes in the northern hemisphere would have been nitrogen-limited. This has been supported by more recent work work (Elser et al. 2009a,b).

There has been a recent controversy about the role of N and P-limitation in lakes and estuaries and the effectiveness of reducing only one of these nutrients (Schindler et al. 2008; Howarth & Pearl 2008; Schindler & Heckey 2008). In a Policy Forum Review in Science, Conley et al. (2009) rehearsed the various arguments and concluded that effective control of the negative impacts of nutrient enrichment should be made by control and reduction of both nitrogen and phosphorus.

2.4   Role of climate change

As noted above, in addition to nutrient enrichment lakes are sensitive to other environmental perturbation of which the most pervasive is climate change. A recent book is devoted to the effects of climate change on lakes (George 2010). Most effects of climate change are likely to be negative for water quality and conservation. For example, forecasts for northern Britain (UKCP09:   http://www.ukcip.org.uk/index.php?option=com_content&task=view&id=163) suggest that:

- winters will be wetter- which will potentially increase the input of nutrients from the catchment
- summers will be drier- which will reduce hydraulic losses that reduce phytoplankton biomass in some lakes
- summers will be warmer- this will strengthen stratification

Drier, warmer summers are likely to promote the growth of cyanobacteria (Paerl & Huisman 2008) which can be toxic, disrupt linkages to higher trophic levels and on decomposition lead to anoxic conditions. In addition warmer waters may have an indirect effect by opening niches for non-native species that are introduced into the area, wittingly or unwittingly, by human transport.

3. THE ECOLOGY OF THE MERES

3.1 Introduction

In some ways the meres are not typical of the general lakes discussed in section 2. They are believed to be chronically nutrient-rich (Fisher et al. 2009), they have a complicated hydrology that is often dominated more by groundwater rather than by surface water (Reynolds 1979) and, like many shallow lakes, biological interactions are believed to be very important in controlling water quality (Moss et al. 1994). Reynolds (1979) recorded 63 open water meres and a further 41 mires or mosses without open water in the region. The meres range in area from around 0.2 ha (Sweat Mere in 1975) to 72.5 ha (Aqualate Mere) and in maximum depth (where known) from less than 1 m (Norbury Big Mere) to 27.5 m (Rostherne Mere). Mean depths (Fisher et al. 2009, again where known) range from 0.7 m (Little Mere) to 13.6 m (Rostherne Mere). The meres have been the subject of intensive and extensive study over many years, particularly recently by teams from Liverpool University. Early reviews include those of Sinker (1962), Reynolds (1979) and the major systematic seasonal surveys of Moss et al. (1992). Natural England (then English Nature) and the Environment Agency commissioned a series of conservation plans for 44 sites from Environmental Consultants, Sheffield University (ECUS) which draws together useful information on the geology, soils, hydrology, landuse, conservation objectives, management and limnology. More recently, Fisher et al. (2009) reviewed the water quality in the meres.

Given the available reviews noted above, this section will outline briefly what is known about the general ecology of the meres. The specific features of the catchment, hydrology, geology and basic limnology of each mere will be described in section 4.

3.2 Geography, geology and history

The meres of the North-West Midlands in the UK lie on the Shropshire-Cheshire Plain between the Mersey to the north, the South Shropshire hills to the south, the Pennines to the east and the Welsh Massif to the west (Reynolds 1979). Geologically, the plain comprises Carboniferous limestones, grits and shales around the perimeter and Triassic sandstones and marls in the centre. However, most of the underlying rocks lie beneath glacial drift deposited

during the Pleistocene glaciation comprising boulder clay and sands and gravels. Based on a review of the early literature, Reynolds (1979) judged that meres started to be formed after the Late Devensian glaciation around 16 - 18, 000 years ago as the ice-sheets started to retreat. A number of processes linked to the glaciation probably led to the formation of the meres including kettle holes (e.g. the central part of Ellesmere Mere), moraine-damned hollows (e.g. 'Crose Mere complex') and possible periglacial pingoes (e.g. Oakhanger and White Moss). Other meres are likely to have formed from post-glacial subsidence hollows resulting from 'wet-head' solution of buried salt deposits (e.g. Budworth Mere).

3.3   Control of phytoplankton populations

A major change in our understanding of how the meres function came about with the publication of a paper by Moss et al. (1994). Based on a detailed seasonal survey of twenty-four meres, they showed that the shallower meres (< 3 m maximum depth) and the deeper meres (>3 m maximum depth) were controlled by different environmental variables. In the shallower meres there was a strong inverse relationship between the growing season phytoplankton chlorophyll *a* concentrations and the density of *Daphnia* zooplankton and total filter-feeding zooplankton (Fig. 3.1). This strongly indicates that in these shallow lakes loss processes caused by zooplankton grazing controls phytoplankton populations, probably because in shallow lakes a large proportion of the lake area can be colonised by macrophytes that provide a refuge for zooplankton from grazing by fish. In contrast, in the deeper lakes the availability of inorganic nitrogen was strongly positively linked to phytoplankton chlorophyll *a* concentrations while no clear relationship was found for total phosphorus, the 'commonly assumed' limiting nutrient (Fig. 3.2). The importance of nitrogen as a limiting nutrient was later confirmed in the studies of James et al. (2003) and Fisher et al. (2009).
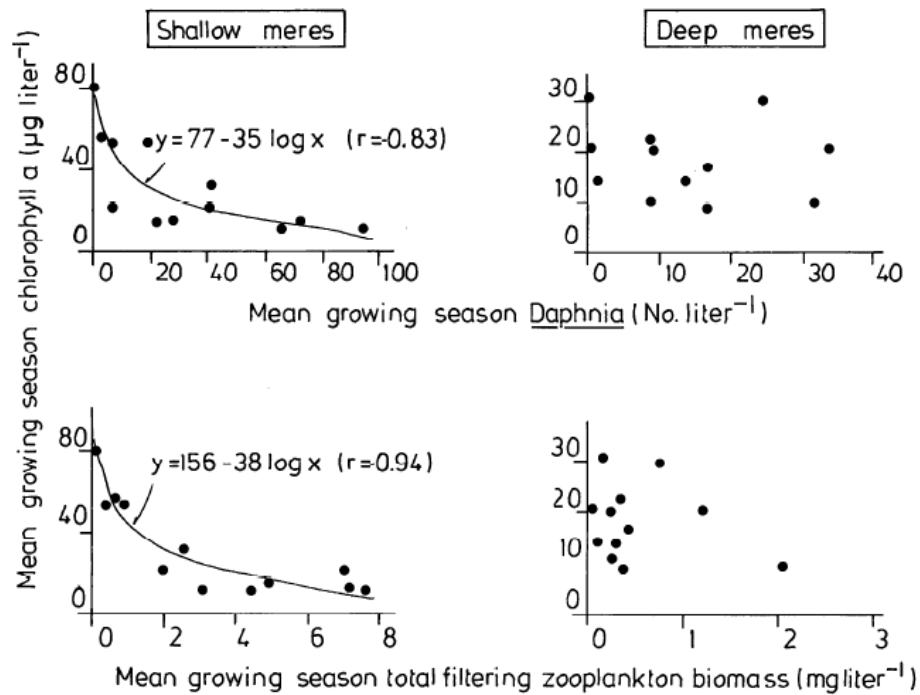
Figure 3.1. Effect of zooplankton populations on growing season phytoplankton chlorophyll a in shallow and deep meres based on maximum depth. Original in Moss et al. (1994), *American Society of Limnology & Oceanography.*
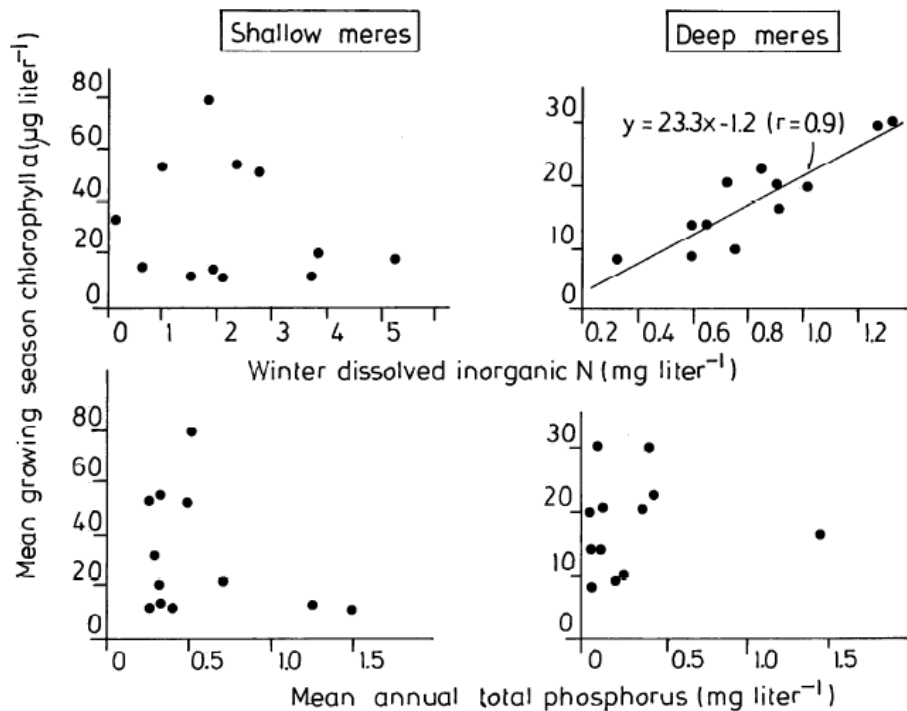
Figure 3.2. Effect of inorganic nutrients on growing season phytoplankton chlorophyll a in shallow and deep meres based on maximum depth. Original in Moss et al. (1994), *American Society of Limnology & Oceanography.*

4. LIMNOLOGY AND INFORMATION ON INDIVIDUAL MERES

The following brief descriptions give an overview of the most important features of the meres and mosses discussed in this report. This provides the context for the setting of nutrient targets for each site. The information is derived mainly from the series of reports produced by ECUS between 2001 and 2003 and a limnological survey of most of these sites carried out by Moss et al. (1992) between July 1991 and July 1992 provides the baseline chemical background, supplemented where necessary with information in Fisher et al. (2009). Where available, recent data from the Environment Agency (mainly from 2005 to 2009) are also given for concentration of total phosphorus (TP), dissolved inorganic nitrogen (DIN, the sum of nitrate, nitrite and ammonium) and phytoplankton chlorophyll a.

Hydrological source of water is classified into either drainage where water-level is strongly influenced by surface flows and seepage where water-level is maintained by atmospheric exchange and groundwater (Saunders et al. 2000).

The final row for each lake gives the Water Framework Directive (2000/60/EC) lake typology based on alkalinity and mean depth. For alkalinity (mequiv L^{-1}): High (HA) > 1; Moderate (MA) 0.2 - 1.0; Low (LA) <0.20. For mean depth (m): Deep (D) >15.0, Shallow (S) 3.0 – 15.0, Very Shallow (VS) <3.0.

The salient features are given in a table for each mere but also compiled into a single table at the end of this section.

4.1 Aqualate Mere

Aqualate Mere (NGR, SJ770 205) is the largest of the meres in the Shropshire-Cheshire Plain with a surface area of about 75 ha (Table 4.1) but a more recent estimate is only 59 ha (ESI 2009; Fig. 4.1) that excludes fringing reedbeds. It is also one of the shallowest, a survey in 2009 recorded a maximum depth of about 1 m (ESI 2009). The catchment area (Fig. 4.1) is estimated to be 58 km^2. The surface geology is dominated by Quarternary deposits of peat, gravel and sand. Land use is mainly pastoral with small areas of woodland and wet-grassland. The mere receives surface water from three main streams: The Coley Brook (68% catchment area), Wood Brook and Humesford Brook. During high-water levels, inflow to Wood Brook may be supplemented by storm overflow from the adjacent Shropshire Union Canal (ESI 2009). The sediment in the mere comprises a clayey-silt layer up to 1.3 m thick that is deposited on more organic-rich post-glacial sediments (ECUS 2003). The mere is probably connected to groundwater with minor superficial aquifers and with the regional Sherwood Sandstone aquifer (ECUS 2001a, 2003) and groundwater is likely to make a contribution to hydraulic input in Aqualate Mere. The land use in the catchment is mainly arable and semi-improved grassland, but numerous woodlands and villages are present in the large catchment.

Table 4.1. Characteristics of Aqualate Mere.

Characteristic	Value	Unit	Reference and notes
Altitude	67	m	
Area	59	ha	ESI (2009); 75ha in Reynolds (1979)
Catchment area	58	km^2	ESI (2009)
Max water depth	1	m	Survey in 2009
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	D & S	-	ECUS (2001a)
Annual conductivity	610	$\mu S\ cm^{-1}$	Fisher et al. (2009)
Annual alkalinity	0.88	mequiv L^{-1}	Fisher et al. (2009)
Annual TP	469 (250)	$\mu g\ L^{-1}$	Fisher et al. (2009) (Recent EA data)
Annual DIN	870 (6820)	$\mu g\ L^{-1}$	Fisher et al. (2009) (Recent EA data)
Annual Chlorophyll *a*	68 (25)	$\mu g\ L^{-1}$	Fisher et al. (2009) (Recent EA data)
WFD Lake type	MA, VS	-	

*D = Drainage; S = Seepage
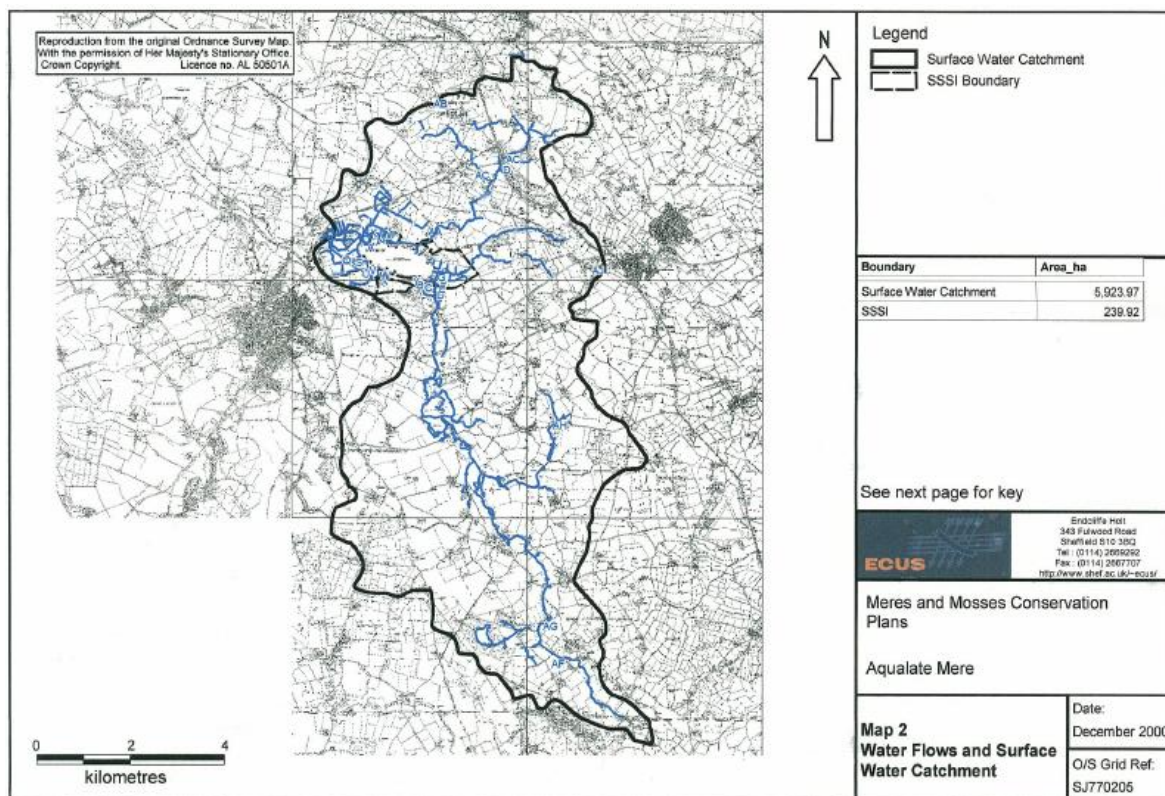
Figure 4.1 Map of Aqualate Mere showing surface water catchment (ECUS 2001a).

4.2   Berrington Pool

Berrington Pool (NGR, SJ526 073) is a small, alluvium-lined kettlehole mere 2.5 ha in area but around 12 m deep with a mean depth of about 6.7 m (Table 4.2). It lies in a cup-shaped basin. It has a very small catchment area (Fig. 4.2), the surface geology of which is glacial till and glaciofluvial drift, although it is possible that the catchment is slightly larger than currently thought. The catchment includes the small water body Top Pool but connexions to Berrington Pool are unclear. There are no major stream inputs (ECUS 2001b; Fig. 4.2), and Moss et al. (1992) concluded that the mere was largely fed by groundwater. However, there is also no evidence that the mere is linked to the regional aquifer and the water level appears to be substantially above the groundwater level. It is possible that water is derived by lateral transport from saturated soils and overland flow during high rainfall. The hydrology of the mere is therefore unclear and a retention time has not been calculated.

Table 4.2. Characteristics of Berrington Pool.

Characteristic	Value	Unit	Reference and notes
Altitude	78	m	
Area	2.5	ha	Reynolds (1979)
Catchment area	0.36	km^2	ECUS (2001b)
Max water depth	12.2	m	Reynolds (1979)
Mean water depth	6.7	m	Unpub survey in 1982 held by NE
Mean retention time	-	y	-
Main source of water*	S	-	ECUS (2001b); Moss et al. (1992)
Annual conductivity	392	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	1.8	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	113 (180)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	384 (1020)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll a	16.6 (20.3)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
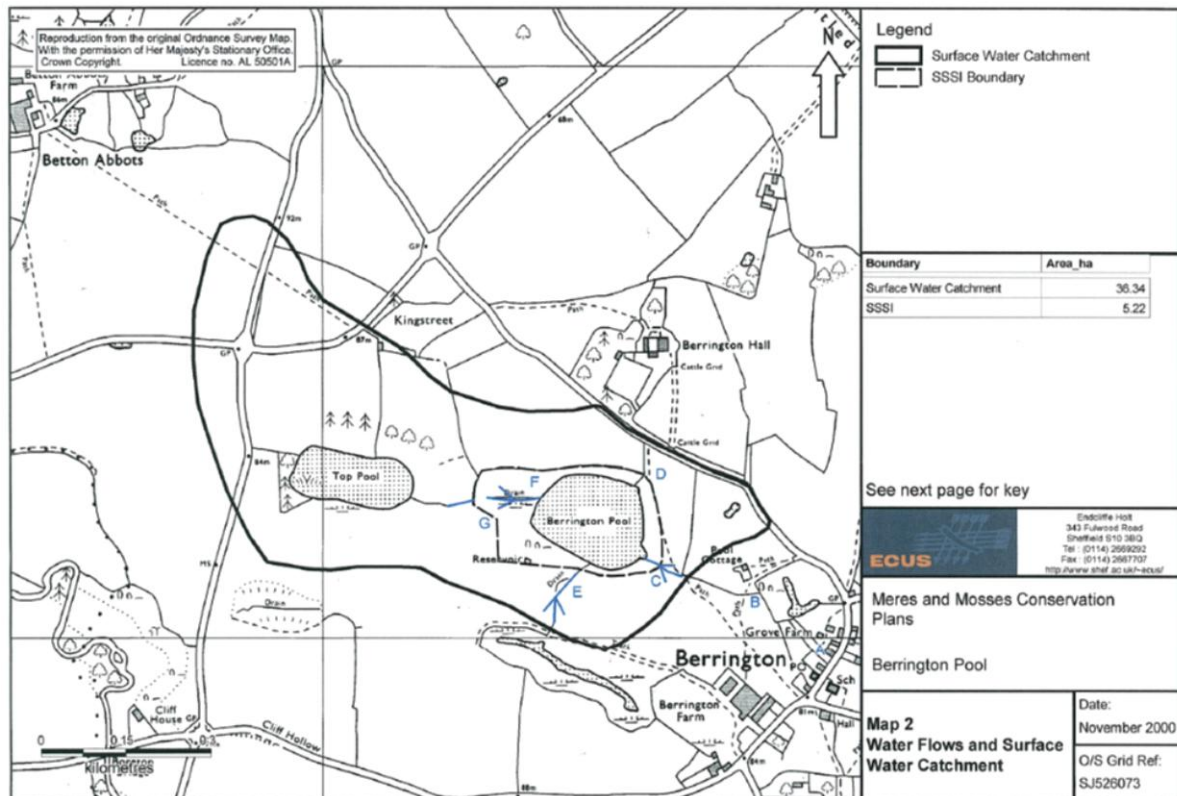
Figure 4.2 Map of Berrington Pool showing surface water catchment (ECUS 2001b).

4.3 Betley Mere

Betley Mere (NGR, SJ747 482) occupies a shallow valley in glacial deposits overlying Triassic strata and is bounded on three sides by extensive peat deposits (ECUS 2001c). It is shallow with a maximum water depth of about 1.8 m and an area of about 9.3 ha (Table 4.3). The catchment area (Fig. 4.3) is 8.3 km^2 and comprises arable and semi-improved pasture for cattle with pockets of neutral grassland and woodland. Betley Mere receives water mainly from two inflowing streams and has one outflow (Moss et al. 1992). There is believed to be a small contribution of groundwater to the hydraulic input. The estimated inflow exceeded the outflow suggesting substantial loss of water to the groundwater or adjacent wetland areas. The estimated flushing rate is high with a mean retention time of 0.07 y but this declines markedly in the summer to 0.97 y (Moss et al. 1992).

Table 4.3. Characteristics of Betley Mere

Characteristic	Value	Unit	Reference and notes
Altitude	58	m	
Area	9.3	ha	Reynolds (1979)
Catchment area	8.31	km^2	ECUS (2001c)
Max water depth	1.8	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	0.07	y	Moss et al. (1992)
Main source of water*	D (S)	-	ECUS (2001c); Moss et al. (1992)
Annual conductivity	659	µS cm^{-1}	Moss et al. (1992)
Annual alkalinity	3.93	mequiv L^{-1}	Moss et al. (1992)
Annual TP	506 (480)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual DIN	1060 (2180)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	63 (74)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
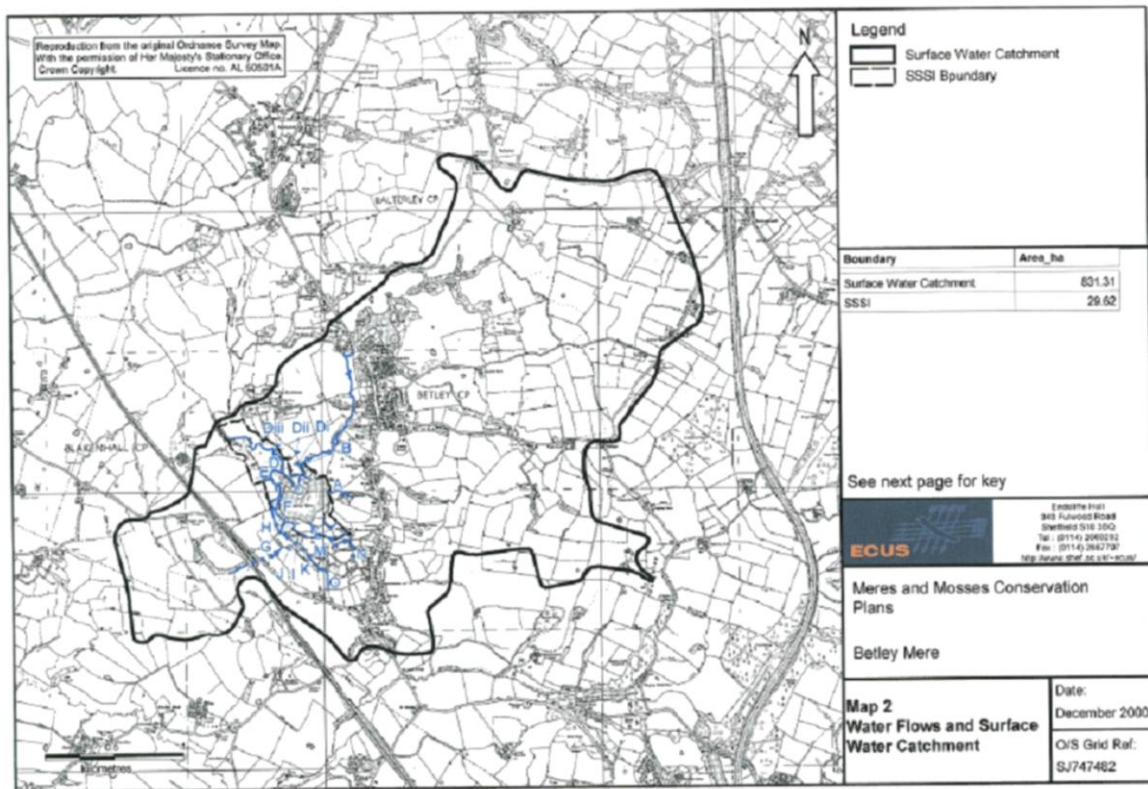
Figure 4.3 Map of Betley Mere showing surface water catchment (ECUS 2001c).

4.4   Black Firs and Cranberry Bog: Black Mere

Black Firs and Cranberry Bog (NGR, SJ748 503) are a drained wetland with a valley-woodland and a small well-preserved schwingmoor basin mire respectively (ECUS 2001d; Fig. 4.4). Cranberry Bog has an adjoining dystrophic lake, Black Mere, which is the focus of this report. The solid geology of Triassic siltstones and mudstones (Keuper marls) is overlain by drift of peat and deposits of glacial sands and gravels. The surface water catchment (Fig. 4.4) lies to the east and north of Black Mere and is agricultural land with improved grazing pasture and arable. The small hamlet of Gorstyhill lies in the catchment. There is one inflowing stream to Black Mere but it has been suggested that the water is connected to the water beneath the schwingmoor at Cranberry Bog and may also be in connection with groundwater (Natural England note, mentioned by ECUS 2001d). There are few data on Black Mere but there is a noted concern about organic pollution at the mere.

Table 4.4. Characteristics of Black Mere

Characteristic	Value	Unit	Reference and notes
Altitude	75	m	
Area	1.5	ha	Natural England unpublished
Catchment area	1.49	km^2	ECUS (2001d)
Max water depth	-	m	
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	D & S	-	ECUS (2001d)
Annual conductivity	-	μS cm^{-1}	
Annual alkalinity	-	mequiv L^{-1}	
Annual TP	1300	μg L^{-1}	Natural England unpublished
Annual DIN	560	μg L^{-1}	Natural England unpublished
Annual Chlorophyll *a*	-	μg L^{-1}	
WFD Lake type	-		

*D = Drainage; S = Seepage
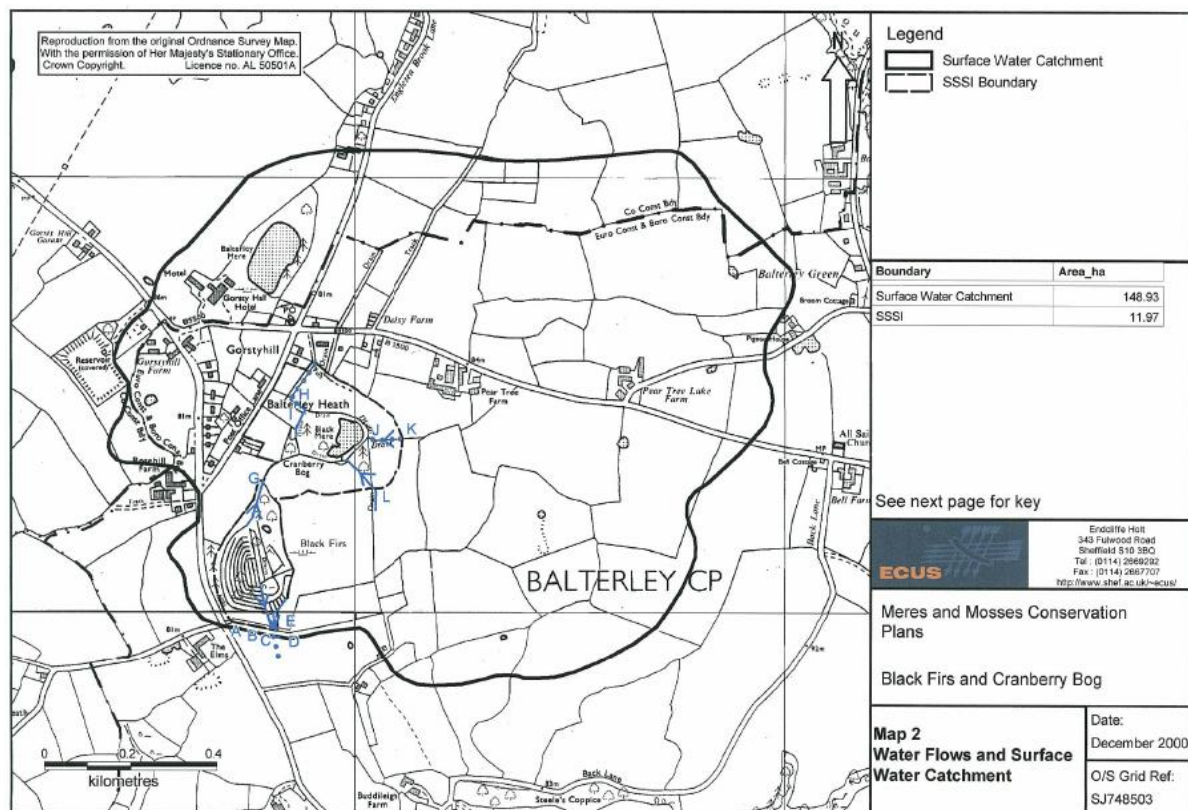
Figure 4.4 Map of Black Mere within the Black Firs and Cranberry Bog system showing surface water catchment (ECUS 2001d).

4.5   Bomere, Shomere and Betton Pools

Bomere Pool, Shomere Pool and Betton Pool (NGR, SJ500 080) are three adjacent meres (Fig. 4.5) that lie in mounded morainic material in the south of the region. Bomere is underlain by alluvium over glacial till, Shomere by peat over glacial till and Betton Pool directly by glacial till (ECUS 2001e). For all three meres, the glacial till is thought to be sufficiently thick to prevent major hydraulic connection with the solid geology of Carboniferous Keele beds. All three meres are believed to have perched water tables as there are no inflowing streams and only one outflow although Moss et al. (1992) suggested that there may be groundwater inputs. Bomere and Shomere are surrounded by deciduous woodland, and the rest of the catchment comprises arable land and a small amount of improved pasture, a farm and a few houses. Betton Pool is fringed by a narrow strip of deciduous trees and immediately surrounded by arable fields. Bomere has a low alkalinity for the meres (Table 4.5). All three meres have high conservation value, particularly for their macrophyte flora.

Table 4.5. Characteristics of Bomere (B), Shomere (S) and Betton Pool (P).

Characteristic	Value B/ S/ P	Unit	Reference and notes
Altitude	75.3	m	
Area	10.3/ 1.3/ 6.4	ha	Reynolds (1979)
Catchment area	1.32 (total for all)	km^2	ECUS (2001e)
Max water depth	15.2 / 4.3/ 10.9	m	ECUS (2001e)
Mean water depth	5.1/ - /3.6	m	Fisher et al. (2009)
Mean retention time	4.5/ - /1.85	y	James et al. (2003)
Main source of water*	D & S	-	ECUS (2001e), Moss et al. (1992)
Annual conductivity	120/ 129 /231	μS cm^{-1}	Fisher et al. (2009), Reynolds (1979)
Annual alkalinity	0.56/ 0.27 / 2.14	mequiv L^{-1}	Fisher et al. (2009), Reynolds (1979)
Annual TP	49 (40)/ - /97	μg L^{-1}	Fisher et al. (2009) (Recent EA data)
Annual DIN	44 (220)/ - /126	μg L^{-1}	Fisher et al. (2009) (Recent EA data)
Annual Chlorophyll *a*	11 (11)/ - /27	μg L^{-1}	Fisher et al. (2009) (Recent EA data)
WFD Lake type	MA S/ - / HA S		Fisher et al. (2009)

*D = Drainage; S = Seepage
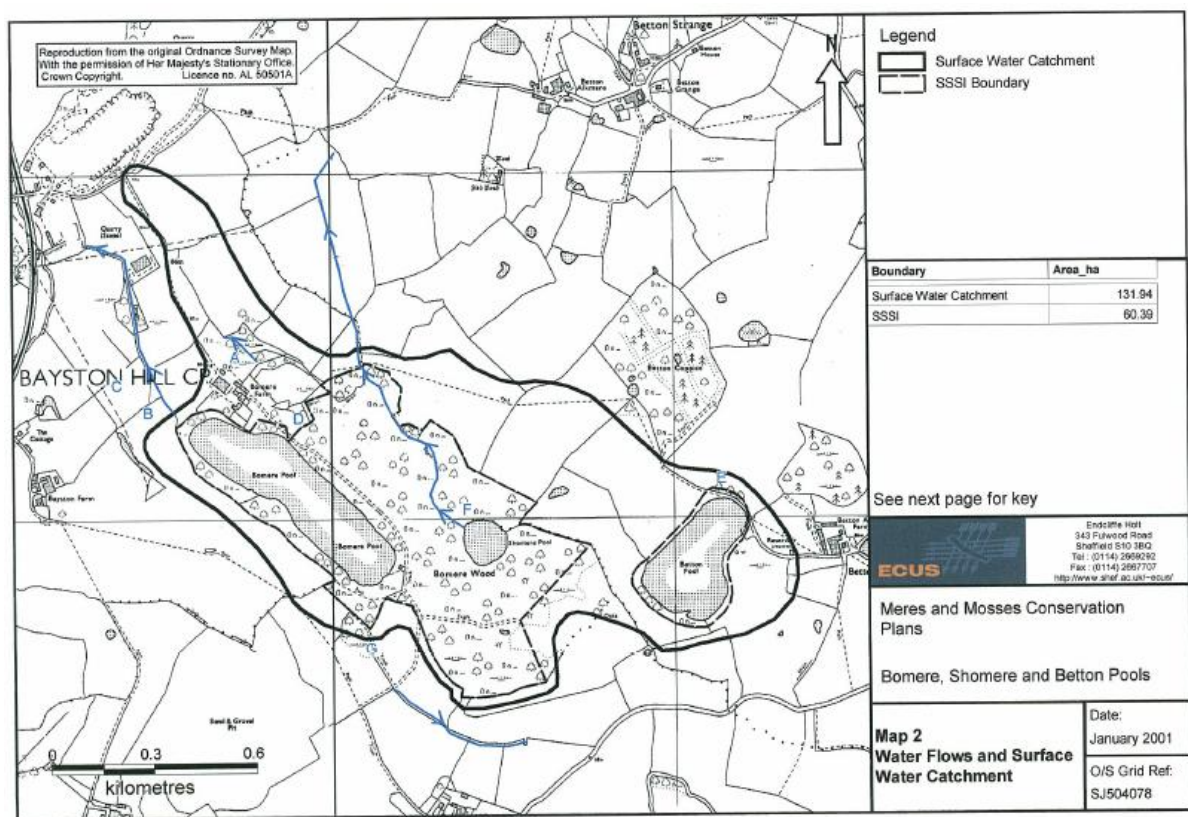
Figure 4.5 Map of Bomere, Shomere and Betton Pool showing surface water catchment (ECUS 2001e).

4.6   Brown Moss

Brown Moss (NGR SJ562 395) comprises a series of about five pools set in a heathland. The pools lie on poorly-draining peaty soils on glacial sands and gravels that overlie Lower Liassic mudstones, limestones, siltstones and sandstones. The largest pool (which will be dealt with here) is about 3.3 ha in area. Each pool has been reported to have different and fluctuating water quality so the limited data available may only be applicable to the largest pool. The small catchment (Fig. 4.6) comprises improved or semi-improved grassland and a few arable fields. The largest (and one other) pool was dredged in 1976 to increase water depth (ECUS 2001f). There are no natural direct surface inflows to the pools although inflow may occur during high rainfall from drains and a culvert. Water levels in the pools can fluctuate greatly suggesting input from rainfall and overland flow but there is also likely to be input from groundwater. As this report was being completed a detailed nutrient budget was published 'early-online' but too late to incorporate fully into this report (Chaichana et al. 2010).

Table 4.6. Characteristics of the major pool on Brown Moss

Characteristic	Value	Unit	Reference and notes
Altitude	104	m	ECUS (2001f)
Area	3.3	ha	Fisher et al. (2009)
Catchment area	1.28	km^2	ECUS (2001f)
Max water depth	1	m	Fisher et al. (2009)
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	S (D)	-	ECUS (2001f)
Annual conductivity	150	$\mu S\ cm^{-1}$	Fisher et al. (2009)
Annual alkalinity	0.78	$mequiv\ L^{-1}$	Fisher et al. (2009)
Annual TP	775 (389)	$\mu g\ L^{-1}$	Fisher et al. (2009) Chaichana et al. (2010)
Annual DIN	-	$\mu g\ L^{-1}$	
Annual Chlorophyll *a*	2	$\mu g\ L^{-1}$	Fisher et al. (2009)
WFD Lake type	MA VS		

*D = Drainage; S = Seepage
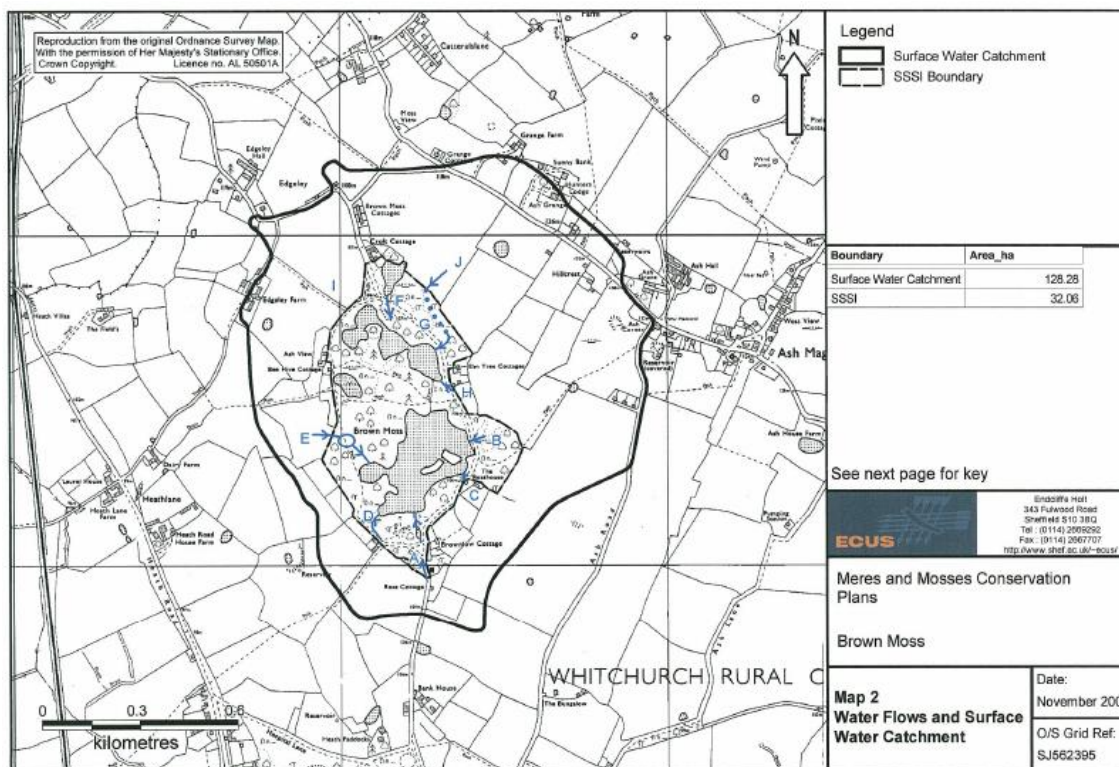
Figure 4.6 Map of Brown Moss showing surface water catchment (ECUS 2001f).

4.7   Chapel Mere

Chapel Mere (NGR, SJ540 519) is a small (6.5 ha) relatively shallow (maximum depth 2.4 m) mere in the south of Cheshire (Table 4.7). The solid geology is Triassic but it is mainly covered by boulder clay with small areas of alluvium and terrace deposits (ECUS 2001g). It has two major surface-water inflows and a single outflow (Fig. 4.7) and the hydrological balance suggests a minimal input of water from groundwater (ECUS 2001g; Moss et al. 1992). The immediate catchment is in parkland with some improved pasture and arable.

Table 4.7. Characteristics of Chapel Mere.

Characteristic	Value	Unit	Reference and notes
Altitude	88	m	
Area	6.5	ha	Reynolds (1979)
Catchment area	2.38	km^2	ECUS (2001g)
Max water depth	2.4	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	0.15	y	Moss et al. (1992)
Main source of water*	S	-	ECUS (2001g), Moss et al. (1992)
Annual conductivity	721	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	4.68	mequiv L^{-1}	Moss et al. (1992)
Annual TP	1267 (300)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	600 (1030)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll a	12 (26)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
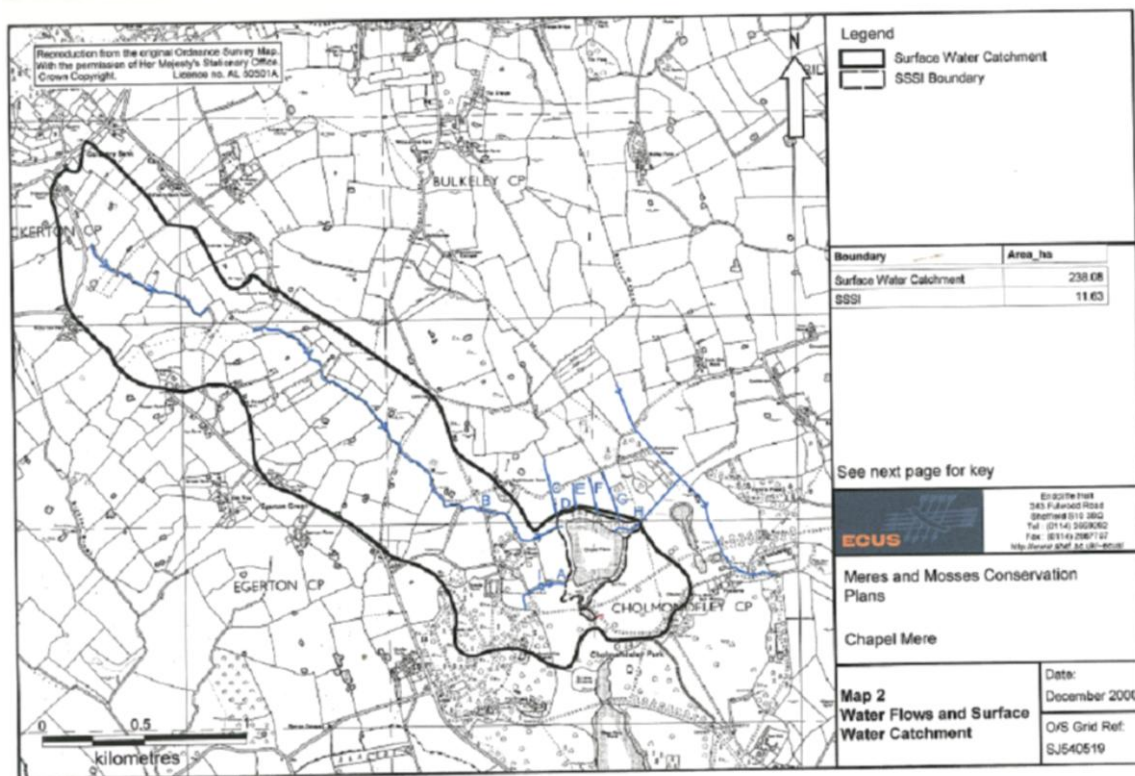
Figure 4.7 Map of Chapel Mere showing surface water catchment (ECUS 2001g).

4.8   Cole Mere

Cole Mere (NGR SJ433 332) is a relatively large and deep mere with a surface area of 28 ha and a maximum depth of 11.5 m (Table 4.8). Cole Mere is situated in a hollow within glacial drift (ECUS 2001h). The surface water catchment, largely to the south of the mere (Fig. 4.8) is only about 1.72 km^2 and is predominantly arable and semi-improved pasture but also includes the village of Cole Mere. There is a small inflow stream to the north-west and an outflow to the east that can also act as an inflow under some hydrological conditions. It probably also receives overflow from the nearby Shropshire Union Canal. However, between 61 to 82% of the water supplied to the mere is believed to derive from groundwater (ECUS 2001h).

Table 4.8. Characteristics of Cole Mere.

Characteristic	Value	Unit	Reference and notes
Altitude	88	m	
Area	28	ha	Reynolds (1979)
Catchment area	1.72	km^2	ECUS (2001h)
Max water depth	11.5	m	Reynolds (1979)
Mean water depth	3.3	m	Fisher et al. 2009
Mean retention time	1.25	y	Moss et al. (1992)
Main source of water*	S (D)	-	ECUS (2001h)
Annual conductivity	239	µS cm^{-1}	Moss et al. (1992)
Annual alkalinity	1.49	mequiv L^{-1}	Moss et al. (1992)
Annual TP	400 (130)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual DIN	740 (330)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	22 (25)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
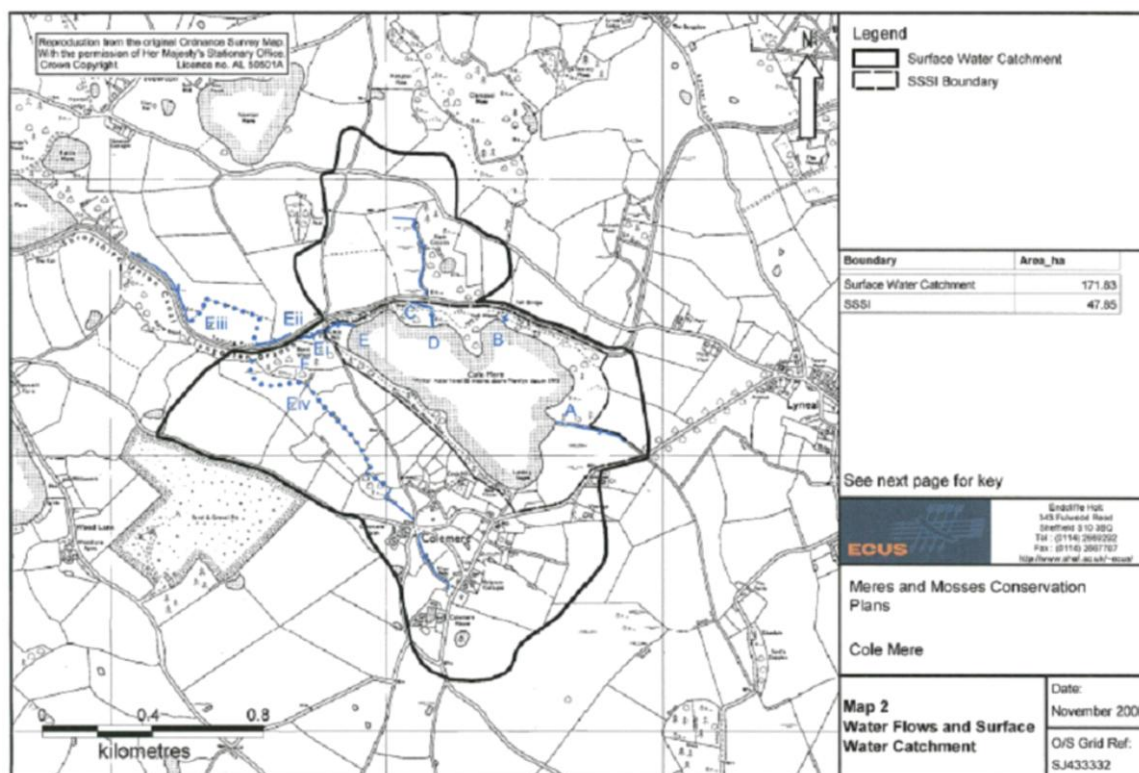
Figure 4.8 Map of Cole Mere showing surface water catchment (ECUS 2001h).

4.9 Comber Mere

Comber Mere (NGR, SJ587 455) is one of the largest West Midland meres with a surface area of 51.5 ha and a maximum depth of 11.8 m (Table 4.9). Comber Mere is situated in an agricultural catchment of about 8.1 km^2 on Triassic mudstones overlain by boulder clay with a ridge of glacial sand and gravel along the northern margin (ECUS 2001i). The hydrology of the mere is probably dominated by surface water and several small streams flow into the mere from the south-west (Fig. 4.9). Direct precipitation on the mere surface may also contribute to the water budget and the average retention time is long at 1.66 year (Moss et al. 1992). The large catchment to the south and west of the mere is primarily agricultural land (ECUS 2001i).

Table 4.9. Characteristics of Comber Mere

Characteristic	Value	Unit	Reference and notes
Altitude	78	m	
Area	51.5	ha	Reynolds (1979)
Catchment area	8.1	km^2	ECUS (2001i)
Max water depth	11.8	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	1.66	y	Moss et al. (1992)
Main source of water*	D	-	Moss et al. (1992)
Annual conductivity	513	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	3.0	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	362 (190)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	860 (980)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	14.7 (31)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
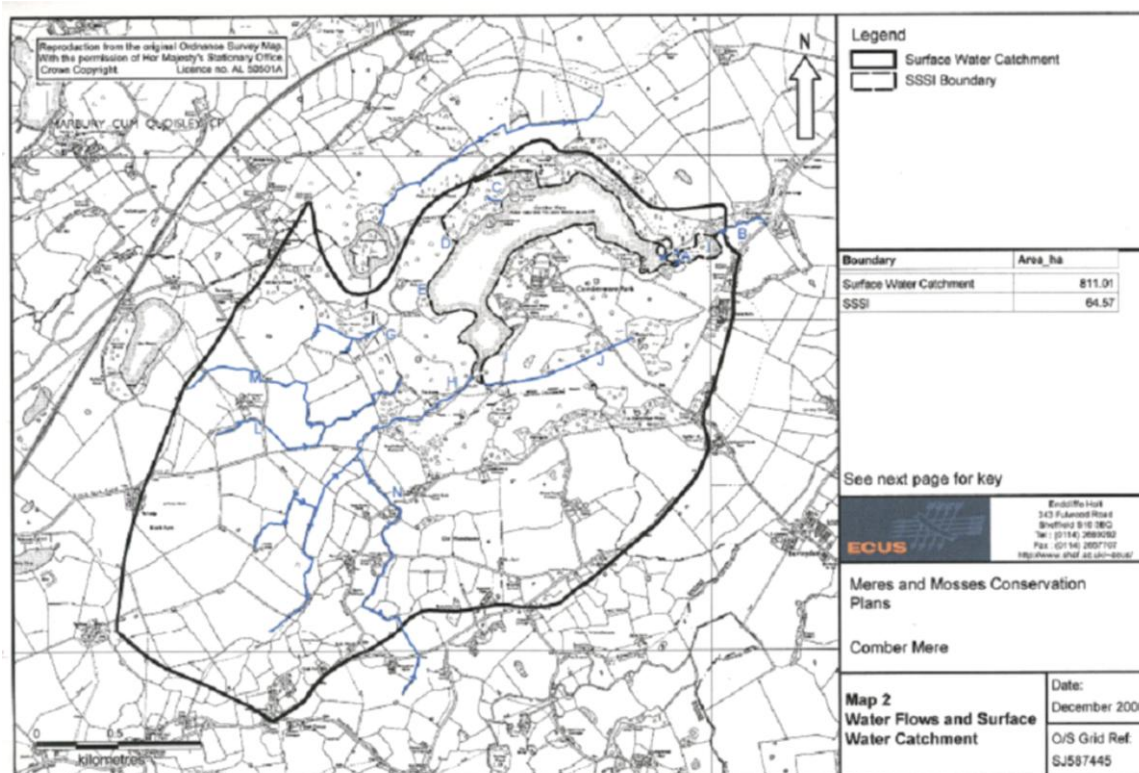
Figure 4.9 Map of Comber Mere showing surface water catchment (ECUS 2001i).

4.10   Cop Mere

Cop Mere (NGR, SJ800 298) is a shallow (maximum depth 2.7 m) moderately sized (16.8 ha) mere (Table 4.10). Its catchment is relatively large and lies in a complicated geological area of Triassic strata comprising sandstones, conglomerates, marl and mudstones. In contrast to many of the other meres, glacial drift is sparse (ECUS 2001j). The catchment comprises arable and pasture with many pockets of broad-leaved woodland and scrub. Many farms and small villages are also present. The main input to the mere is the River Sow (Fig. 4.10) and surface flows dominate the hydrological input, although groundwater probably enters the inflowing river as baseflow. As a consequence of the major river inflow, the average retention time is very short, only about 4 weeks (Moss et al. 1993).

Table 4.10. Characteristics of Cop Mere

Characteristic	Value	Unit	Reference and notes
Altitude	88	m	
Area	16.8	ha	Reynolds (1979)
Catchment area	13.64	km^2	ECUS (2001j)
Max water depth	2.7	m	Reynolds (1979)
Mean water depth	1	m	Fisher et al. 2009
Mean retention time	0.08	y	Moss et al. (1992)
Main source of water*	D	-	ECUS (2001j)
Annual conductivity	457	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	2.95	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	315	$\mu g\ L^{-1}$	Moss et al. (1992)
Annual DIN	1800 (3490)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	59.6 (9.4)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
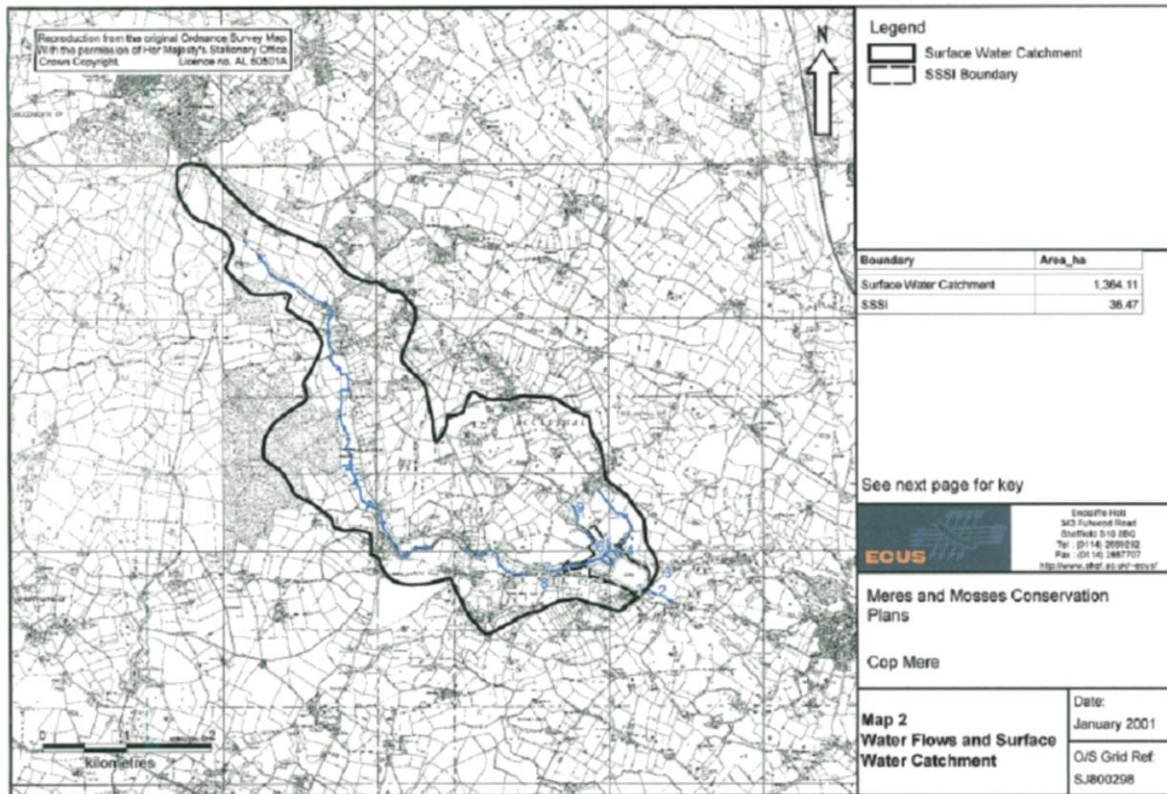
Figure 4.10 Map of Cop Mere showing surface water catchment (ECUS 2001j).

4.11 Fenemere

Fenemere (NGR, SJ445 228) is a moderate sized (9.4 ha) shallow (maximum depth 2.2 m) mere that is part of a hydrologically complex system that comprises two other water bodies, Marton Pool and Birchgrove Pool, that flow into Fenemere (Fig. 4.11) and may once have been part of the same water body as they are at a similar elevation (ESI 2002a; Table 4.11). Fenemere itself lies in a peaty hollow, but the catchment lies on glacial sands and gravels that overlie glacial till and a solid geology of mudstones. The catchment is arable or improved grassland with small pockets of woodland. Only 5% of the outflow from Fenemere can be supported by the measured surface inflow, the remainder is believed to derive from groundwater.

Table 4.11. Characteristics of Fenemere

Characteristic	Value	Unit	Reference and notes
Altitude	78	m	
Area	9.4	ha	Reynolds (1979)
Catchment area	11.2	km^2	ESI (2002a)
Max water depth	2.2	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	0.21	y	Moss et al. (1992)
Main source of water*	S (D)	-	ECUS (2001k)
Annual conductivity	756	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	4.76	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	487	$\mu g\ L^{-1}$	Moss et al. (1992)
Annual DIN	1230 (5979)	$\mu g\ L^{-1}$	Moss et al. (1992) (EA data 2000-02)
Annual Chlorophyll *a*	56.1	$\mu g\ L^{-1}$	Moss et al. (1992)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
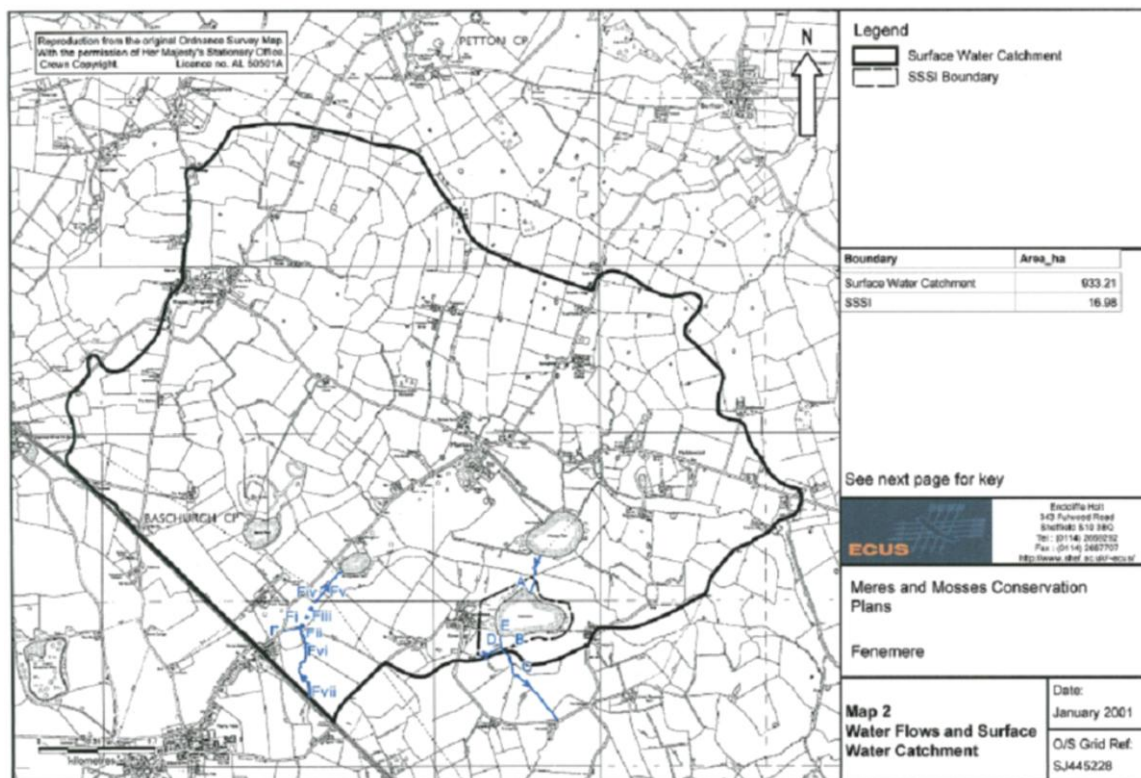
Figure 4.11 Map of Fenemere showing surface water catchment (ECUS 2001k).

4.12   Hatch Mere

Hatch Mere (NGR, SJ552 723) is a small (4.7 ha) relatively shallow (maximum depth 3.8 m) mere that is close to the basin mire of Flaxmere (Table 4.12). The surface water catchment of 2.2 km^2 lies on a varied geology including Lower Keuper marl and Keuper waterstones but is mainly covered with drift deposits of glacial sand and gravel with some peat, alluvium and boulder clay (ECUS 2001ℓ). The land is largely arable and improved grassland with a western fringe of coniferous woodland and contains numerous farms and the village of Hatchmere on the southern boundary. There are a number of small field drains and ditches and an outflow stream from the mere (Fig. 4.12) but the mere is believed to be largely fed from groundwater with an estimated retention times of 0.4 year but there is less flow in the summer with an estimated retention time of 0.94 y (Moss et al. 1992).

Table 4.12. Characteristics of Hatch Mere

Characteristic	Value	Unit	Reference and notes
Altitude	76	m	
Area	4.7	ha	Reynolds (1979)
Catchment area	2.2	km^2	ECUS (2001 ℓ)
Max water depth	3.8	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	0.4	y	Moss et al. (1992)
Main source of water*	S	-	ECUS (2001 ℓ), Moss et al. (1992)
Annual conductivity	484	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	2.36	mequiv L^{-1}	Moss et al. (1992)
Annual TP	85 (70)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	1610 (3180)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	29.5 (29.0)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
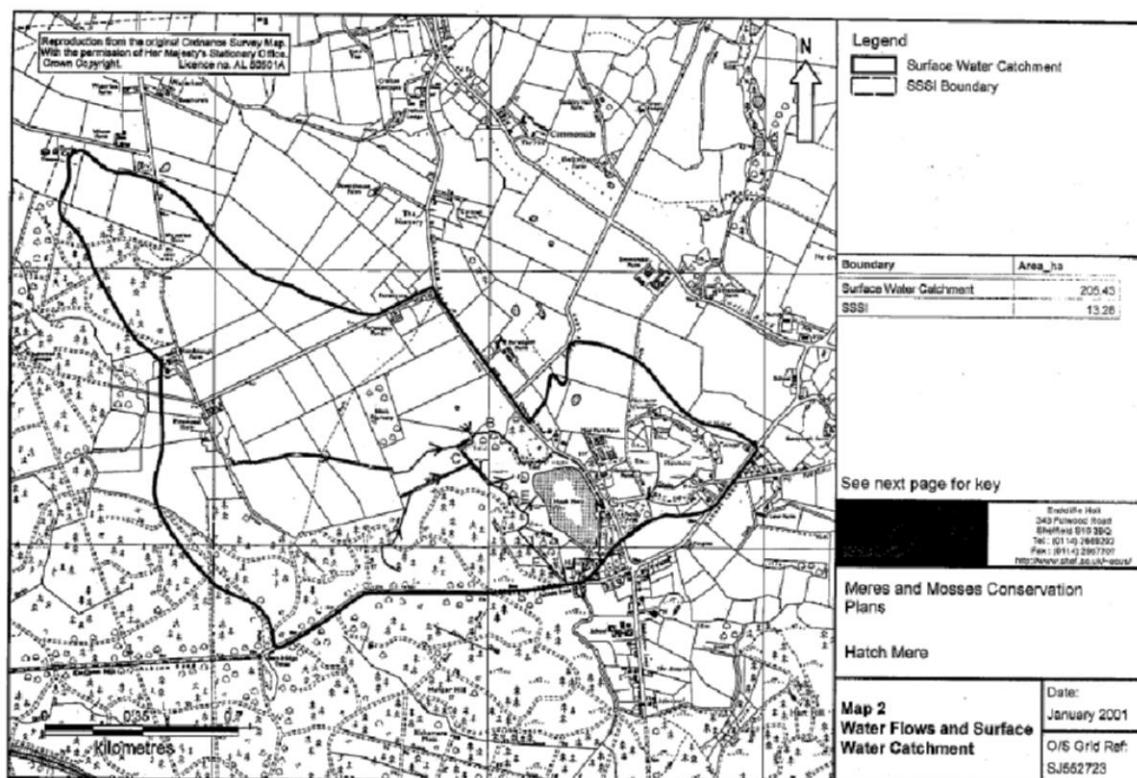
Figure 4.12 Map of Hatch Mere showing surface water catchment (ECUS 2001 ℓ).

4.13   Maer Pool

Maer Pool (NGR, Sj789 384) is a small (surface area 5.5 ha) shallow (maximum depth 1.7 m) mere immediately north-west of the village of Maer (Table 4.13). It has the greatest altitude of any of the meres (118 m) and is the headwater of the River Tern. The surface water catchment is 1.82 km^2. Unlike most of the meres, the catchment is largely drift free, but there is peat in the vicinity of the mere and small areas of glaciofluvial deposits. The solid geology is Permo-Triassic sandstone with outcrops of mudstones. Most of the landuse in the catchment is agricultural but also includes the small village of Maer. There are two small inflows (Fig. 4.13), but water is mainly derived from the Sherwood Sandstone aquifer (ECUS 2001m). There is relatively little water chemistry available for this site.

Table 4.13. Characteristics of Maer Pool

Characteristic	Value	Unit	Reference and notes
Altitude	118	m	
Area	5.5	ha	Reynolds (1979)
Catchment area	1.82	km^2	ESI (2002b)
Max water depth	1.7	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	S (D)	-	ECUS (2001m), Moss et al. (1992)
Annual conductivity	585	µS cm^{-1}	Reynolds (1979)
Annual alkalinity	4.27	mequiv L^{-1}	Reynolds (1979)
Annual TP	-	µg L^{-1}	
Annual DIN	-	mg L^{-1}	
Annual Chlorophyll *a*	15.5	µg L^{-1}	Moss et al. (1992)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
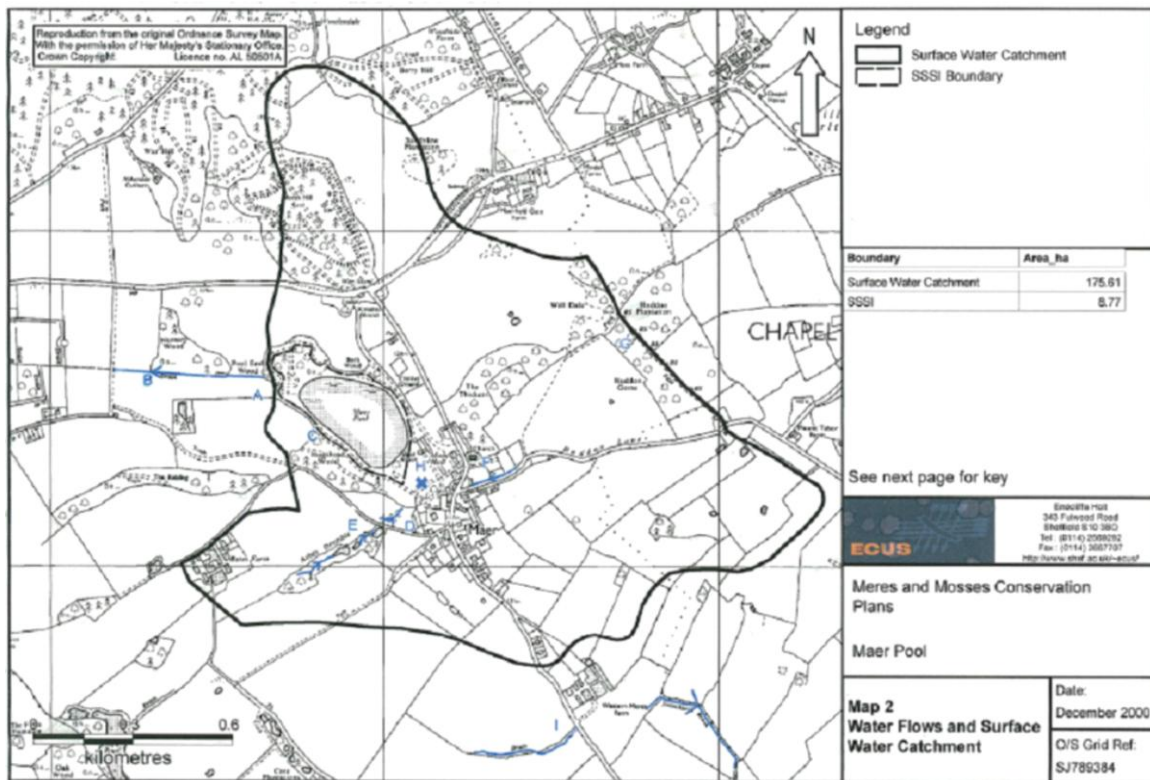
Figure 4.13 Map of Maer Pool showing surface water catchment (ECUS 2001m).

4.14   Marton Pool (Chirbury)

Marton Pool (NGR, SJ296 025) is of moderate area (13.7 ha) and depth (maximum depth 8 m) and is believed to lie in a kettle-hole within a former valley of the River Severn (ECUS 2001n; Table 4.14). It is one of the few meres lying at an altitude of more than 100 m. The solid geology comprises Silurian shales and mudstones with small patches of alluvium and glacial sands and gravels within the catchment which has an area of 5.01 km^2. The catchment is largely arable and improved pasture but there are also large areas of broadleaved woodland and coniferous plantation. The main inflow is Lowerfield Brook and there is one outflow (Fig. 4.14). Most of the water input is believed to be surface water. There appears to be limited water chemistry available for this site.

Table 4.14. Characteristics of Marton Pool (Chirbury)

Characteristic	Value	Unit	Reference and notes
Altitude	105	m	
Area	13.7	ha	Reynolds (1979)
Catchment area	5.01	km^2	ECUS (2001n)
Max water depth	8	m	ECUS (2001n)
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	S	-	ECUS (2001n)
Annual conductivity	-	$\mu S\ cm^{-1}$	
Annual alkalinity	4.40	mequiv L^{-1}	Reynolds (1979)
Annual TP	-	$\mu g\ L^{-1}$	
Annual DIN	-	mg L^{-1}	
Annual Chlorophyll *a*	-	$\mu g\ L^{-1}$	
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
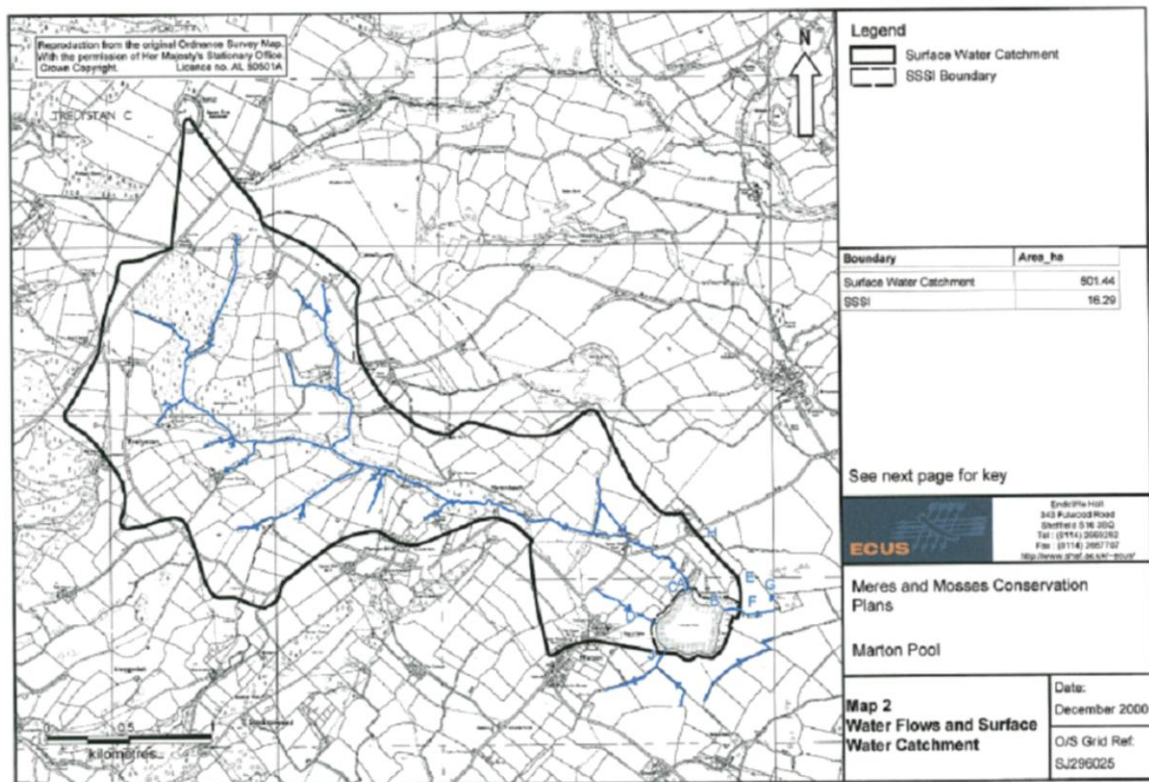
Figure 4.14 Map of Marton Pool (Chirbury) showing surface water catchment (ECUS 2001n).

4.15 Oak Mere

Oak Mere (NGR, SJ574 679) is moderately sized (18.3 ha) but relatively shallow (maximum depth 5.6 m; Table 4.15). It lies in a sandy basin with peat underlying its north-western end. The catchment of 3.5 km^2 (ECUS 2001o) is mixed with agricultural land, forestry plantations, flooded lagoons and numerous farms and houses. The surface geology is principally glacial sandy drift and peat overlying Triassic mudstones that are exposed at the western edge of the catchment. Oak Mere lacks direct inflows or outflows (Fig. 4.15) and is believed to be a surface manifestation of the water table (Carvalho & Moss, 1999). Its hydrology is believed to be supported entirely from direct rainfall and by subsurface flow within the soils. Oak Mere is notable within the meres because its water has low alkalinity and relatively low conductivity (Moss et al. 1992). Carvalho (1993) considers a number of hypotheses for the low alkalinity and conductivity and provides strong evidence that it is because Oak Mere lies at the top-end of a hydrological landscape and so is largely rain-fed, with only a relatively minor influence of catchment soils and geology on the water quality.

Table 4.15. Characteristics of Oak Mere.

Characteristic	Value	Unit	Reference and notes
Altitude	73	m	Savage et al. (1992)
Area	22.9	ha	Savage et al. (1992)
Catchment area	3.50	km^2	ECUS (2001o)
Max water depth	5.6	m	Reynolds (1979)
Mean water depth	2.0	m	Savage et al. (1992)
Mean retention time	0.81	y	Calculated from values in Savage et al. (1992)
Main source of water*	S	-	ECUS (2001o); Carvalho (1993)
Annual conductivity	187	µS cm^{-1}	Moss et al. (1992)
Annual alkalinity	0.028	mequiv L^{-1}	Moss et al. (1992)
Annual TP	61 (80)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual DIN	230 (200)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	7.4 (29)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
WFD Lake type	LA, VS		

*D = Drainage; S = Seepage
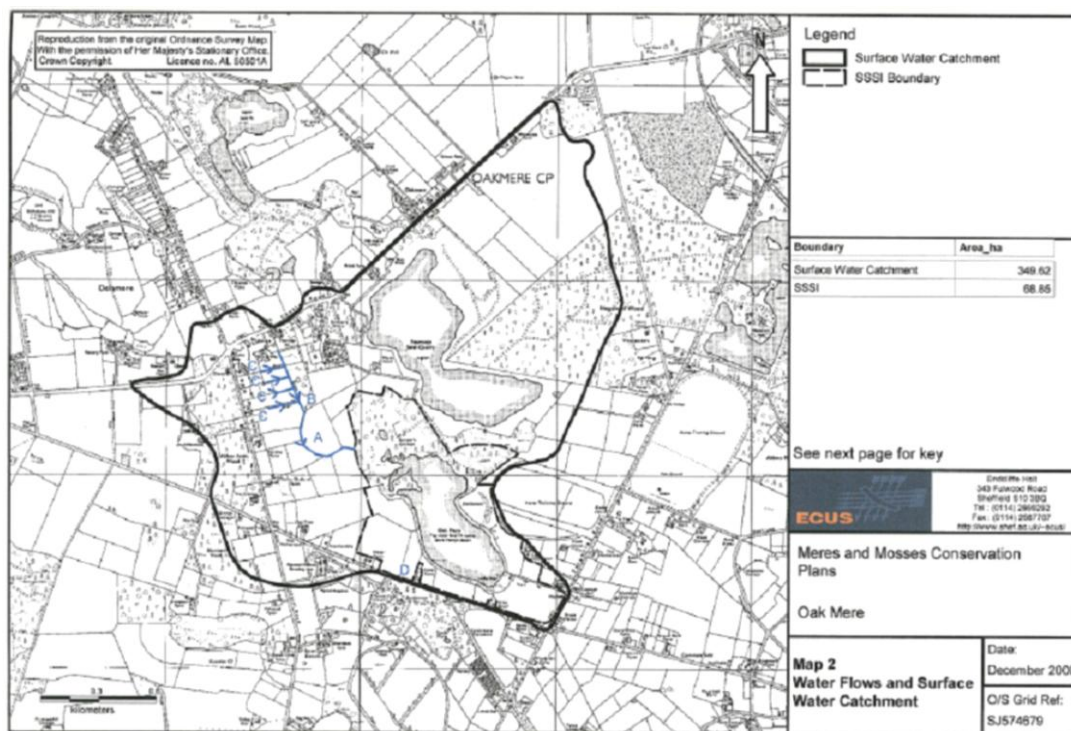
Figure 4.15 Map of Oak Mere showing surface water catchment (ECUS 2001o).

4.16   Oss Mere

Oss Mere (NGR, SJ565 438) is a small (area 9.5 ha) and shallow (maximum depth 3 m) mere bordered by reedswamp, alder carr and dry woodland (Table 4.16). It is one of the few meres lying at an altitude of more than 100 m. Its catchment of 1.8 km^2 overlies Upper Keuper saliferous beds overlain by a thick layer of boulder clay with an outcrop of morainic sands. The catchment land use comprises semi-improved pasture with a few arable fields and patches of broad-leaved woodland (ECUS 2001p). Although there as some minor inflowing streams (Fig. 4.16) the water is believed to be supplied from groundwater and there is no outflow stream. Because of this, there is no information on retention time.

Table 4.16. Characteristics of Oss Mere.

Characteristic	Value	Unit	Reference and notes
Altitude	105	m	
Area	9.5	ha	Reynolds (1979)
Catchment area	1.80	km^2	ECUS (2001p)
Max water depth	3.0	m	ECUS (2001p)
Mean water depth	-	m	
Mean retention time	-	y	
Main source of water*	S	-	ECUS (2001p)
Annual conductivity	491	µS cm^{-1}	Moss et al. (1992)
Annual alkalinity	3.02	mequiv L^{-1}	Moss et al. (1992)
Annual TP	296 (155)	µg L^{-1}	Moss et al. (1992) (EA data 2005 – 08)
Annual DIN	230 (1273)	µg L^{-1}	Moss et al. (1992) (EA data 2007 – 08)
Annual Chlorophyll *a*	35.4 (21)	µg L^{-1}	Moss et al. (1992) (EA data 2005 – 08)
WFD Lake type	HA, VS		

D = Drainage; S = Seepage
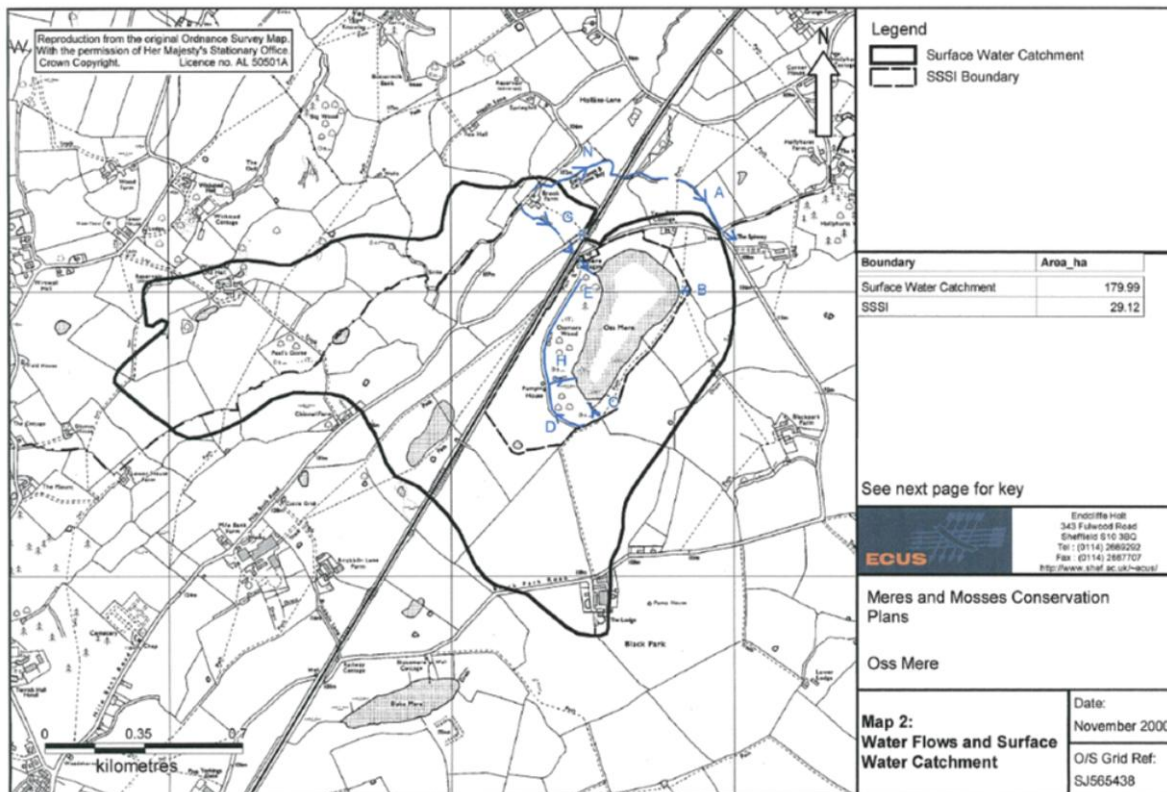
Figure 4.16 Map of Oss Mere showing surface water catchment (ECUS 2001p).

4.17 Quoisley Meres

There are two meres at Quoisley (NGR, SSJ548 455). Quoisley Little Mere has an area of 2.2 ha and maximum depth of 1.8 m and normally flows into Quoisley Big Mere which has an area of 4.0 ha and a maximum depth of 2.4 m (Table 4.17). Each mere is surrounded by well-developed reedswamp and alder carr. The catchment for both meres is 1.73 km^2 and the solid geology is Triassic mudstones including Upper Keuper saliferous beds overlain by thick layers of drift. The drift is largely made up of boulder clay with glaciofluvial deposits of boulder clay and peat, sands and gravels. The land use in the catchment is intensively managed farmland with improved pasture and arable. (ECUS 2001q). The hydrology is largely via surface inflow from streams (Fig. 4.17) and surface runoff but there could be some contribution from groundwater from the nearby sandy-drift deposits.

Table 4.17. Characteristics of the Quoisley Meres.

Characteristic	Value (Little/ Big)	Unit	Reference and notes
Altitude	78	m	
Area	2.2 / 4.0	ha	Reynolds (1979)
Catchment area[a]	1.73	km^2	ECUS (2001q)
Max water depth	1.8 / 2.4	m	Reynolds (1979)
Mean water depth	- /	m	
Mean retention time	0.27[a]	y	Moss et al. (1992)
Main source of water*	S	-	ECUS (2001q)
Annual conductivity	639 / 611	µS cm^{-1}	Moss et al. (1992)
Annual alkalinity	5.02 / 4.69	mequiv L^{-1}	Moss et al. (1992)
Annual TP	264 / 404	µg L^{-1}	Moss et al. (1992)
Annual DIN	1350 / 640	µg L^{-1}	Moss et al. (1992)
Annual Chlorophyll *a*	8.4 / 14.2	µg L^{-1}	Moss et al. (1992)
WFD Lake type	HA, VS (both)		

[a] average for both meres.

*D = Drainage; S = Seepage

Figure 4.17 Map of Quoisley Meres showing surface water catchment (ECUS 2001q).
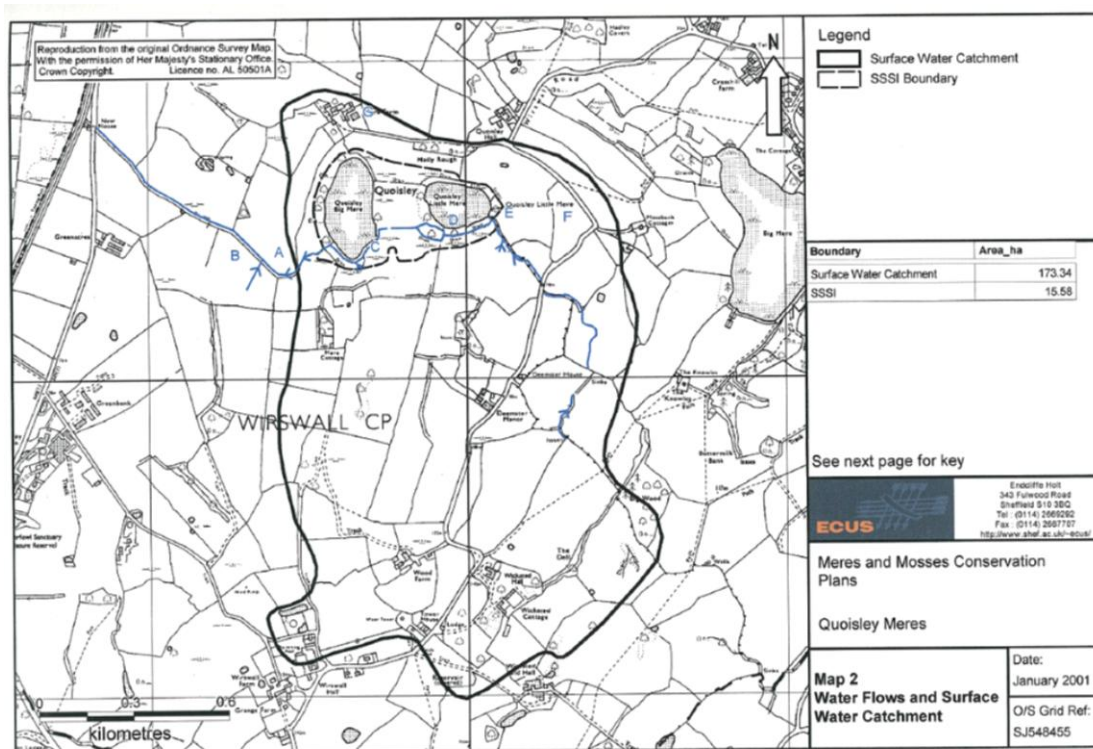
4.18   Rostherne Mere

Rostherne Mere (NGR, SJ745 842) is one of the best-studied, largest (surface area 48.7 ha) and deepest (maximum depth 31 m) of the meres and also has the lowest altitude of the ones studied here (Table 4.18). It lies in a deep hollow in glacial drift and is fringed by a reedswamp for much of its perimeter. The catchment of 10.28 km^2 has a solid geology of Lower Keuper saliferous beds overlain by alluvium and glaciofluvial deposits of boulder clay, ands and gravels. The landuse in the catchment is mainly arable or improved pasture for cattle with a few pockets of woodland. Rostherne Mere receives water from several inflowing streams and has one outflow (Fig. 4.18). The main inflowing stream is ultimately derived from Little Mere and The Mere Mere. Surface water is likely to be the main source of water but a small input from groundwater is possible (ECUS 2001r). The retention time is long at between 1.1 and 3.4 years (Carvalho 1993), although this was measured over two exceptionally dry years (1990 & 1991).

Table 4.18. Characteristics of Rostherne Mere

Characteristic	Value	Unit	Reference and notes
Altitude	27	m	
Area	48.7	ha	Reynolds (1979)
Catchment area	10.3	km^2	ECUS (2001r)
Max water depth	31	m	Woof & Wall (1984)
Mean water depth	13.6	m	Woof & Wall (1984)
Mean retention time	1.1 – 3.4	y	Carvalho (1993)
Main source of water*	D	-	ECUS (2001r); Carvalho (1993)
Annual conductivity	382	µS cm^{-1}	Reynolds (1979)
Annual alkalinity	2.65	mequiv L^{-1}	Moss et al. (1992)
Annual TP	419 (180)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual DIN	840 (960)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	16.3 (30)	µg L^{-1}	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
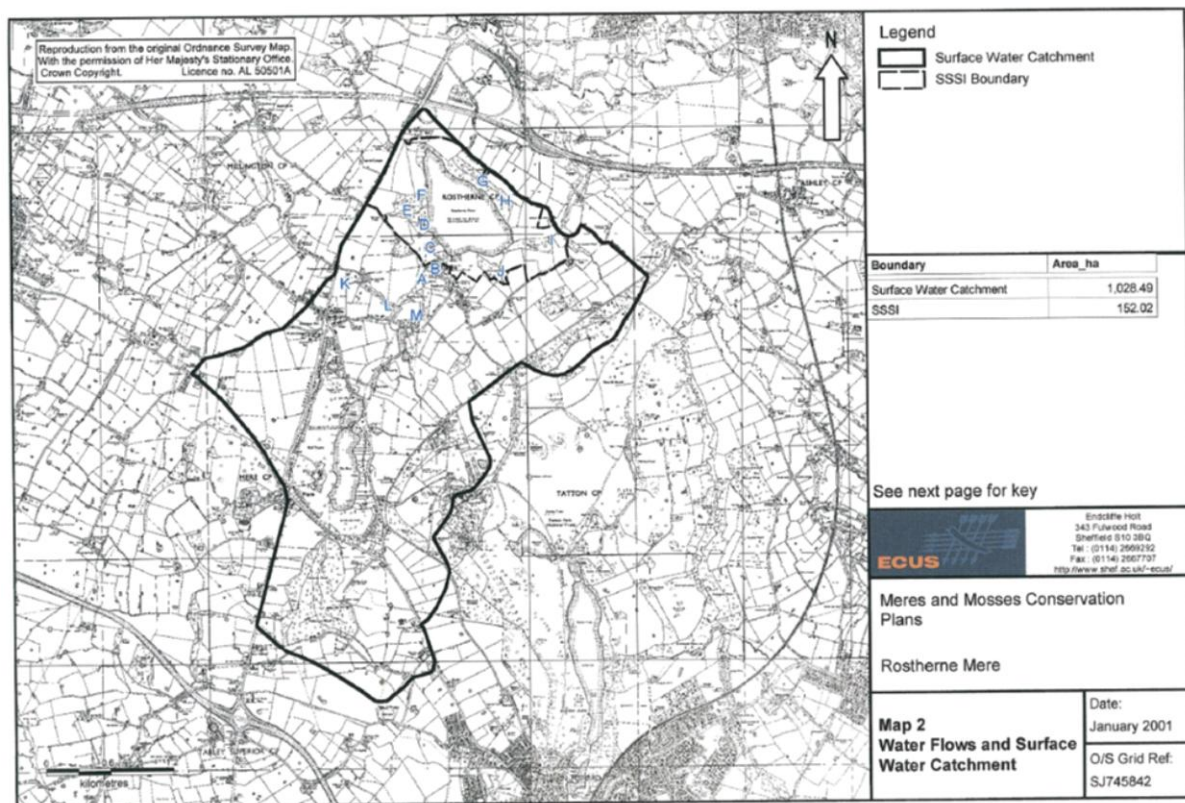
Figure 4.18 Map of Rostherne Mere showing surface water catchment (ECUS 2001r).

4.19   Sweat Mere & Crose Mere

Sweat Mere and Crose Mere (NGR, SJ434 304) are two linked meres of which Crose Mere is the larger (surface area 15.2 ha) and deeper (maximum depth 9.3 m; Table 4.19). Currently, there is little open water at Sweat Mere (ECUS 1998) and this review will therefore concentrate on the water quality in Crose Mere. The mere lies in a kettlehole with an underlying geology of Keuper marls overlain by glacial sands and gravels. Crose Mere is mainly groundwater-fed with no inflowing streams (Fig. 4.19) but overland flows may occur during heavy rain. The land use in the catchment is mainly arable, improved grassland and permanent pasture with a small amount of woodland and some farms and hamlets.

Table 4.19. Characteristics of Crose Mere

Characteristic	Value	Unit	Reference and notes
Altitude	88	m	
Area	15.2	ha	Reynolds (1979)
Catchment area	3.6	km^2	ECUS (1998)
Max water depth	9.3	m	Reynolds (1979)
Mean water depth	4.8	m	Fisher et al. (2009)
Mean retention time	5.6; (2.25)	y	Moss et al. (1992); Reynolds (1979)
Main source of water*	S (D)	-	ECUS (1998); Reynolds (1979)
Annual conductivity	474	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	3.05	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	214 (110)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	350 (610)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	9.8 (24.9)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
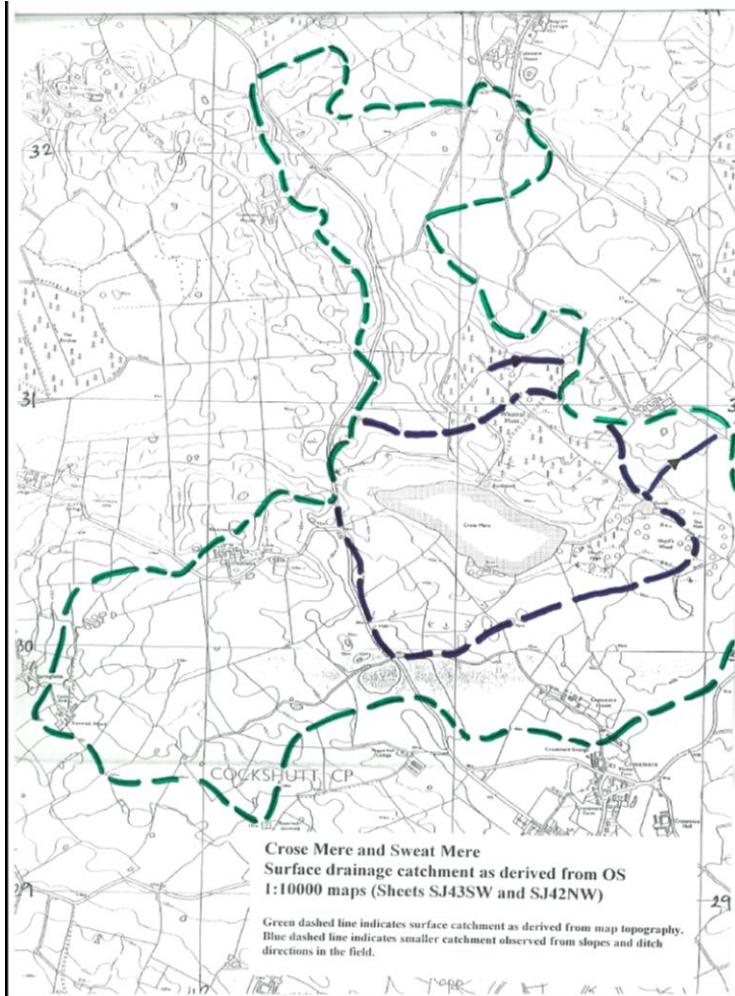
Figure 4.19 Map of Sweat & Crose Mere showing surface water catchment (ECUS 1998).

4.20   Tabley Mere

Tabley Mere (NGR, SJ723 769) is about 19.4 ha in area with a maximum depth of 4.4 m and linked to a smaller mere, Moat Mere, that is about 2 ha (Table 4.20). Both are at a lower altitude (32 m) than the other meres apart from Rostherne Mere. Both meres were enlarged in the 1760s when Tabley House was built (ECUS 2001s). Tabley Mere formed in a hollow in saliferous beds but these are overlain by thick boulder clay and some alluvium and glacial sands and gravel. The land use in the catchment is mainly pasture and arable fields although the village of Knutsford extends into the eastern side of the catchment and there is some semi-improved grassland and woodland. Tabley Mere is mainly fed by surface water and has two main inflows, one of which drains from the vicinity of the M6 motorway which runs through the catchment and two outflows, of which one feeds into Tabley Moat (Fig. 4.20). The conductivity is high and also high relative to its alkalinity, probably reflecting its geology but roadsalt from the motorway may also have contributed to this.

Table 4.20. Characteristics of Tabley Mere

Characteristic	Value	Unit	Reference and notes
Altitude	32	m	
Area	19.4	ha	Reynolds (1979)
Catchment area	8.05	km^2	ECUS (2001s)
Max water depth	4.4	m	Reynolds (1979)
Mean water depth	-	m	
Mean retention time	0.33	y	Moss et al. (1992)
Main source of water*	D	-	ECUS (2001s); Moss et al. (1992)
Annual conductivity	701	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	2.45	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	323 (350)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	2460 (1950)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	17.6 (92)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
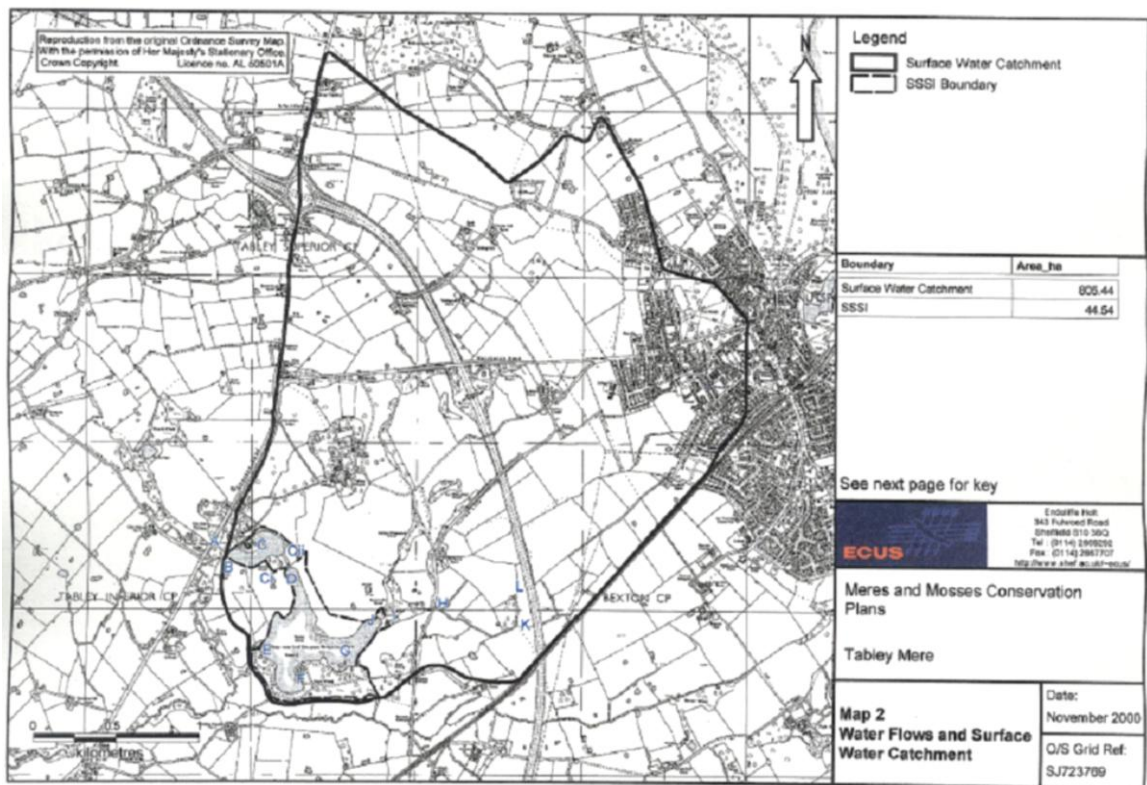
Figure 4.20 Map of Tabley Mere showing surface water catchment (ECUS 2001s).

4.21 Tatton Mere

Tatton Mere (NGR, SJ755 800) is moderate in area (31.7 ha) and moderately deep (11 m; Table 4.21) and is associated with a smaller mere, Melchett Mere (8 ha).The two meres lie in a natural hollow caused by subsidence of Keuper saliferous beds and their area might be increasing as subsidence continues (ECUS 2001t). This geology is overlain by glacial sands and gravels with some boulder clay and alluvium. There is one main inflow from the south in the vicinity of Knutsford and one main ouflow to the north (Fig. 4.21) and Tatton mere is probably mainly fed by surface water while Melchett Mere is probably mainly groundwater fed. The catchment comprises the town of Knutsford and the grounds of Tatton Park which is mainly semi-acid natural grassland with numerous stands of woodland.

Table 4.21. Characteristics of Tatton Mere

Characteristic	Value	Unit	Reference and notes
Altitude	46	m	
Area	31.7	ha	Reynolds (1979)
Catchment area	5.51	km^2	ECUS (2001t)
Max water depth	11	m	Fisher et al. (2009)
Mean water depth	-	m	
Mean retention time	0.88	y	Moss et al. (1992)
Main source of water*	D	-	ECUS (2001t); Moss et al. (1992)
Annual conductivity	518	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	2.6	mequiv L^{-1}	Moss et al. (1992)
Annual TP	233 (160)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	455 (410)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	12.1 (17.4)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
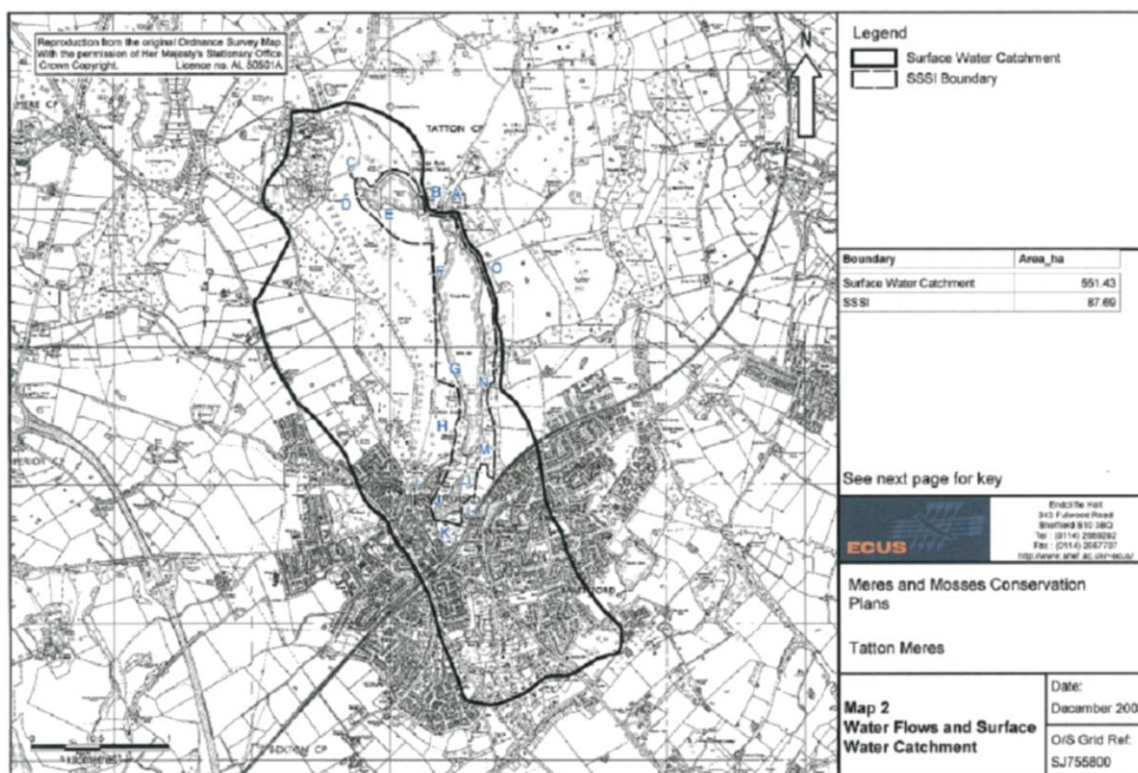
Figure 4.21 Map of Tatton Mere showing surface water catchment (ECUS 2001t).

4.22   The Mere Mere

The Mere Mere (NGR, SJ733 819) is of moderate area (15.8 ha) and maximum depth (8.0 m; Table 4.22). It lies in a natural basin formed by dissolution of salt in underlying Keuper saliferous beds that are overlain by thick glacial deposits of sand, gravel and boulder clay (ECUS 2001u). The Mere Mere receives water from the catchment to the south via Rostherne Brook (Fig. 4.22) and discharges to Little Mere to the north and subsequently to Rostherne Mere. It has a relatively high salinity for its alkalinity, which probably reflects its geology. The Mere Mere is bordered to the south and west by a golf course and to the east by houses with gardens abutting the shore. Elsewhere in the catchment there is a mixed planted-woodland plus arable and improved pasture with some houses and farms. The Mere Mere is mainly fed by surface water.

Table 4.22. Characteristics of The Mere Mere

Characteristic	Value	Unit	Reference and notes
Altitude	52	m	
Area	15.8	ha	Reynolds (1979)
Catchment area	3.82	km^2	ECUS (2001u)
Max water depth	8.1	m	Reynolds (1979)
Mean water depth	2.8	m	Carvalho (1993)
Mean retention time	0.8 – 9.5	y	Carvalho (1993)
Main source of water*	D	-	ECUS (2001u); Moss et al. (1992)
Annual conductivity	523	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	1.51	$mequiv\ L^{-1}$	Moss et al. (1992)
Annual TP	53.5 (70)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	910 (1090)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	15.5 (28)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, VS		

*D = Drainage; S = Seepage
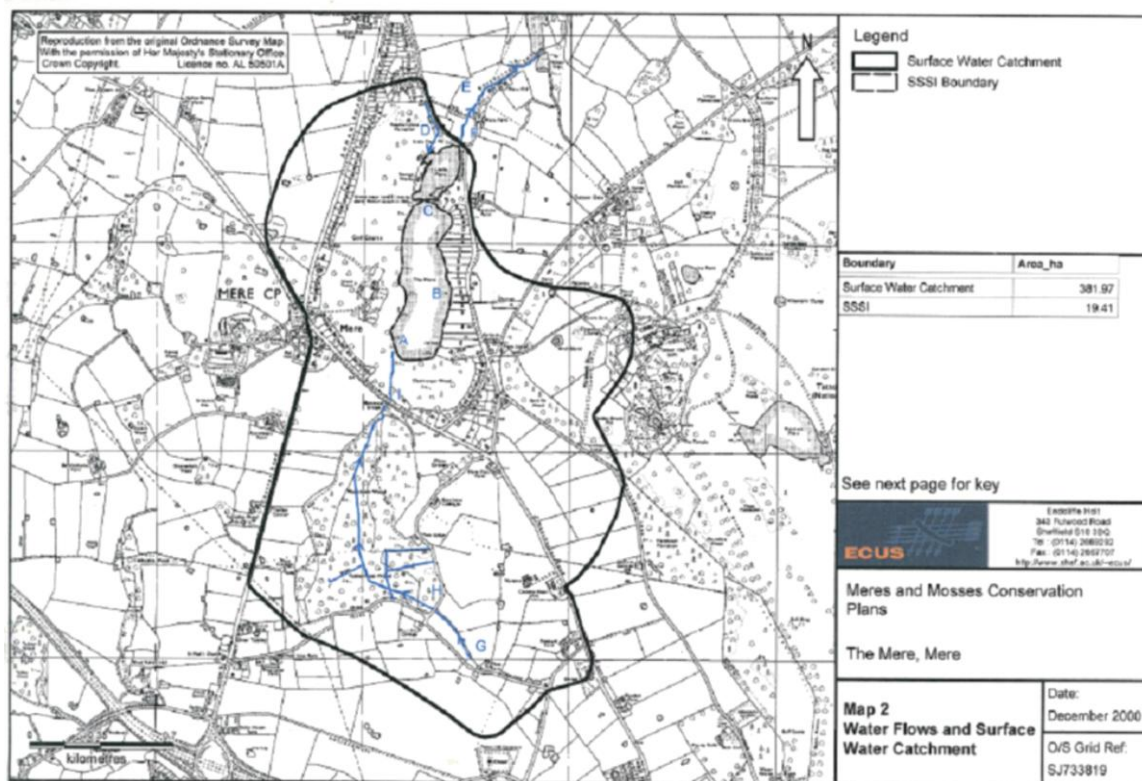
Figure 4.22 Map of The Mere Mere showing surface water catchment (ECUS 2001u).

4.23   White Mere

White Mere (NGR, SJ414 300) is of moderate area (25.5 ha) and moderately deep (13.8 m; Table 4.23). The Mere lies within a kettlehole in a drift of glacial sands and gravels lined by boulder clay. The catchment is also largely boulder clay and glacial sand and gravel with some peat, all overlying Keuper waterstones (sandstones, siltstones and mudstones; ECUS 2001v). The catchment area is small and there are no obvious inflowing streams (Fig. 4.23) and it is assumed that the mere is largely fed from groundwater. The land use in the catchment is primarily agricultural: arable with improved pasture grazed by sheep and cattle. The Mere has extremely high concentration of phosphorus (Table 4.23).

Table 4.23. Characteristics of White Mere

Characteristic	Value	Unit	Reference and notes
Altitude	96	m	
Area	25.5	ha	Reynolds (1979)
Catchment area	0.93	km^2	ECUS (2001v)
Max water depth	13.8	m	Reynolds (1979)
Mean water depth	4.4	m	Fisher et al. (2009)
Mean retention time	-	y	Moss et al. (1992)
Main source of water*	S	-	ECUS (2001v); Moss et al. (1992)
Annual conductivity	309	$\mu S\ cm^{-1}$	Moss et al. (1992)
Annual alkalinity	1.88	mequiv L^{-1}	Moss et al. (1992)
Annual TP	1456 (470)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual DIN	522 (360)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
Annual Chlorophyll *a*	15.3 (32)	$\mu g\ L^{-1}$	Moss et al. (1992) (Recent EA data)
WFD Lake type	HA, S		

*D = Drainage; S = Seepage
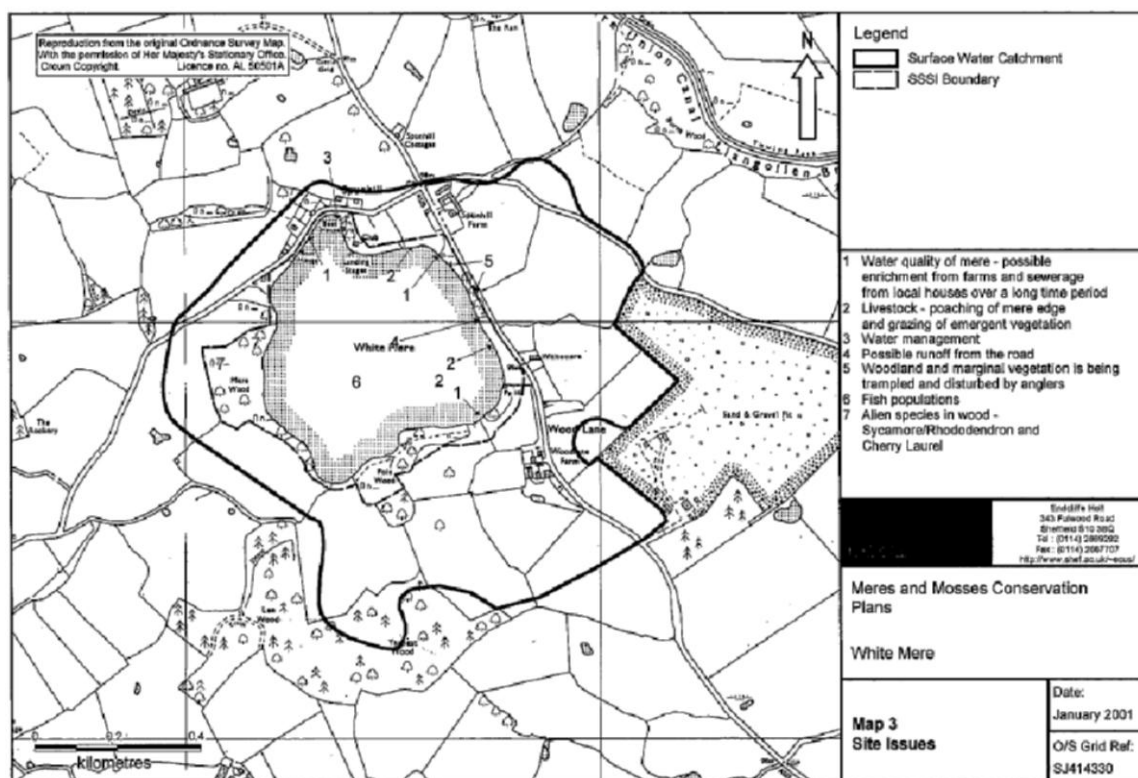
Figure 4.23 Map of White Mere showing surface water catchment (ECUS 2001v).

4.24   Summary

The twenty six meres studied here (Table 4.24) are largely lowland (median altitude 78 m), small (median area 9.9 ha) and relatively shallow (median maximum depth 4.4 m) standing waters. Although the annual median conductivity (491 µS cm^{-1}) and alkalinity (2.6 mequiv L^{-1}) is high, at several sites it is relatively low such as Oak Mere and Shomere. The annual median concentration of total phosphorus is high (323 µg L^{-1}) while the concentration of phytoplankton chlorophyll *a* is moderate (15 µg L^{-1}). Out of all the relevant information compiled in Table 4.24, information on mean depth (11 sites) and retention time (12 sites) is least available. These two statistics are linked since mean depth allows the calculation of lake volume and hence retention time. Mean depth can be ascertained relatively easily by soundings or echo-sounding. Retention time estimates are more complicated in systems such as the meres with suspected or known substantial input from groundwater. However, this information is crucial if robust nutrient loads are to be calculated. In section 5, statistical relationships are used to estimate mean depth and retention time where these are unknown.

Table 4.24. Summary characteristics for the twenty six meres in this study taken from Tables 4.1 to 4.23. We have used chemical data from the survey of Moss et al. (1992) where it is available to maximise comparability across sites.

Characteristic	Altitude	Area	Catchment area	Max. depth	Mean depth	Mean retention	Main water source	Annual conductivity	Annual alkalinity	Annual TP	Annual DIN	Annual Chl *a*	WFD category
Unit	m	ha	km^2	m	m	y	-	µS cm^{-1}	mequiv L^{-1}	µg L^{-1}	µg L^{-1}	µg L^{-1}	-
Aqualate	67	59	58	1	-	-	D & S	610	0.88	469	870	68	MA, VS
Berrington Pool	78	2.5	0.36	12.2	6.7	-	S	392	1.8	113	384	16.6	HA, S
Betley Mere	58	9.3	8.31	1.8	-	0.07	D (S)	659	3.93	506	1060	62.9	HA, VS
Betton Pool	75	6.4	1.3[a]	10.9	3.6	1.85	D & S	231	2.14	97	126	27	HA, S
Black Mere	75	1.5	1.49	-	-	-	D & S	-	-	1300	-	-	-
Bomere	75	10.3	1.3[a]	15.2	5.1	4.5	D & S	120	0.56	49	44	11	MA, S
Brown Moss	104	3.3	1.28	1.0	-	-	S	150	0.78	775	-	2	MA, VS
Chapel Mere	88	6.5	2.38	2.4	-	0.15	S	721	4.68	1267	600	12	HA, VS
Cole Mere	88	28	1.72	11.5	3.3	1.25	S (D)	239	1.49	400	740	21.7	HA, S
Comber Mere	78	51.5	8.1	11.8	-	1.66	D	513	3	362	860	14.7	HA, S
Cop Mere	88	16.8	13.64	2.7	1	0.08	D	457	2.95	315	1800	59.6	HA, VS
Fenemere	78	9.4	11.2	2.2	-	0.21	S (D)	756	4.76	487	1230	56.1	HA, VS
Hatch Mere	76	4.7	2.2	3.8	-	0.4	S	484	2.36	85	1610	29.5	HA, VS
Maer Pool	118	5.5	1.82	1.7	-	-	S (D)	585	4.27	-	-	15.5	HA, VS
Marton Pool	105	13.7	5.01	8.0	-	-	S	-	4.40	-	-	-	HA, S
Oak Mere	73	22.9	3.50	5.6	2.0	0.81	S	187	0.028	61	230	7.4	LA, VS
Oss Mere	105	9.5	1.8	3.0	-	-	S	491	3.02	296	230	35.4	HA, VS
Quoisley Big Mere	78	4	1.73[b]	2.4	-	0.27[c]	S	611	4.69	404	640	14.2	HA, VS
Quoisley Little Mere	78	2.2	1.73[b]	1.8	-	0.27[c]	S	639	5.02	264	1350	8.4	HA, VS
Rostherne Mere	27	48.7	10.3	27.5	13.6	1.1 – 3.4	D		2.65	419	840	16.3	HA, S
Crose Mere	88	15.2	3.6	9.3	4.8	5.6 (2.25)	S (D)	474	3.05	214	350	9.8	HA, S
Shomere	75	1.3	1.3[a]	4.3	-	-	D & S	129	0.27	-	-	-	MA, VS
Tabley Mere	32	19.4	8.05	4.4	-	0.33	D	701	2.45	323	2460	17.6	HA, VS
Tatton Mere	46	31.7	5.51	11	-	0.88	D	518	2.6	233	455	12.1	HA, S
The Mere Mere	42	15.8	3.82	8.1	2.8	0.8-9.5	D	523	1.51	53.5	910	15.5	HA, VS
White Mere	96	25.5	0.93	13.8	4.4	-	S	309	1.88	1456	522	15.3	HA, S

a, Total catchment for Bowmere, Shomere and Betton Pool; b, Total catchment for both Quoisley Meres; c, Retention time for both Quoisley Meres. Main water sources are designated: D = Drainage, S = Seepage.

5.   IDENTIFICATION OF SITES WITH DIFFERENT TYPES OF NUTRIENT LIMITATION

5.1   Identifying processes that control phytoplankton populations

Many processes control the rates of growth and loss of phytoplankton and in turn the biomass or standing stock of an individual species or the community as a whole. The schematic of Nõges et al. (2010) gives an overview of the main gain and loss processes (Fig. 5.1) and these have been discussed in section 2. Because of this complexity, no one approach is likely to be completely successful in diagnosing the environmental factors that limit phytoplankton: as a corollary, several approaches are needed to identify factors controlling phytoplankton.
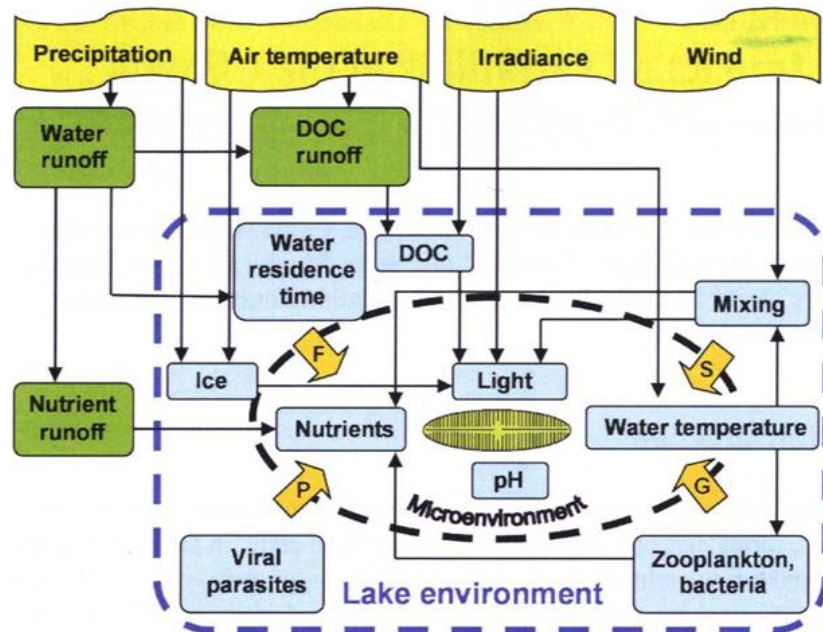
Figure 5.1. Schematic of the main mechanisms controlling phytoplanktion populations. Loss processes are designated as: F, flushing; P, parasitism including viruses; S, Sedimentation; and G, grazing (Nõges et al. 2010).

5.2   Ratios of inorganic nutrients

Redfield (1958) showed that, on average, marine algae require nitrogen and phosphorus in a ratio of about 16:1 by atom (7:2 by weight). If concentration is related to nutrient availability, then an increase in the ratio of total N: total P in the water column above the Redfield ratio may tend to make phosphorus the nutrient limiting growth. Conversely, a decrease in the

61

total N: total P ratio to below the Redfield ratio may tend to make nitrogen limiting. The OECD (1982) considered growth rate limitation due to N deficiency to occur at molar dissolved inorganic N: soluble reactive phosphorus ratios of <16:1 and P deficiency at ratios >33:1. However, the validity of using these ratios, and in fact of referring to nutrient ratios at all, in order to identify nutrient limitation is debatable. A number of fairly obvious problems with this approach can be recognised. For example, if the concentrations of both nutrients are present in excess then the nutrient ratio is uncoupled from nutrient limitation (Reynolds, 1999) and concentrations below a threshold may give a better indication of limitation. Secondly, although the Redfield ratio is normally defined in terms of total N and total P or dissolved inorganic N and soluble reactive P, not all of the 'total element' may be available (Axler et al. 1994). Thirdly, although the Redfield ratio reflects the average nutrient requirement of algae, different species may have different nutritional requirements (Klausmeier et al. 2004; Quigg et al 2003). Fourthly, a nutrient ratio does not take 'luxury consumption' (uptake and storage of a nutrient in excess of current requirements) into account nor the ability of some species to fix nitrogen and so grow after nutrient depletion has occurred.

Nevertheless, studies have generally found a broad relationship between nutrient ratios and nutrient limitation, although the ratios that delimit N- or P- limitation are understandably, given the above, rather variable. For example, in lakes and oceans, N limitation has been found at total N: total P molar ratio of less than 20 (Guildford & Hecky 2000) or less than 24 (Levine, 1983). In a study of UK upland lakes Maberly et al. (2002) found N limitation to occur at ratios of dissolved inorganic nitrogen to total dissolved phosphorus of <53. Maberly et al. (2002) argued that N-limitation may still prevail, even at these higher N:P ratios, as N-fixing cyanobacteria are inhibited by the low nutrient concentrations and pH in such environments. Similarly, the dissolved inorganic N: soluble reactive phosphorus ratio has been used to assess the nutrient limitation potential in rivers. Dodds et al. (1997) concluded, however, that strategies to control external nutrient loading and manage stream eutrophication should not be based on in-stream dissolved inorganic N or soluble reactive P levels, because in-stream dissolved inorganic nutrient concentrations are poorly related to benthic algal biomass. Wold & Hershey (1999) also stated that dissolved inorganic N: soluble reactive phosphorus ratios were not useful in predicting nutrient limitation. This study highlighted the differences in results by using a variety of analysis methods. The

dissolved inorganic N: soluble reactive phosphorus ratios (<10) were indicative of N limitation for most of the season, but the bioassay experiments indicated co-limitation. They concluded that dissolved inorganic N: soluble reactive phosphorus ratios were not useful in predicting the limiting nutrient(s). An earlier study by Axler et al. (1994) came to a similar conclusion but suggested that absolute N-concentration may be more useful. They found that in a study of phytoplankton in acid-sensitive lakes in Minnesota, that N-limitation could be predicted with 79% accuracy by a concentration of dissolved inorganic nitrogen < 25 µg L^{-1}, and with 87% accuracy when the concentration of nitrate was < 5 µg L^{-1}. It is unclear how relevant these concentrations are to UK lakes: Maberly et al. (2002), in a study of 30 unproductive upland lakes on three occasions in a year, only found such low values in mid-summer at 46% of the sites for dissolved inorganic nitrogen and 40% of the sites for nitrate. They found that concentrations of dissolved inorganic nitrogen at N-limited sites were below 91 µg L^{-1}: this is about 3.6 times higher than the values in Axler et al. (1994).

Despite all these caveats, if used with caution N:P ratios can give a give a preliminary assessment of which lakes could be limited by phosphorus or nitrogen, especially where the conclusions can be complemented with other approaches.

In this report, the N:P ratio was used to give some indication of the relative availability of nitrogen and phosphorus for the whole year and for each season (Table 5.1). Winter ratios best represent the balance in supply of nutrients to the mere when uptake by phytoplankton and macrophytes, or loss processes such as denitrification, are at a minimum. Summer ratios are a better representation of potential limitation. As an approximate indication, N-limitation may be considered more probable where N:P is <10:1, and P-limitation where N:P is >10:1. Nutrient datasets for 17 meres where data were adequate, were analysed. In summary, the winter ratios indicated nitrogen was supplied in excess requirements of phosphorus in 9 meres (winter N:P >20), phosphorus was supplied in excess of nitrogen in 5 meres (winter N:P <10) and their supply in relation to demand was relatively balanced in 3 meres (winter N:P 10-20) (Table 5.1). In terms of the summer ratios, there is a strong indication that nitrogen is used up relatively quickly compared with the demand for phosphorus, as many of the summer N:P ratios are <10. This may be associated with both denitrification and internal release of P from sediments during summer. There are three meres where P appears to be the more likely limiting nutrient (Mere Mere, Aqualate Mere, Hatch Mere; Table 5.1).

Table 5.1. Annual and seasonal N:P ratios, ordered by winter N:P. Values indicating potential N-limitation are coloured in orange and P-limitation are coloured in blue. Unclassified values (i.e. on the boundary) are not coloured.

Site	DIN:SRP Annual	DIN:SRP Winter	DIN:SRP Spring	DIN:SRP Summer	DIN:SRP Autumn
White Mere	1	2	1	0	1
Tatton Mere	4	7	5	1	2
Rostherne	7	7	8	9	6
Cole Mere	5	8	5	3	3
Comber Mere	9	8	16	6	4
Oak Mere	8	11	11	6	4
Berrington Pool	10	15	5	8	9
Betton Pool	22	18	50	13	5
Chapel Mere	27	21	85	1	2
Bomere Pool	20	22	34	17	6
Crose Mere	62	25	177	34	11
Tabley Mere	35	35	93	2	9
Cop Mere	54	50	136	13	18
Betley Mere	29	50	55	2	10
The Mere	87	51	170	105	20
Aqualate Mere	77	61	96	127	26
Hatch Mere	281	91	676	249	108

5.3   Ratios of chlorophyll a to potentially limiting nutrient

The amount of chlorophyll *a* produced per unit nutrient is a more direct way of assessing whether or not a particular nutrient is limiting phytoplankton, especially if other factors linked to lake type (for example depth and so light availability) can be removed from the analysis. A recent large-scale analysis of data from over 1000 European lakes has produced a new analysis of the average relationship between Chla and total phosphorus during the growing season for different types of lakes where depth is one of the lake characteristics (Phillips et al. 2008). Figure 5.2. shows the responses for two lake types (high alkalinity either shallow or very shallow and low or moderate alkalinity either shallow or very shallow). The response of 36 meres using summary data in Fisher et al. (2009) is shown for comparison. The data show that some meres convert phosphorus to chlorophyll in a similar stoichiometry to that of an average European lake of its type, while one was slightly more efficient than the average while others produce substantially less chlorophyll *a* per unit of phosphorus (Table 5.2). Figure 5.2 also shows that many of the meres have higher

concentrations of TP than in any of the over 1000 European lakes used to produce the correlation.
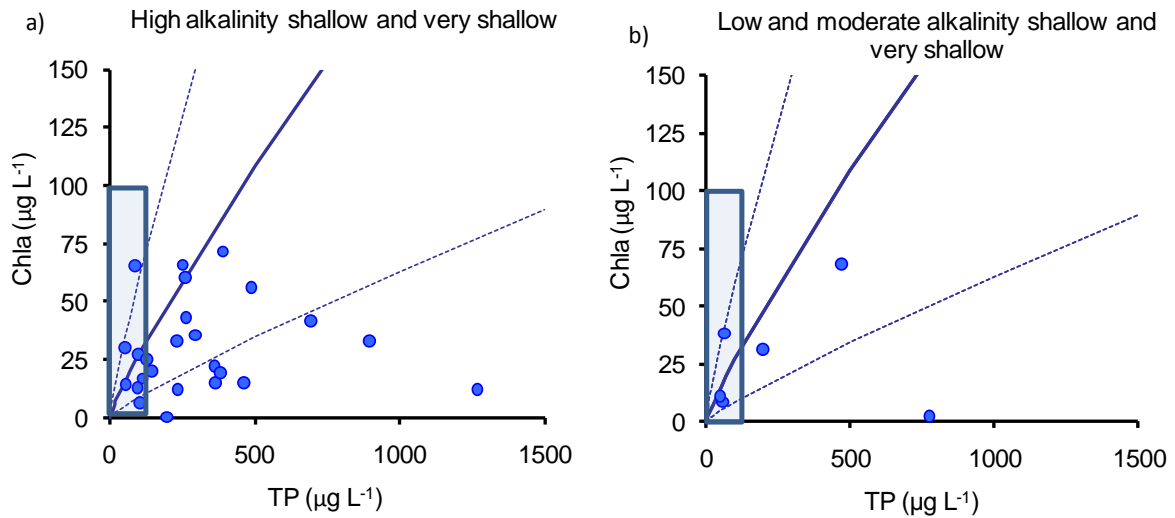
Figure 5.2. Growing season chlorophyll a (Chla) vs total phosphorus (TP) for: a) high alkalinity shallow or very shallow lakes and b) low and moderate alkalinity shallow and very shallow lakes. The symbols show the meres using data from Fisher et al. (2009). *The lines show the equations in* Phillips et al. (2008) *for a) model 6 and b) model 5. The heavy line is the average response and the upper and lower dotted lines represent 90% confidence limits. The boxes at the lower left-had corner of each graph show the range of values used in the original calibration.*

This provides circumstantial evidence that lakes with high or average conversion of phosphorus into chlorophyll *a* could be phosphorus limited while lakes with lower than average conversion of phosphorus to chlorophyll *a* are limited by another environmental factor such as nitrogen or light or one of the loss processes mentioned in section 5.1.

Table 5.2. Comparison of conversion of total phosphorus to chlorophyll a using type-specific regressions in Phillips et al. (2008) *and growing season data compiled in* Fisher et al. (2009). *'Low' represents chlorophyll a concentrations less than then 90% boundary, 'high' represents chlorophyll a concentrations more than the 90% boundary and 'Average' represents chlorophyll a concentrations between these two boundaries. Meres shown in bold form the subject of this report.*

Low	Average	High
Aqualate Mere	Alkmund Park Pool	**The Mere Mere**
Bar Mere	**Berrington Mere**	
Betley Mere	**Betton Pool**	
Brown Moss	Blake Mere	
Budworth Mere	**Bomere**	
Chapel Mere	**Cole Mere**	
Comber Mere	**Crose Mere**	
Cop Mere	**Fenemere**	
Ellesmere	**Hatch Mere**	
Hanmer Mere	Martbury Big Mere	
Little Mere	**Oss Mere**	
Maer Pool	Petty Pool	
Newton Mere	Pick Mere	
Norbury Big Mere	**Quoisley Mere**	
Norbury Little Mere	Redes Mere	
Oak Mere	**Rostherne Mere**	
Tabley Mere		
Tatton Mere		
White Mere		

The analysis of the large European dataset also investigated the relationship between phytoplankton and concentration of total nitrogen. Statistically significant and strong relationships were produced again, although with slightly less predictive power than for phosphorus. Using the same approach for nitrogen (Fig. 5.3), again many lakes fall within

the 95% confidence limits while some fall above and others below the confidence limits. Table 5.3. lists the lakes that produce less than, more than or the average concentration of chlorophyll *a* forecast from the concentration of total nitrogen in the growing season. A few of the meres have higher concentrations of total nitrogen than the over 1000 European lakes used to produce the correlation, but the excess is much less marked than for total phosphorus.

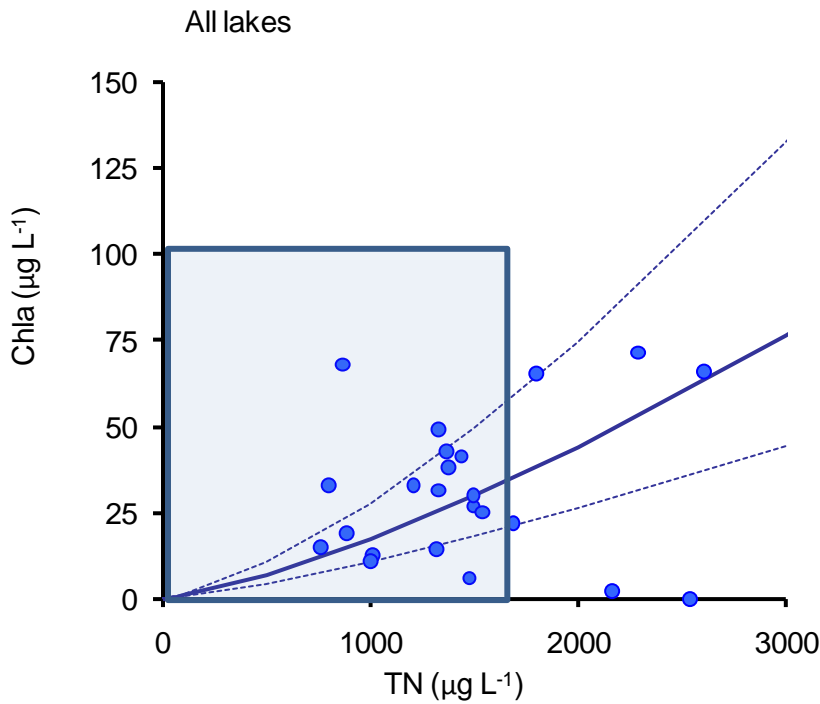*Figure 5.3. Growing season chlorophyll a (Chla) vs total nitrogen (TN) for all lake types. The symbols show the meres using data from Fisher et al. (2009). The lines show the equations in Phillips et al. (2008). The heavy line is the average response and the upper and lower dotted lines represent 95% confidence limits. The box at the lower left-had corner of the graph shows the range of values used in the original calibration.*

Table 5.3. Comparison of conversion of total nitrogen to chlorophyll a using type-specific regressions in Phillips et al. (2008) and growing season data compiled in Fisher et al. (2009). 'Low' represents chlorophyll a concentrations less than then 90% boundary, 'high' represents chlorophyll a concentrations more than the 90% boundary and 'Average' represents chlorophyll a concentrations between these two boundaries. Meres shown in bold form the subject of this report.

Low	Average	High
Crose Mere	**White Mere**	Hanmer Mere
Little Mere	**Cole Mere**	**Quoisley Mere**
Cop Mere	Ellesmere	**The Mere Mere**
Redes Mere	**Betton Pool**	**Aqualate Mere**
Brown Moss	**Rostherne Mere**	
	Pick Mere	
	Martbury Big Mere	
	Hatch Mere	
	Alkmund Park Pool	
	Betley Mere	
	Budworth Mere	
	Tabley Mere	
	Bomere	
	Blake Mere	
	Newton Mere	

A related way of assessing nutrient limitation is to look directly at the Chl*a*:TP and Chl*a*:TN ratios of the meres. In Figure 5.4, the annual average chlorophyll *a* concentrations from the recent data from the Environment Agency are plotted against annual mean TP or annual mean TN in the upper row. This shows a declining ratio with increasing nutrient concentration. There is an element of circularity here because the phytoplankton chlorophyll *a* will also contribute to TP and TN although in the case of the meres, the circularity will be less severe than in many other lakes because a relatively large proportion of the nutrient is soluble rather than particulate. However to test if this is a large problem, the annual mean

chlorophyll *a* was also plotted against the winter (Jan-Feb) concentrations of soluble nutrient: SRP or DIN (Fig. 5.4 lower row). Both ways of plotting the data show a similar pattern lending some credence to the approach. There is not a precise cut-off that can be set to distinguish P- and N-limitation, but for the purpose of this report, a value of >0.3 Chl*a*:TP was used to define sites with potential P-limitation and >0.02 Chl*a*:TN to define sites with potential N-limitation.
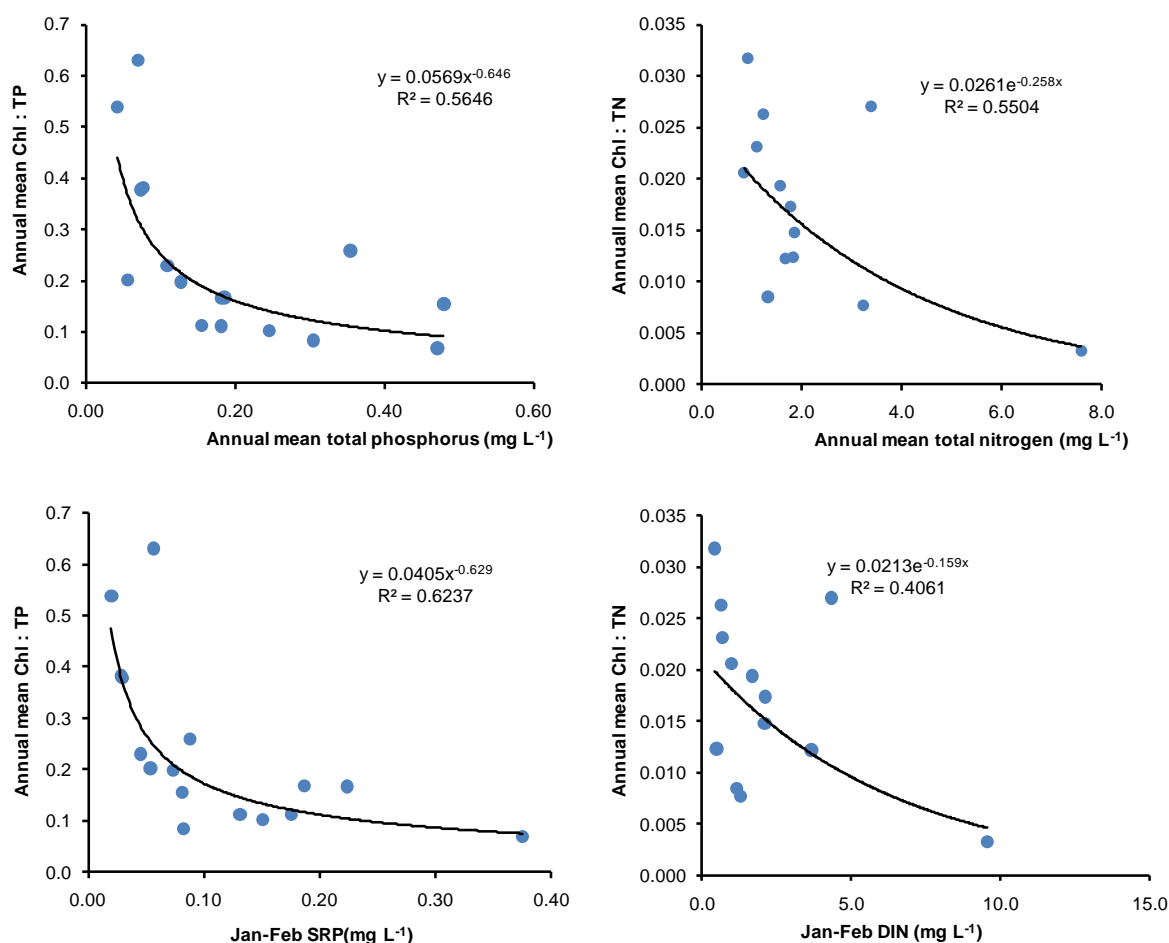
Figure 5.4. Relationship between annual mean Chl:TP or Chl:TN mass ratios and annual mean total phosphorus or total nitrogen (Upper row) or winter availability(lower row) of SRP (soluble reactive phosphorus) or DIN (dissolved inorganic nitrogen).

Using the criteria defined above, the sites are divided into P-limitation and N-limitation in Table 5.4. Note that Oak Mere is highlighted as potential P- and N-limited site, although it could just mean that relative to the other meres it is efficient at converting nutrients into phytoplankton chlorophyll *a*.

69

Table 5.4. Sites with potential P-limitation (Chla: TP>0.3) or N-limitation (Chla:TN>0.02) based on mass ratios.

P-limitation	N-limitation
Hatch Mere	Oak Mere
Oak Mere	Tabley Mere
The Mere	White Mere
Bomere	Cole Mere
	Tatton Mere

5.4   Seasonal nutrient minima

Ratios outlined in sections 5.2 & 5.3 do not necessarily indicate limitation, especially in lakes, like the meres, where TP concentrations can be extremely high. A more reliable picture of potential limitation can be obtained by examining the seasonality in available nutrients (SRP and DIN or NOx-N). P-limitation is possible in months where SRP <10 µg L^{-1}. N-limitation is possible in months where DIN <0.1 mg L^{-1} (Maberly et al. 2002). Not all meres had NH$_4$-N data and so DIN is sometimes an underestimate based only on NOx-N.

Note: in Jan 2008 the TP detection limit of UK environment agencies improved to 3 µg L^{-1}, but prior to Jan 2008 the detection limit was often around 100 µg L^{-1}. For this reason only TP data from Jan 2008 were used. The agency detection limit for NOx-N was usually 0.2 mg L^{-1}, for NH$_4$-N it was 0.03 mg L^{-1}. If values were below the detection limit, the detection limit was halved in order to estimate monthly means.
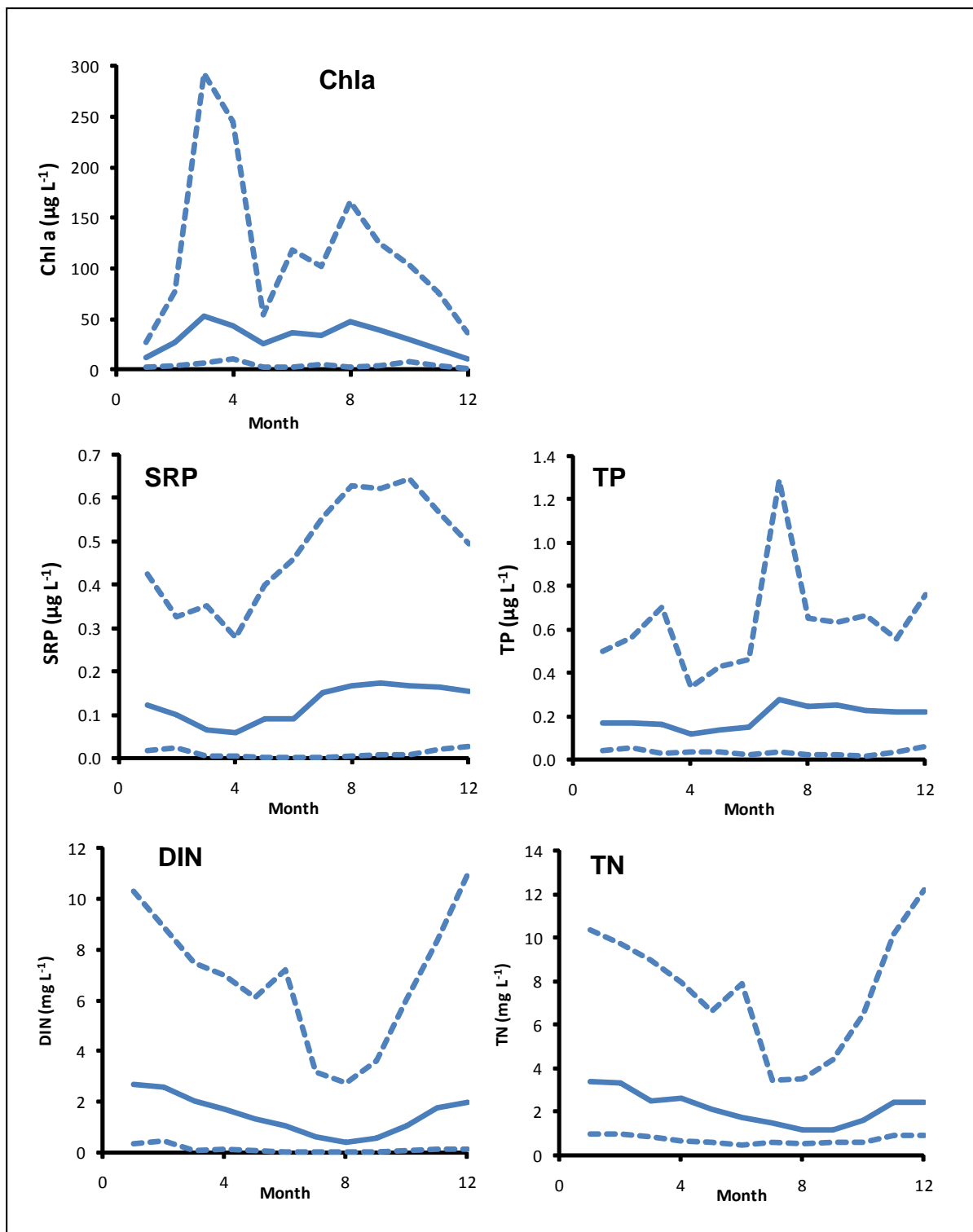
Figure 5.5. Average seasonal patterns for seventeen meres (see Table 5.1) with recent data available (mainly 2005 to 2009) collected by the Environment Agency. Solid line shows the mean, and upper and lower dotted lines show the monthly minima and maxima respectively.

Average seasonal patterns for meres with new data collected by the Environment Agency are shown in Figure 5.5. The data show that there is a large dynamic range of concentrations for all the values presented. The average seasonality for chlorophyll *a* is for a spring bloom, a slight early-summer decline and then a recovery in late summer. The average seasonal pattern for SRP is very unusual with lowest concentrations in spring and a steady increase during summer. This is consistent with a large internal loading of phosphorus into the lake from the sediment coupled with a low demand for phosphorus. The pattern for total phosphorus was more conservative but the data show that SRP comprises an extremely large part of the total phosphorus (overall average of 64%). DIN and TN followed similar seasonal patterns with a decline during the growing season to a minimum in July or August, probably as a result of uptake and microbial denitrification. DIN was about 68% of TN suggesting a potentially substantial amount of organic or particulate nitrogen.

Seasonal patterns of individual meres were analysed to determine whether or not nutrients fell to potentially limiting concentrations (Table 5.5). The seasonal plots can also be used to infer whether internal (summer and autumn increases) or external (winter increase) nutrient sources need targeting. There are four possible groups of response:

1. Only DIN falls below threshold: N-limitation indicated – N targets most beneficial
2. Only SRP fall below threshold: P-limitation indicated – P targets most beneficial
3. Both DIN and SRP fall below threshold: Co-limitation by N & P indicated – N & P targets beneficial
4. Neither DIN nor SRP fall below threshold: both nutrients in excess throughout year – N & P targets beneficial but no immediate effect likely

Table 5.5. Number of months where NOx, DIN and SRP are potentially limiting nutrients, ordered by #Months of low DIN concentrations. Occasions where concentrations fell below the stated thresholds are shaded. [Based on 2005-2009 data provided by the Environment Agency].

Site	#Months NOx-N ≤ 0.1 mg L^{-1}	#Months DIN ≤ 0.1 mg L^{-1}	#Months SRP ≤ 0.01 mg L^{-1}
Bomere Pool	8	5	6
Betton Pool	4	4	5
Berrington Pool	4	4	0
Cole Mere	6	3	0
Oak Mere	6	3	0
White Mere	6	2	0
Tatton Mere	4	2	0
The Mere	2	1	6
Crose Mere	2	1	5
Chapel Mere	1	1	1
Hatch Mere	0	0	4
Tabley Mere	4	0	0
Comber Mere	2	0	0
Aqualate Mere	0	0	0
Betley Mere	0	0	0
Cop Mere	0	0	0
Rostherne	0	0	0

Table 5.5 indicates that:

- nitrogen may be the sole limitation in 5 meres (Berrington Pool, Cole Mere, Oak Mere, White Mere, Tatton Mere)
- nitrogen and phosphorus may be co-limiting in 5 meres (Betton Pool, Bomere, The Mere Mere, Crose Mere, Chapel Mere)
- phosphorus may be the sole limitation in 1 mere (Hatch Mere)
- neither nutrient is likely to limit phytoplankton biomass in 6 meres (Tabley Mere, Comber Mere, Aqualate Mere, Betley Mere, Cop Mere, Rostherne Mere)
- In 9 meres, summer (internal) sources of NH$_4$ reduced the months of N-limitation (i.e. the difference in number of months below a threshold for NOx and DIN).

Group 1: Only N-limitation indicated – N targets most beneficial

Berrington Pool, Cole Mere, Oak Mere, White Mere and Tatton Mere all show at least 2 months where DIN concentrations remain below 0.1 mg L^{-1}. In all cases this occurs between

June and September and is probably related to uptake by phytoplankton and macrophytes and denitrification by microbes.

Example 1: Cole Mere (Fig. 5.6)

- There is evidence of strong N-limitation in summer (Jul-Sep) as DIN below the threshold.
- Chlorophyll *a* is very variable – no clear seasonal pattern or response to N-limitation.
- P may rise through summer from both external load (if supply is greater than demand) and internal release from sediments
- Benefit most from N loading reductions and so a N target is most relevant

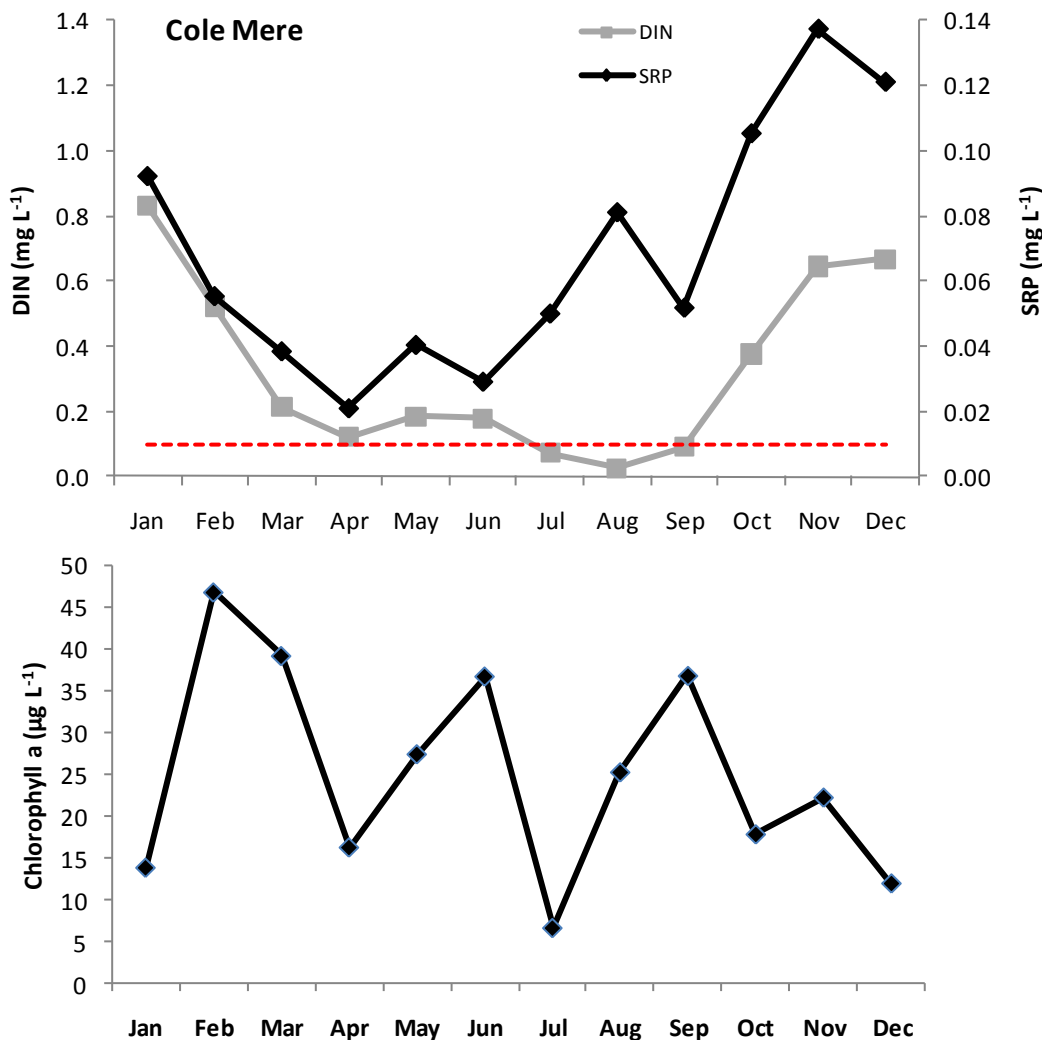*Figure 5.6. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Cole Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.*

Example 2: White Mere (Fig. 5.7)

- N-limitation is evident in summer (Jul-Aug), but DIN remains low throughout the year.

- P is very high throughout year, the rise in summer is probably caused by internal release from the sediments.

- Chlorophyll *a* is highly variable – with no clear seasonal pattern or response to N-limitation

- White Mere would benefit most from N loading reductions and so a N target is most relevant.

Figure 5.7. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in White Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Example 3: Oak Mere (Fig. 5.8)

- Nutrients concentrations are generally much lower concentrations than in other meres, although chlorophyll *a* is relatively high.

- Evidence of N-limitation (Aug-Oct) that may be the cause of the late summer decline in chlorophyll *a*.

- SRP concentrations were quite low, but never declined to limiting concentrations

- Oak Mere would benefit most from N loading reductions – N target most relevant
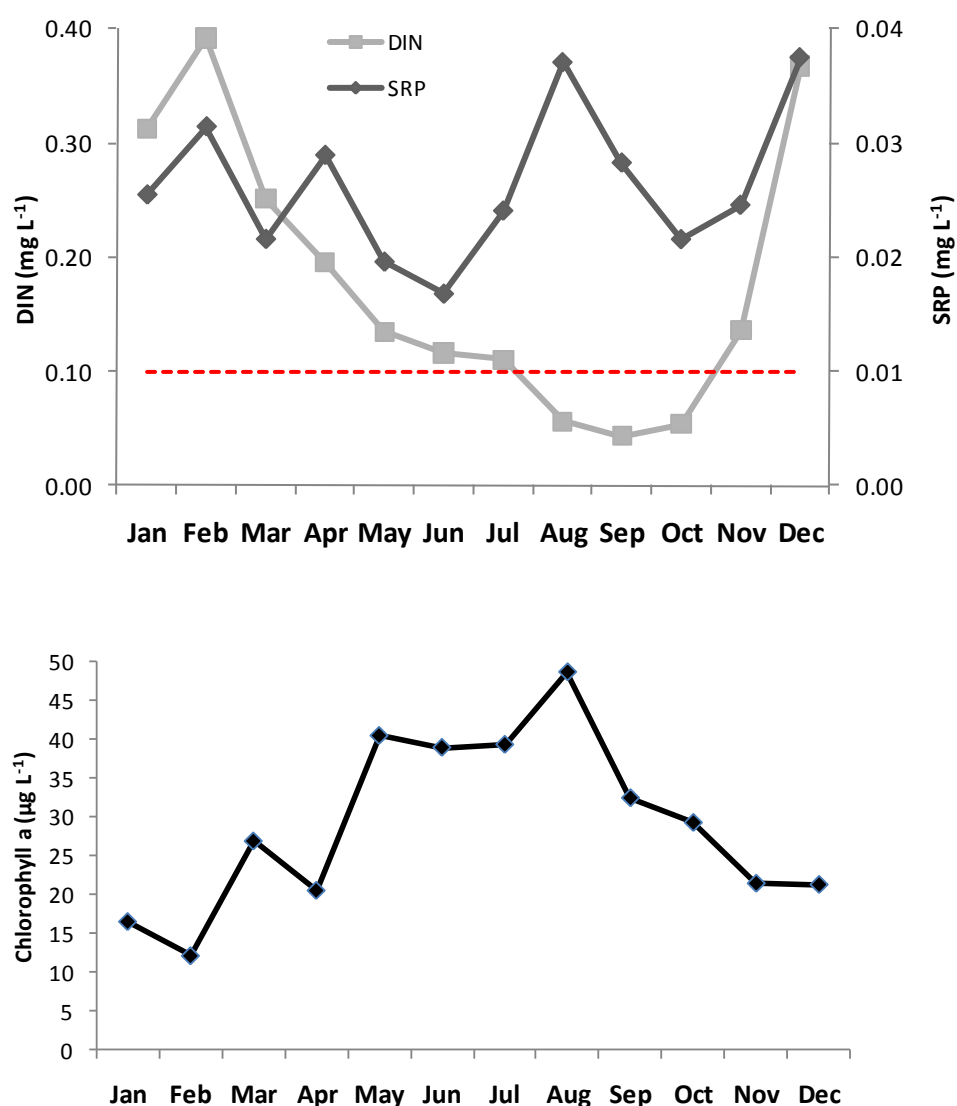
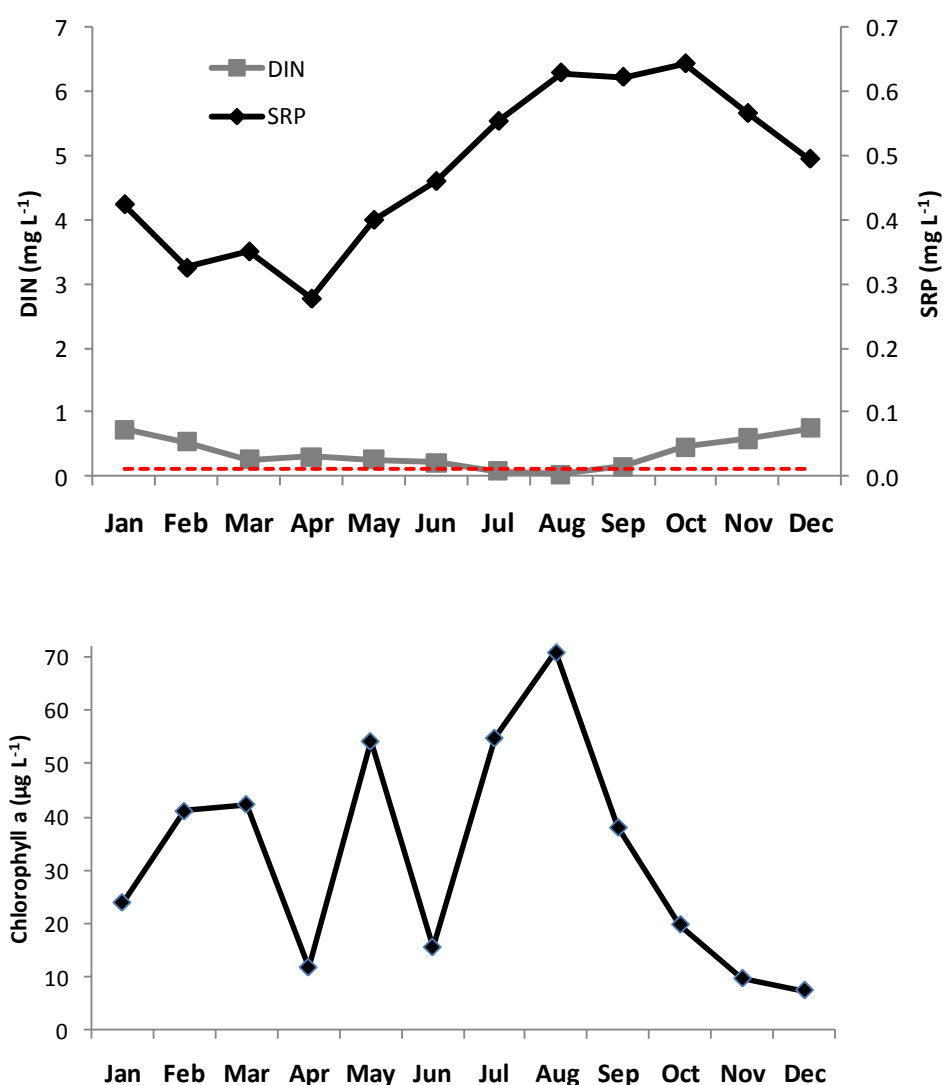*Figure 5.8. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Oak Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.*

Group 2: N- and P-limitation indicated – N & P targets beneficial

Bomere Pool, Betton Pool, Chapel Mere, Crose Mere and The Mere have summer minima of both SRP and DIN below the threshold.

Example 4: Bomere Pool (Fig. 5.9)

- External (winter) sources of N & P are both relatively low for the meres (low alkalinity like Oak Mere suggests Bomere is largely rain-fed).
- N & P are mostly below potentially limiting concentrations from May to October, although chlorophyll *a* does not show any evidence of limitation from June to August.
- Bomere may benefit from reducing both nutrients further, so N & P targets applicable.

Figure 5.9. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Bomere Pool. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Example 5: Betton Pool (Fig. 5.10)

- Both N & P decline to potentially limiting concentrations by June and this may the cause of declining chlorophyll *a* during summer. Limited NH_4 data to estimate DIN.

- N & P appear to be largely external (winter) sources and there is no evidence a summer increase indicating internal loading.

- Betton Pool would almost certainly benefit from reducing N & P further, so N & P targets beneficial.
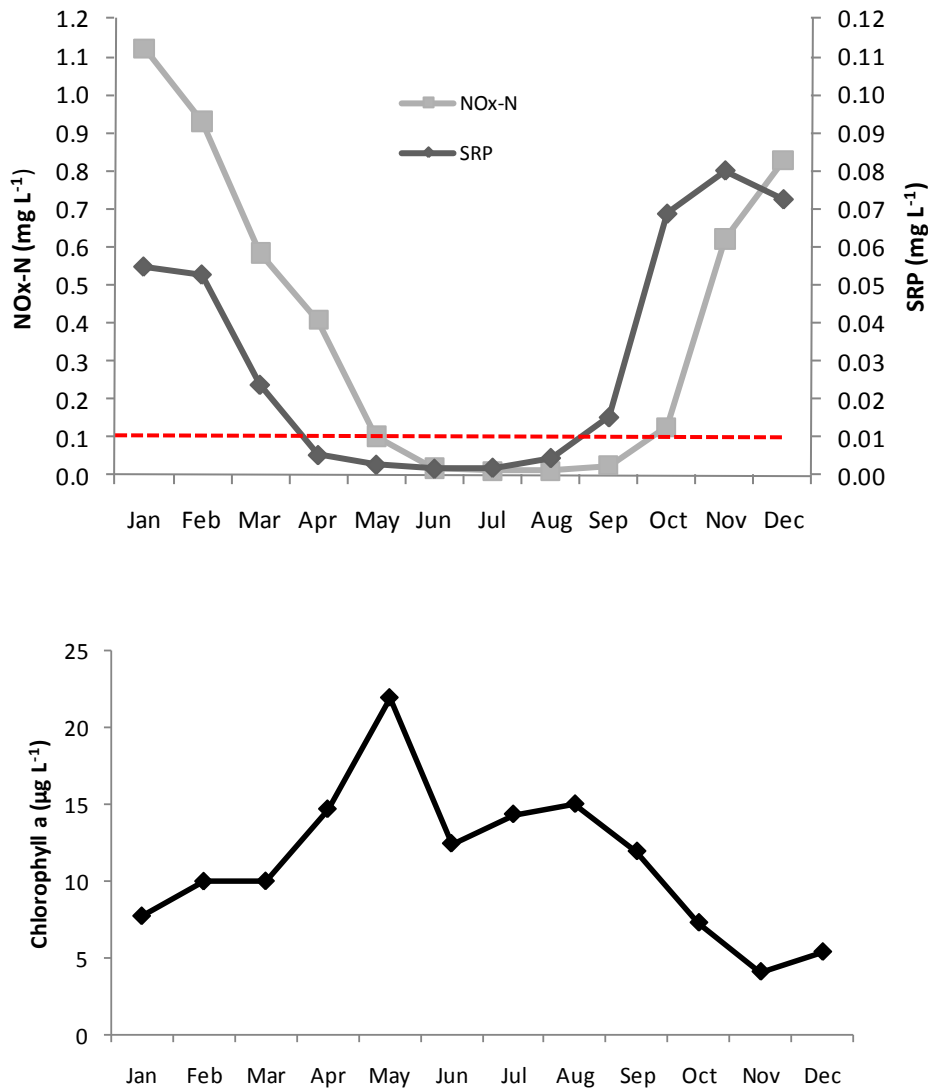
Figure 5.10. a) Seasonality in total oxidised nitrogen (NOx-N) and soluble reactive phosphorus (SRP) in Betton Pool. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Example 6: The Mere, Mere (Fig. 5.11)

- There are potentially limiting levels of P from May-Sep and N in Aug-Sep.
- Chlorophyll *a* concentrations are relatively high (high Chl:TP), suggesting that P is being well utilised and possibly grazer population may be low.
- Internal process of denitrification may be important in summer as there is a sharp decline in concentration of DIN.
- The Mere Mere could benefit from both N & P loading reductions –P target most relevant, N target could be beneficial too.
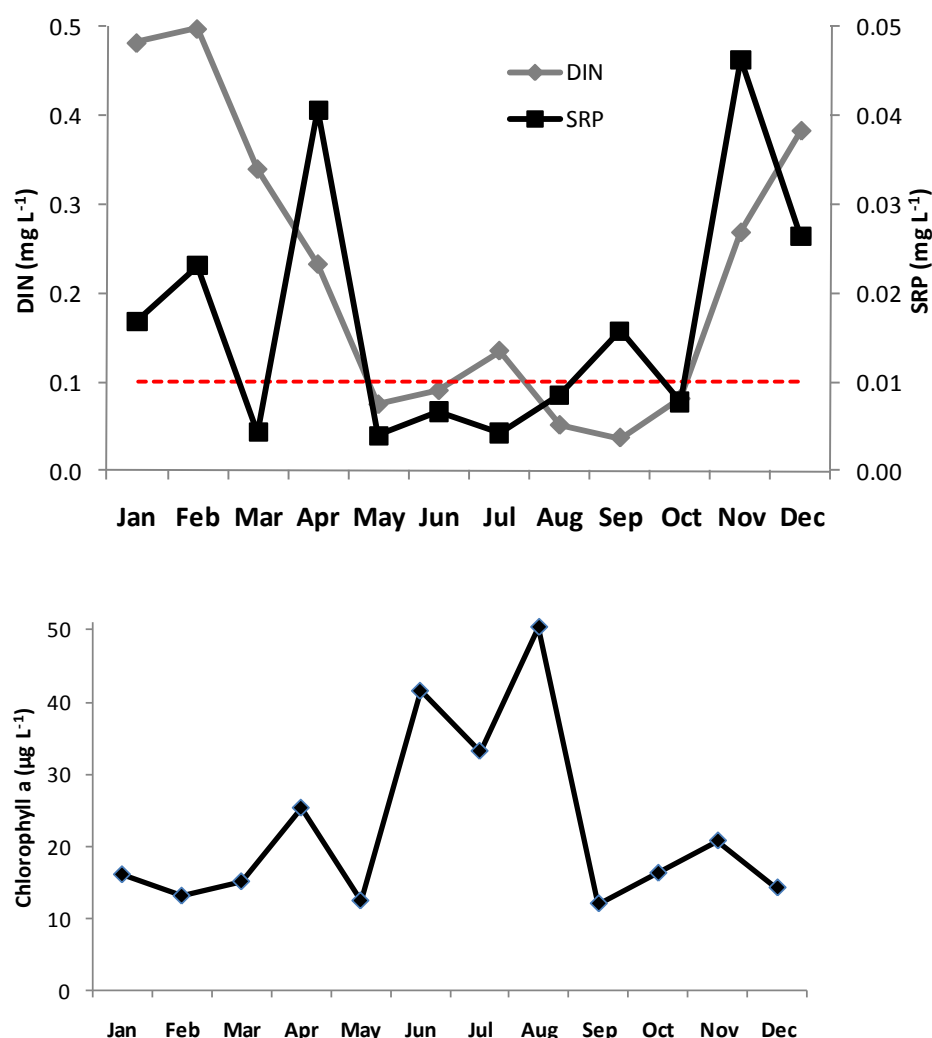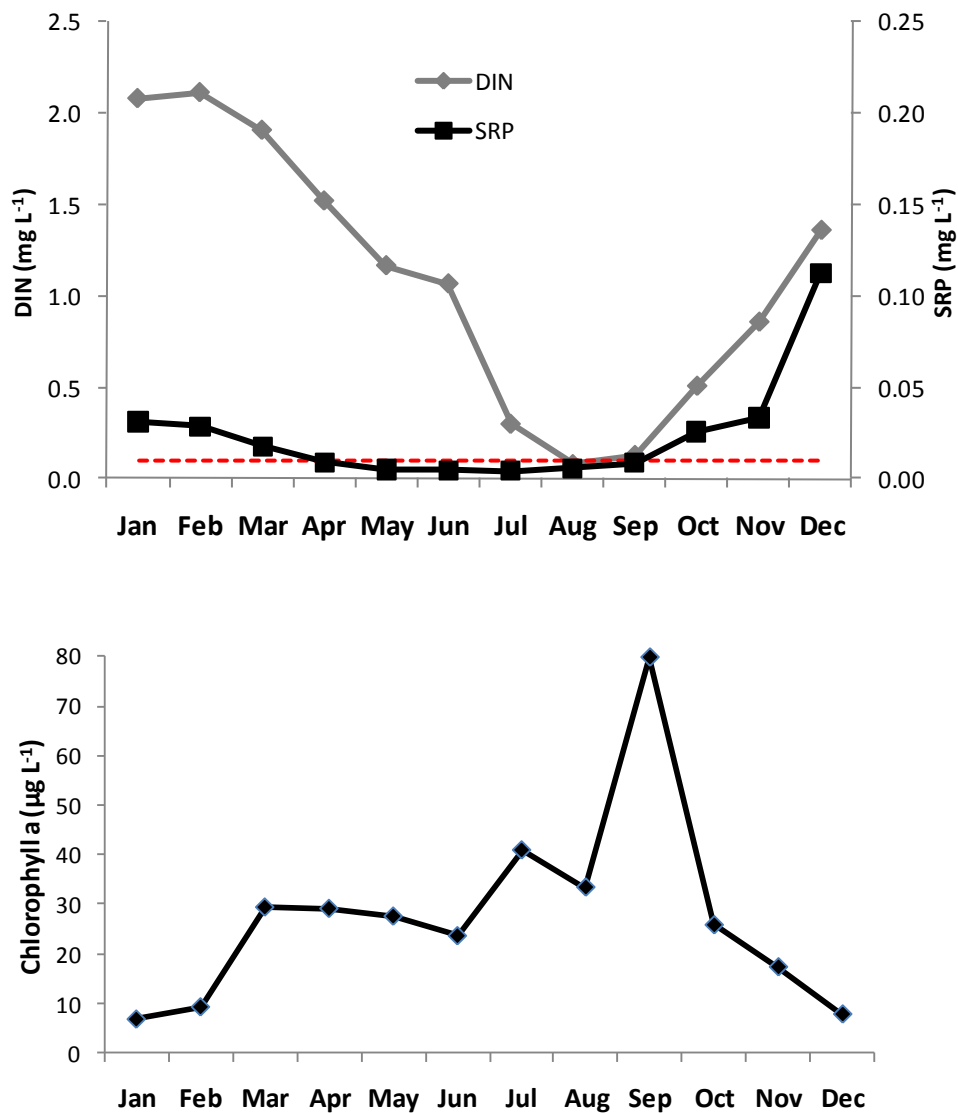

Figure 5.11. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in The Mere, Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Group 3: - P-limitation indicated – P targets beneficial

Hatch Mere only.

Example 7: Hatch Mere (Fig. 5.12)

- SRP is low all year and below the threshold indication P-limitation Apr-Sep.

- DIN is relatively high throughout the year and never fell to limiting concentrations despite a summer decline.

- Chlorophyll *a* peaked in summer – but there was no clear response to P-limitation.

- Hatch Mere would benefit most from P loading reductions and so a P target is most relevant.

Figure. 5.12. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Hatch Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Group 4: Both nutrients in excess – N & P targets beneficial but no immediate effect likely
Aqualate Mere, Betley Mere, Cop Mere and Rostherne Mere.

Example 8: Aqualate Mere (Fig. 5.13)

- DIN & SRP show contrasting seasonal cycles. SRP peaked in summer – indicating internal release, N-peaked in winter – indicating high external catchment loadings.

- Neither nutrient declined below limiting concentrations, although summer chlorophyll *a* is very low. Light limitation (suspended sediment) may be a possible reason.

- Aqualate Mere could benefit from tackling summer sources of P – probably from sediment release.

Figure 5.13. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Oak Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

Example 9: Rostherne Mere (Fig. 5.14)

- DIN & SRP show similar seasonal cycle: peak winter concentrations and summer minima, although never declining low enough to limit phytoplankton biomass. Phytoplankton thought to be light-limited (Reynolds & Bellinger 1992; Carvalho & Moss, 1995).

- External loading appears to be the main driver of nutrients although autumn overturn may replenish water column with nutrients released from sediments (SRP and NH_4).

- Rostherne Mere could benefit from further N & P catchment loading reductions – N & P targets both relevant
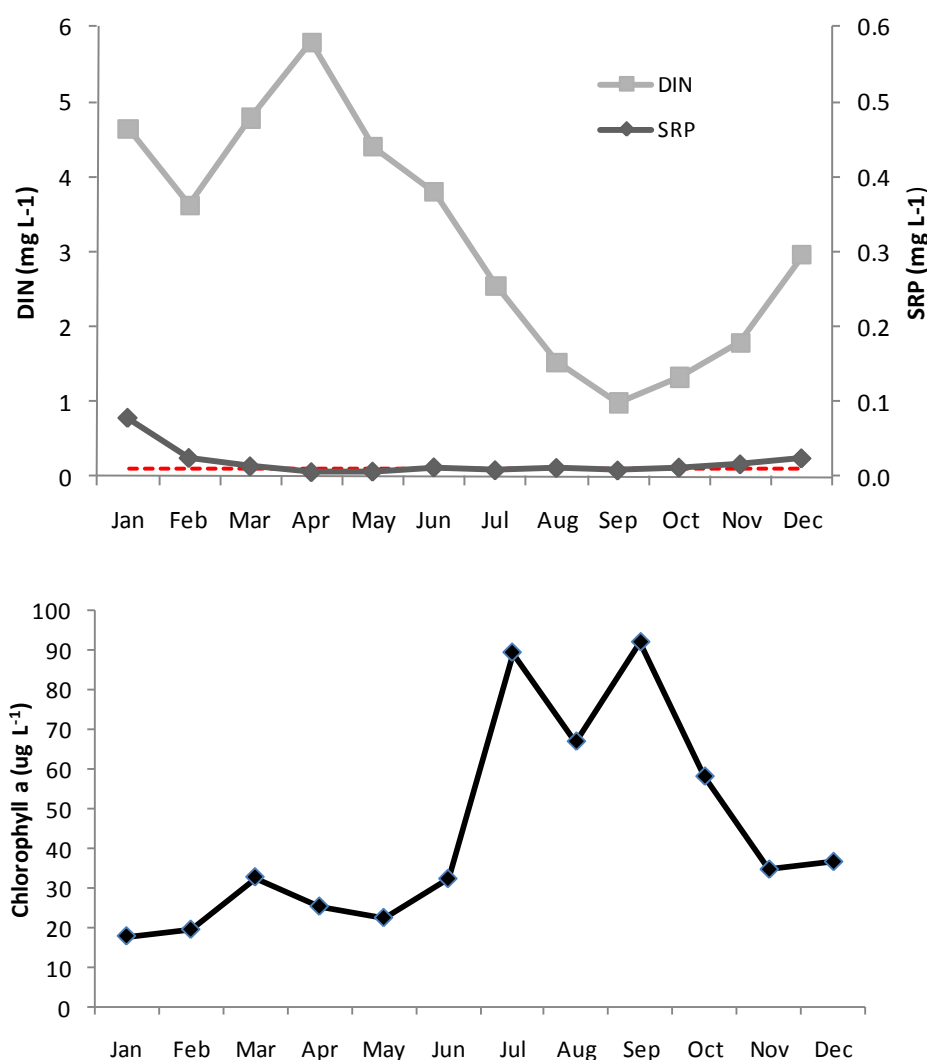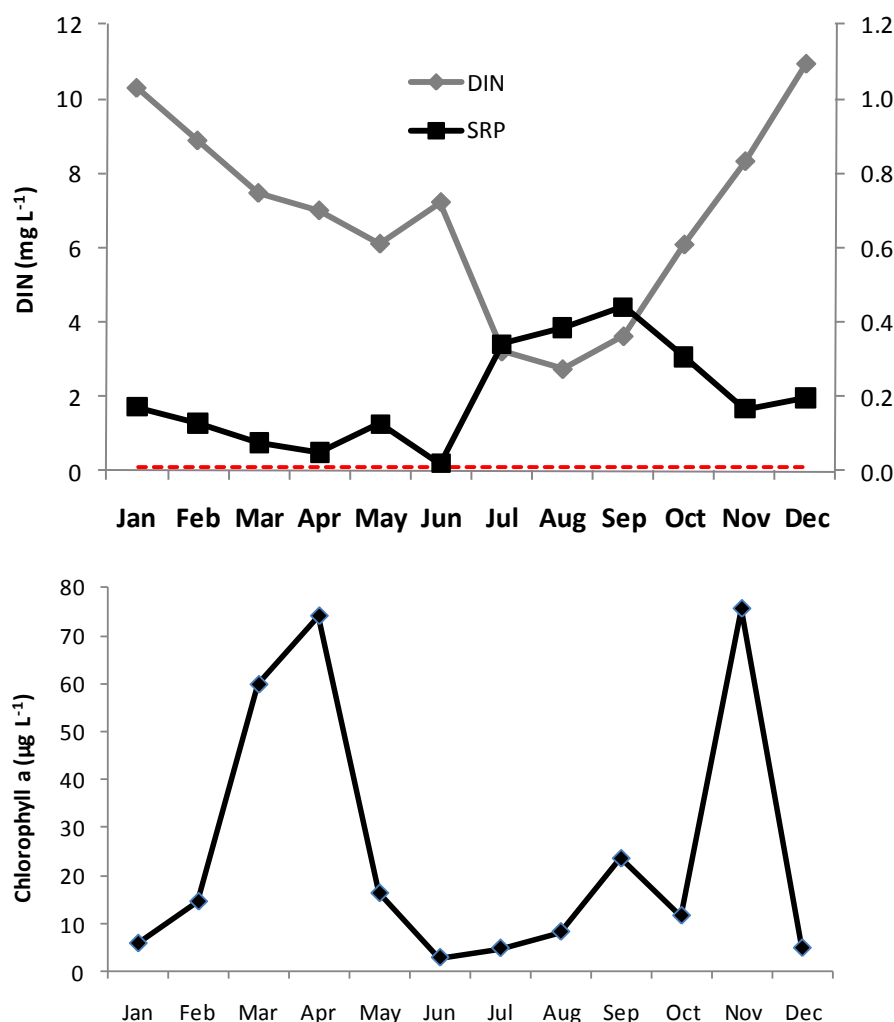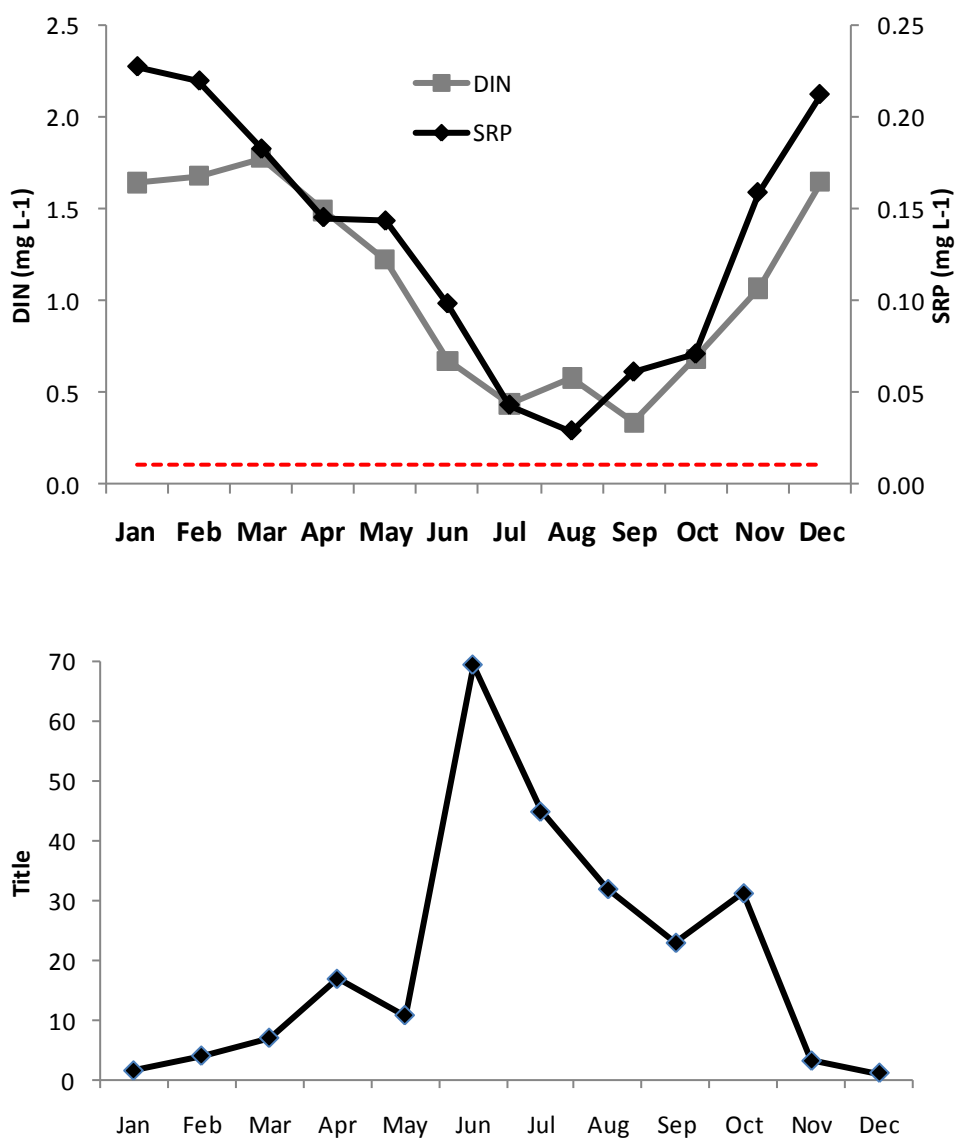

Figure 5.14. a) Seasonality in dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP) in Rostherne Mere. Red dashed line indicates potentially-limiting concentrations. b) Seasonality in chlorophyll a. Based on 2005-2009 data from the EA.

82

5.5   Stoichiometric modelling: Metabolake

Rationale and Approach

This stoichiometric approach was outlined by Reynolds & Maberly (2002) and is based on the relative availability of energy and different material resources needed to produce new algal biomass. The supportive capacity of each potentially-limiting resource is defined by the theoretical biomass yield in terms of phytoplankton carbon or chlorophyll *a*, assuming standard stoichiometric compositional ratios of healthy algal cells. Working through these in turn, the smallest yield is produced by the resource most likely to control local maxima of the phytoplankton. It is, therefore, an application of 'Liebig's Law of the Minimum'.

Nitrogen

The theoretical stoichiometric yield of phytoplankton cell carbon for nitrogen, supposing an ideal molecular ratio of 6.6:1, is close to 5.6 g C (g N)$^{-1}$ where total assimilable nitrogen is taken to be dissolved inorganic nitrogen (DIN = NO_3-N + NO_2-N +NH_4-N). Making the further supposition of a typical ratio of chlorophyll a to cell carbon (1:50 by mass), we deduce a maximum standing-crop yield of 0.11 g chlorophyll *a* (g N)$^{-1}$.

Phosphorus

Following similar logic, the yield against bioavailable phosphorus (BAP), mostly, but not entirely the molybdate-reactive fraction in the water plus the intrabiotic fraction of the particulate phosphorus: Reynolds & Davies (2001) is close to 41 g C (g P)$^{-1}$. In terms of chlorophyll *a*, the theoretical yield is 0.82 g chlorophyll *a* (g P)$^{-1}$. However, more detailed investigation of the maximum chlorophyll yields observed in lakes and experimental enclosures have been found consistently to conform to the first-order equation of Reynolds (1992):

$$\text{Chlorophyll } a = 6.32 \, [\text{BAP}]^{0.585} \qquad \text{(Equn 1)}$$

where [BAP] is the concentration of bioavailable phosphorus in µg L^{-1} and this is the equation used here.

Silicon

Against the availability of soluble reactive silicon (expressed in terms of SiO_2), the synthesis of the 10^9 cells of the diatom *Asterionella formosa* requires the supply of 140 mg SiO_2

(Lund 1965) for a typical chlorophyll yield of 85 mg cell C and 1.7 mg chlorophyll *a*. We propose a maximum standing-crop yield of 0.61 g C (g SiO_2)$^{-1}$ and 0.012 g chlorophyll *a* (g SiO_2)$^{-1}$. Noting the variability in the ratio of frustule silicon to protoplast carbon encountered among the diatoms (Reynolds 1984), it could be appropriate to use alternative values in locations where diatoms other than *Asterionella* are typically dominant.

Light

Analogous calculations are available for the supportive capacity of underwater light, the derived equation of Reynolds (1992) states:

[chlorophyll *a*] = (1/εs) [0.75 P/R . Γ/24 . 1/H . ln (0.7 I max/0.5 Ik) - (εw + εp)] (Equn 2)

Assuming constant values for P/R, the ratio of maximum photosynthetic rate to basal respiration rate at the same temperature is set at 15, and Ik, the onset of light limitation of photosynthesis, is set, somewhat generously, at 20 μmol photon m^{-2} s^{-1} and εs, the light extinction coefficient due to algal chlorophyll at 0.01 m^2 (mg chlorophyll *a*)$^{-1}$, and attributing a realistic background extinction due to particulates and colour in the source water, (εw + εp), the equation can be solved for representative conditions in the water body in question. H is the depth of the lake or of its trophogenic layer(s). The maximum attainable at 50ºN is under a cloudy sky at the summer solstice (daylength, Γ, = 16 h, mean daytime I max = 1000 μmol photon m^{-2} s^{-1}). In winter, the values fall (Γ = 8 h, mean daytime I max = 400 μmol photon m^{-2} s^{-1}). It is useful to derive some intermediate, ambient annual value: we make a calculation for the equinox, with 50% cloud (Γ = 12 h, mean daytime I max = 450 μmol photon m^{-2} s^{-1}). These quantities may be adjusted according to latitude.

To simplify calculations a loading table may be prepared. The entries may be calculated or, if the equations are first entered into an appropriate spreadsheet, completed automatically. Analogous calculations can be undertaken in respect of the other resources and the light received in the water column. If loads are not known accurately, it may be sufficient to use the highest measured concentrations in the lake as a surrogate for calculated mean availability.

The data in Table 4.24 were used to start to construct the loading table needed for the calculations. Mean depth was often missing and so at these sites it was estimated from the regression equation calculated from known maximum and mean depths in Table 4.24 (Fig. 5.15) which explained about 90% of the variation. Similarly, retention time was frequently not known: this was estimated from a regression between known retention time and the ratio of lake volume (m^3) and catchment area (m^2) shown in Figure 5.16. Since the annual DIN load was not known for most sites, availability of biologically available nitrogen (BAN) was calculated from the average concentration of DIN in January and February plus the average concentration of phytoplankton chlorophyll a in those months divided by 0.11 to convert to nitrogen. A similar approach was taken for phosphorus: biologically available phosphorus (BAP) was computed from the average concentration of soluble reactive phosphorus in January and February plus the concentration of phytoplankton chlorophyll a converted to phosphorus using equation 1
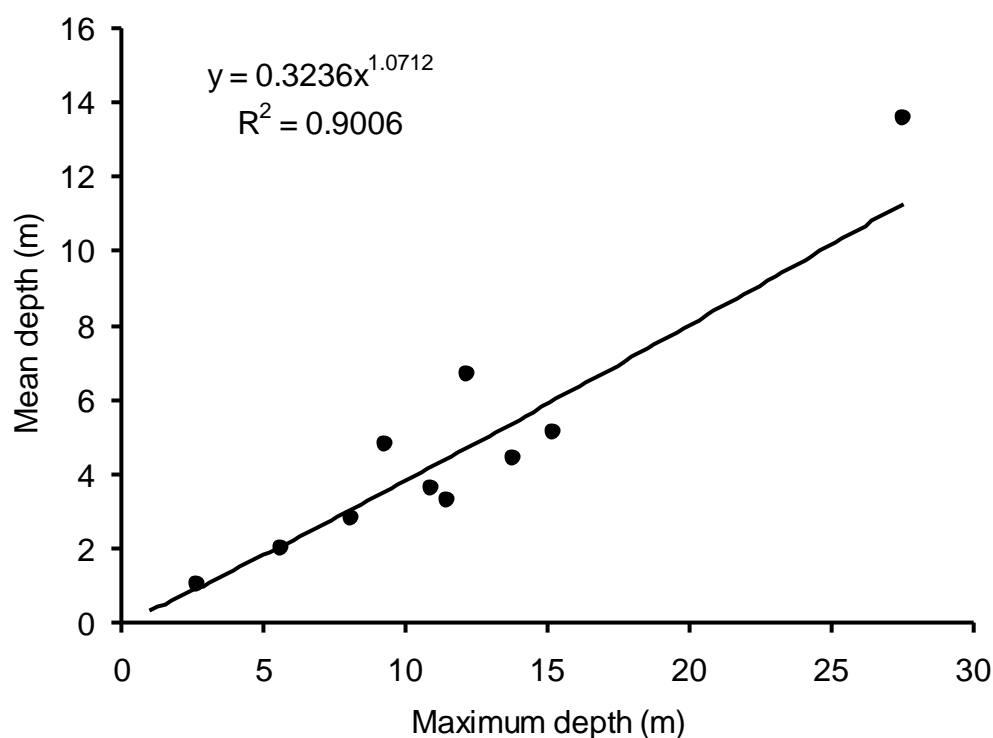
Figure 5.15. Relationship between mean and maximum depth for the meres in Table 4.24. The line shows a power-regression between mean and maximum depth.
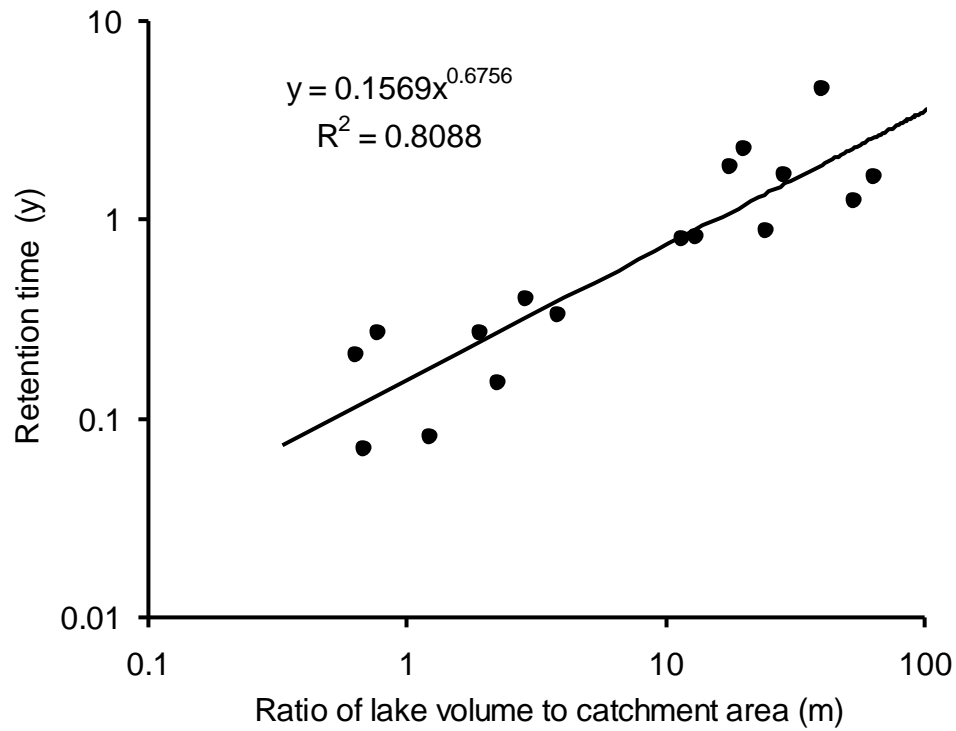
Figure 5.16. Relationship between annual mean retention time and the ratio of lake volume (m^3) to catchment area (m^2). Note that both axes are plotted on a logarithmic scale. The line shows a power-regression between retention time and the ratio.

Table 5.6. Calculated amount of phytoplankton chlorophyll a ($\mu g\ L^{-1}$) than can be produced for available amounts of phosphorus, nitrogen, silicon and light. The final four columns show the minimum predicted amount of chlorophyll a, the first and second limiting factor and the ratio of the amount of chlorophyll a produced per available P: amount of chlorophyll a produced per available N.

| Mere | BAP | N | Silicon for diatoms | Maximum Chla for light-supportive capacity | | | Minimum | First limitation | Second limitation | Predicted P:N |
				Summer light	Winter light	Ambient light				
Crose Mere	69	518	39	450	47	191	39	Silicon	Light	0.13
Hatch Mere	72	503	28	2281	849	1360	28	Silicon	P	0.14
Bomere	41	268	12	524	145	280	12	Silicon	P	0.15
Fenemere	170	837		3772	1200	2118	170	P		0.20
Comber Mere	136	622	44	542	116	268	44	Silicon	Light	0.22
Oak Mere	48	213	7	1451	483	828	7	Silicon	P	0.23
Berrington Pool	133	560		349	59	163	59	Light	P	0.24
Rostherne Mere	150	513	38	104	-39	12	-39	Light	Silicon	0.29
Aqualate Mere	120	403	66	9642	3657	5792	66	Silicon	P	0.30
Cole Mere	87	266	23	619	32	241	23	Silicon	Light	0.33
Oss Mere	109	261	91	2948	1103	1762	91	Silicon	P	0.42
Tatton Mere	111	250	58	531	72	236	58	Silicon	Light	0.44
White Mere	208	330	16	563	123	280	16	Silicon	Light	0.63
Tabley Mere	95	140	41	1763	539	976	41	Silicon	P	0.68
Mere Mere	47	68	29	921	230	476	29	Silicon	P	0.70
Betton Pool	66	54	8	757	219	411	8	Silicon	N	1.22
Chapel Mere	100	76	98	3785	1442	2278	76	N	Silicon	1.32

5.6   Direct bioassays

A number of direct bioassays have been undertaken to assess the nutrient limitation of the meres. These involved taking a water sample with natural phytoplankton, removal of large zooplankton, addition of no nutrients (control), or phosphate or nitrate or both and incubation outside under ambient conditions and measuring the chlorophyll *a* concentration after 6 days (James et al. 2003).

Table 5.7 Results of phytoplankton nutrient bioassays from eighteen meres. 0 = no nutrient limitation, P = phosphorus limitation, N = nitrogen limitation, Co = co-limitation. Meres shown in bold form the subject of this report. From James et al. (2003).

Mere	July 2000	October 2000
Alkmund Park Pool	N	0
Betton Pool	Co	0
Blake Mere	Co	0
Bomere	Co	0
Budworth Mere	N	0
Cole Mere	N	0
Crose Mere	P	0
Ellesmere	N	0
Hanmer Mere	N	0
Isle Pool	0	0
Marbury Big Mere	0	0
Newton Mere	N	0
Pick Mere	Co	0
Radnor Mere	N	0
Redes Mere	P	0
Rostherne Mere	Co	0
The Mere Mere	Co	0
White Mere	N	0

The bioassays on eighteen meres in July and October 2000 produced the results in Table 5.7. The results from July showed that seven of the eighteen meres were nitrogen-limited, two

were phosphorus limited, six were co-limited (i.e. required both N and P to elicit an increase in phytoplankton) and two meres showed no response to either N or P suggesting that some other factor could be limiting. In October, none of the meres were nutrient-limited (Table 5.7). This highlights the fact that nutrient-limitation varies seasonally as has been found before (e.g. Maberly et al. 2002; Maberly unpublished) reflecting the fact that nutrient-availability, other environmental conditions and phytoplankton species composition also vary seasonally.

5.7 Summary and final diagnosis of nutrient limitation at the study sites

The different approaches used above produced a variety of different results. They are brought together in Table 5.8.

Seven of the meres appear to be largely P-limited: The Mere Mere, Bomere Pool, Cop Mere, Crose Mere, Hatch Mere plus Fenemere and Oss Mere, but the assessment for the latter two meres is based on a single measure. Of these sites, The Mere Mere and Bomere Pool and Crose Mere and Hatch Mere showed no indication of solely N-limitation, although both seasonal minima and direct bioassay suggests that they could be Co-limited in the summer. Cop Mere had two measures indicating P-limitation and one indicating N-limitation (Chl:TP greater than the WFD 90percentile).

Eight of the meres appeared to be largely N-limited: Tatton Mere, Chapel Mere, Cole Mere, Quoisley Mere, Comber Mere, Betley Mere, White Mere plus Maer Pool (although this latter mere is based on only one assessment). None of these sites showed any indication of P-limitation.

The remaining sites had a mixture of responses

Table 5.8. Summary of nutrient-limitation of phytoplankton in the different meres using different approaches. Phosphorus-limited sites are coloured in blue, nitrogen limited sites are coloured in orange and co-limited or 'neither-limited' sites are coloured in lilac.

Note (No. sites)	A (17)	B (20)	C (13)	D (4)	E (5)	F (17	G (17)	H (7)							
Mere	N:P	Chla:TP vs WFD	Chla:TN vs WFD	Chla:TP >0.3	Chla:TN >0.02	Seasonal minima	Metabo-lake	Direct Bioassay	Count	#P	#N	#Co	#None	P%	N%
Fenemere							P		1	1	0	0	0	100	0
Oss Mere							P		1	1	0	0	0	100	0
The Mere Mere	P	P		P		Co	P	Co	6	4	0	2	0	67	0
Bomere Pool	P	None		P		Co	P	Co	6	3	0	2	1	50	0
Cop Mere	P	N	P			None			4	2	1	0	1	50	25
Crose Mere	P	None	P			Co	None	P	6	3	0	1	2	50	0
Hatch Mere	P	None	None	P		P	N		6	3	1	0	2	50	17
Brown Moss		N	P						2	1	1	0	0	50	50
Aqualate Mere	P	N	N			None	P		5	2	2	0	1	40	40
Berrington Pool	N	None				N	P		4	1	2	0	1	25	50
Oak Mere	N	N		P	N	N	P		6	1	4	1	0	17	67
Betton Pool	P	None	None			Co	N	Co	6	1	1	2	2	17	17
Tabley Mere	N	N	None		N	None	P		6	1	3	0	2	17	50
Rostherne	N	None	None			None	None	Co	6	0	1	1	4	0	17
White Mere	N	None	None		N	N	None	N	7	0	3	0	3	0	43
Betley Mere	N	N	None			None			4	0	2	0	2	0	50
Comber Mere	N	N				None	None		4	0	2	0	2	0	50
Quoisley		None	N						2	0	1	0	1	0	50
Cole Mere	N	None	None		N	N	None	N	7	0	4	0	3	0	57
Chapel Mere	N	N				Co	N		4	0	3	1	0	0	75
Tatton Mere	N	N	N		N	N	None		6	0	5	0	1	0	83
Maer Pool		N							1	0	1	0	0	0	100

Notes: A, Table 5.1; B Table 5.2; C, Table 5.3; D & E Table 5.4; F, Table 5.5; G, Table 5.6; H, Table 5.7; Count is number of assessments.

6. NUTRIENT TARGETS

Nutrient targets are largely a means to an end to manage water quality or achieve conservation objectives for a particular site. Here we examine: (1) existing TP standards for the meres, and possible future nutrient targets based on (2) palaeolimnology, (3) macrophyte diversity and (4) phytoplankton chlorophyll *a*.

6.1 Existing phosphorus targets

Table 6.1 presents TP targets outlined in Common Standards Monitoring guidance (JNCC 2005). The targets were largely derived from draft proposals for WFD boundaries for high-good ecological status and some expert judgement (see JNCC 2005).

Table 6.1 Total phosphorus targets for SSSI lake types (JNCC 2005).

Lake Type	Approximate Feature Type	Depth Category	TP target / limit
Peat	dystrophic	Deep	10
		Shallow	10
Low alkalinity	oligotrophic	Deep	10
		Shallow	10
Medium alkalinity	mesotrophic	Deep	15
		Shallow	20
High alkalinity	eutrophic	Deep	35
		Shallow	50 (35 – 100)

[1]TP targets are annual means ($\mu g\ L^{-1}$).

[2]Lake types and depth categories followed the draft UK WFD typology in 2005. In this respect "Shallow" includes all lakes with a mean depth of 3 m or less (i.e. "Very Shallow" in finalised WFD typology) and "Deep" includes lakes with a mean depth >3 m (i.e. "Shallow" and "Deep" in finalised WFD typology).

More recently, TP targets for UK lakes were agreed as UK Environmental Standards and the above JNCC targets were modified slightly (UK TAG 2008) (Table 6.2). This shows that the high-good boundary was retained more or less as the target for high and low alkalinity very shallow lakes, but that the good-moderate boundary was adopted for the other lake types. These targets are applicable to SAC sites and SSSIs. The choice of whether the high/good or good/moderate boundary should be applicable to the meres is largely academic, as the current status of many meres is generally well above these targets. Palaeolimnology

may, however, be helpful for deciding whether either of these targets is applicable to the meres (see following Section 6.2).

Table 6.2   Total phosphorus targets for WFD lake types (UK TAG 2008).

| Lake Type | No. of Meres | UK TAG Env. Standards | | Habitats Directive target |
		H/G	G/M	Favourable Condition
Low Alk VShallow	1	9	14	10
Mod Alk Shallow	1	11	16	15
Mod Alk VShallow	1	15	22	20
High Alk Shallow	8	25	35	35
High Alk Vshallow	13	35	49	35

[1]TP targets are annual means ($\mu g\ L^{-1}$).

In fact, UK TAG (2008) recommend adopting site-specific TP standards as these take account of an individual lake's characteristics (alkalinity and mean depth) to derive a reference value for a lake. This is based on the Morpho-Edaphic Index (MEI) modelling approach outlined by Cardoso et al. (2007). From this reference value, factors are used to identify TP class boundaries representing increasing degrees of change from reference. These factors are ecologically-based and include the response of phytoplankton chlorophyll *a* to TP, the growing depth of aquatic macrophytes and evidence from palaeolimnology on diatom community responses to TP (UK TAG 2008). The site-specific standards for the meres are outlined in Table 6.3. If alkalinity and mean depth data are unavailable for a lake (as for Maer Pool and Marton Pool), UK TAG (2008) recommends applying the type-specific standards outlined in Table 6.2, although for Black Mere, Brown Moss and Sweat Mere insufficient information was available to assign the water body to an appropriate type.

Table 6.3   Site-specific TP targets for the meres (based on Cardoso et al. 2007).

WBID	Lake Name	Altitude (m a.s.l.)	Alkalinity (mequiv. L⁻¹)	Mean depth (m)	Lake Type	Site-specific TP targets H/G	G/M
35724	Aqualate Mere	67	3.78	2.5	HAVS	44	57
36634	Berrington Pool	78	1.84	6.7	HAS	25	35
34330	Betley Mere	58	3.74	*0.6*	HAVS	44	57
NA	Black Mere						
36544	Bomere Pool	78	0.56	5.1	MAS	18	27
36578	Shomere Pool	78	0.27	*1.5*	MAVS	13	20
36566	Betton Pool	87	2.14	3.6	HAS	27	37
34791	Unnamed pool	105	No data	No data			
34162	Chapel Mere	88	4.36	*0.8*	HAVS	44	56
35079	Cole Mere	88	2.38	3.3	HAS	27	37
34480	Comber Mere	78	3.41	*4.6*	HAS	29	38
35238	Cop Mere	88	2.92	1.1	HAVS	39	52
35620	Fenemere	78	4.43	*0.8*	HAVS	45	57
33210	Hatch Mere	76	2.23	*1.4*	HAVS	35	48
34859	Maer Pool	118	No data	No data			
36881	Marton Pool, Chirbury	105	No data	No data			
33474	Oak Mere	77	0.06	1.7	LAVS	14	21
34545	Oss Mere	105	3.12	*1.0*	HAVS	39	51
34438	Quoisley Big Mere	78	4.49	*0.8*	HAVS	45	57
34441	Quoisley Little Mere	78	5.02	*0.6*	HAVS	46	56
32650	Rostherne Mere	27	2.41	13.6	HAS	23	33
35212	Sweat Mere		No data	No data			
35211	Crose Mere	88	2.93	*4.8*	HAS	30	40
32960	Tabley Mere	32	2.66	1.2	HAVS	41	56
32804	Tatton Mere	46	2.76	*4.2*	HAS	30	40
32744	The Mere, Mere	52	1.80	2.8	HAVS	30	41
35091	White Mere	96	2.10	*4.4*	HAS	25	34

Mean depths in italics and grey shading were estimated from maximum depths using the regression in Figure 5.15.

The site-specific TP standards outlined in Table 6.3 are generally higher than the type-specific standards for the lake type. This is because, in general, many of the meres have particularly high alkalinities, and subsequently higher reference TP concentrations.

6.2   Phosphorus targets from palaeolimnology

Remains of algae and chironomids in lake sediments have been used to reconstruct past environmental change over the Holocene in individual meres (Nelms 1984; O'Sullivan unpublished) and more recently baseline TP concentrations from around 1850 (McGowan 1996; Brooks et al 2001; Bennion pers. comm.). The palaeolimnological evidence suggests

that baseline TP concentrations lie between 30-50 µg L^{-1}, higher than reference TP concentrations derived from the MEI model. The latter was used in part to set UK TAG (2008) TP standards and suggests that the UK TAG standards may be very difficult to achieve. In many cases, the palaeolimnological baselines may also be uncertain and are best used to give a broad indication of trophic status. What is clear is that all the palaeolimnological studies show that there is clear evidence of nutrient impacts in the meres since 1850.

Table 6.4   Reference TP targets (µg L^{-1}) for 5 meres based on the MEI-model (Cardoso et al. 2007) and palaeolimnology.

Site	MEI Reference TP	Palaeo-inferred Reference TP	Source
Bomere Pool	14	50	Bennion, pers. comm.
White Mere	19	40	Bennion, pers. comm.
Hanmer Mere	21	34	Bennion, pers. comm.
Betton Pool	21	51	Brooks et al. (2001)
Crose mere	22	31	McGowan (1996)

6.3   Nitrogen levels and macrophyte species richness

Aquatic macrophytes are often a key feature mentioned in the reasons for notification of the sites as SSSIs (and are central to the designation of Oak Mere as a SAC site, protected under the Habitats Directive). In a wider, ecological context, aquatic macrophytes play a key physical structuring role in lakes and provide habitat for many associated invertebrate, fish and bird communities. Macrophyte depth limits and species composition are impacted by nutrient pollution, particularly through effects on light climate as large phytoplankton populations develop with enrichment. Recently, James et al. (2005) analysed the species richness of submerged and floating-leaved macrophyte communities from 60 shallow lakes in Poland and the UK including several from the Shropshire and Cheshire meres. They established a correlation between declining macrophyte species richness and winter concentrations of nitrate and total nitrogen. Overall, the concentration of winter nitrate, a measure of nitrogen availability during the growing season, was the best predictor of species richness and including the concentration of phosphorus did not add significantly to the statistical correlation. The authors suggest that the mechanism behind the relationship is based on abundant nitrogen promoting rapid growth and leading only to a few competitive

species such as *Ceratophyllum demersum*, *Potamogeton pectinatus*, *Lemna minor* and *Lemna trisulca* and the loss of slower-growing species. While this suggestion is largely speculative, it has received some experimental support from experiments carried out by Barker et al. (2008) who found a greater reduction in species richness in mesocosms where the concentration of nitrate-nitrogen exceeded about 1.5 mg L^{-1}.

If this relationship can be established in the meres then it would provide a response to nutrient availability and means to set a nutrient target. To determine this, macrophyte data from 26 meres from 1975 to 2006 supplied by Dr Genevieve Madgwick of Natural England were analysed. The data were sorted into submerged species and floating-leaved and amphibious species. The data on macrophyte species richness were combined with annual average and winter (January and February samples- using the same time-period as James et al. 2005) concentrations of total phosphorus and NOx-N leading to 16 (total phosphorus) and 17 (NOx-N) meres with data from both macrophyte composition and water chemistry. Each species of macrophyte was allocated to a trophic ranking score (TRS) which is an indication of the type of water the species is typically found in. A score of 1 indicates a species restricted to dystrophic sites, while a score of 10 represents a species restricted to highly eutrophic water. The scoring system of Palmer et al. (1992) and a revised scoring system produced by Dr Nigel Willby from Stirling University (N.J. Willby *pers comm.*) that includes more species, were used.

There were no significant correlations between species richness of submerged macrophytes and annual or winter concentrations of total phosphorus or NOx-N (Fig. 6.1.). A similar analysis based on the floating-leaved species (Fig. 6.2) also failed to find any significant relationships, although there were weak but not statistically significant decreases in floating species richness with annual ($P = 0.07$) and winter ($P = 0.07$) concentrations of NOx-N. The response of total number of species also failed to show any statistically significant relationships.

The analyses were re-run adding in annual mean values for water chemistry data from Table 4.24 where they were not already available. This increased the number of sites that could be analysed from 16 for total phosphorus and 17 for NOx-N to 20 and 22 respectively. This produced a significant negative correlation ($P<0.05$) for both floating and total species

richness vs concentration of total phosphorus but this was caused largely by the low species number and high total phosphorus concentration for Quoisley Little Mere and when this site was removed from the dataset the correlation was not significant. The lack of a significant response did not appear to be caused by an already depleted species composition in the meres since total species numbers were similar to the UK sites analysed by James et al (2005).
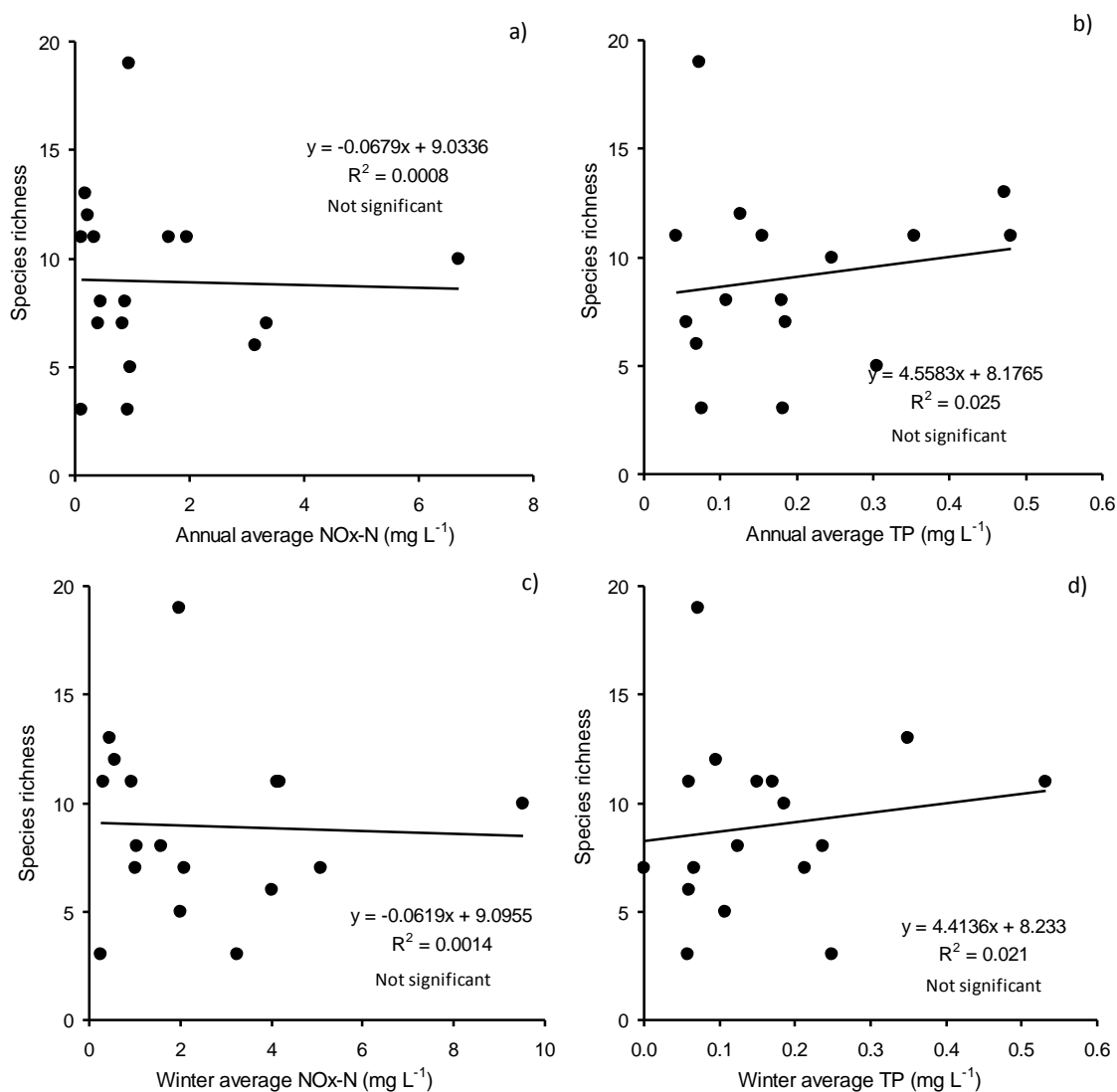

Figure 6.1 Relationship between submerged macrophyte species richness and water chemistry in 21 meres. a) species richness vs annual average concentration of NOx-N; b) species richness vs annual average concentration of TP; c) species richness vs winter average concentration of NOx-N; d) species richness vs winter average concentration of TP.
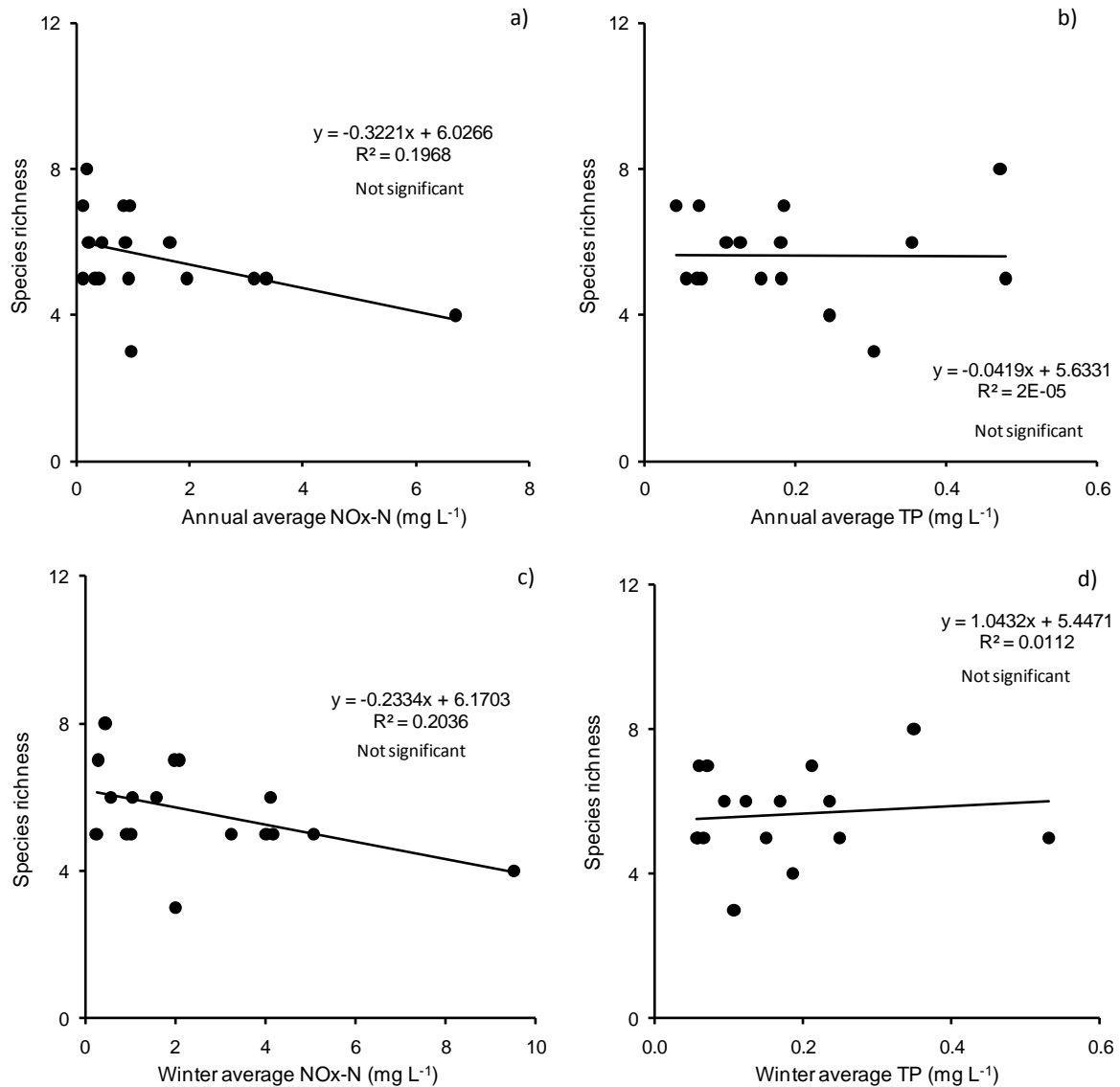
Figure 6.2 Relationship between floating macrophyte species richness and water chemistry in 21 meres. a) species richness vs annual average concentration of NOx-N; b) species richness vs annual average concentration of TP; c) species richness vs winter average concentration of NOx-N; d) species richness vs winter average concentration of TP.

To try to understand the weak/lack of response in the meres of macrophyte species richness versus water chemistry, the macrophyte species were converted to trophic ranking scores using the systems of Palmer et al. (1992) and Willby (pers comm.). The two TRS systems were strongly correlated and had a slope of 1.0 but the Palmer et al. (1992) system produced scores that were greater than the Willby system by 1.5. (Fig. 6.3).
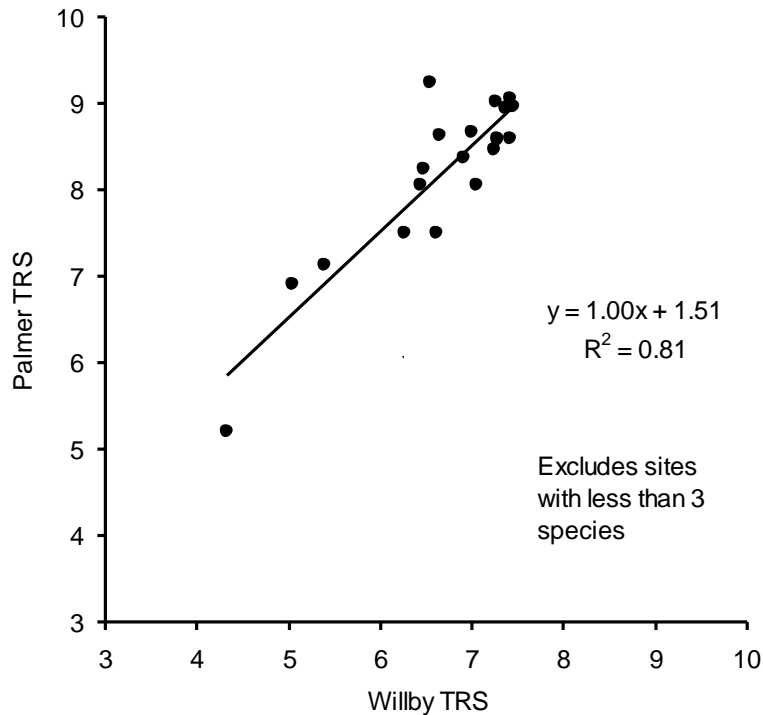
Figure 6.3 Comparison of TRS scores from 23 meres with more than 3 species using the system of Palmer et al. (1992) and updated system of Willby

Relationships between the two Trophic Ranking Scores, based on the average for all the species present at a site, and winter concentrations of NO_x-N or total phosphorus were not significant (Fig. 6.4). The data suggest, however, that above winter concentrations of about 0.5 mg NO_x-N L^{-1} and about 0.08 mg TP L^{-1}, there was not a major increase in Trophic Ranking Score. This may possibly explain the lack of response in the meres: most of the meres had concentrations of nitrogen and phosphorus that were characteristic of eutrophic water bodies. This lack of sites at lower nutrient concentrations truncates the macrophyte response to the higher, more insensitive end of the nutrient gradient. This result suggests that macrophyte species-richness in the meres cannot be used as a response to set nutrient targets, although the values obtained from the combined study of UK and Polish lakes (James et al. 2005; Barker et al. 2008) could still be applicable, suggesting targets of around 1.5 mg L^{-1} NO_3-N.
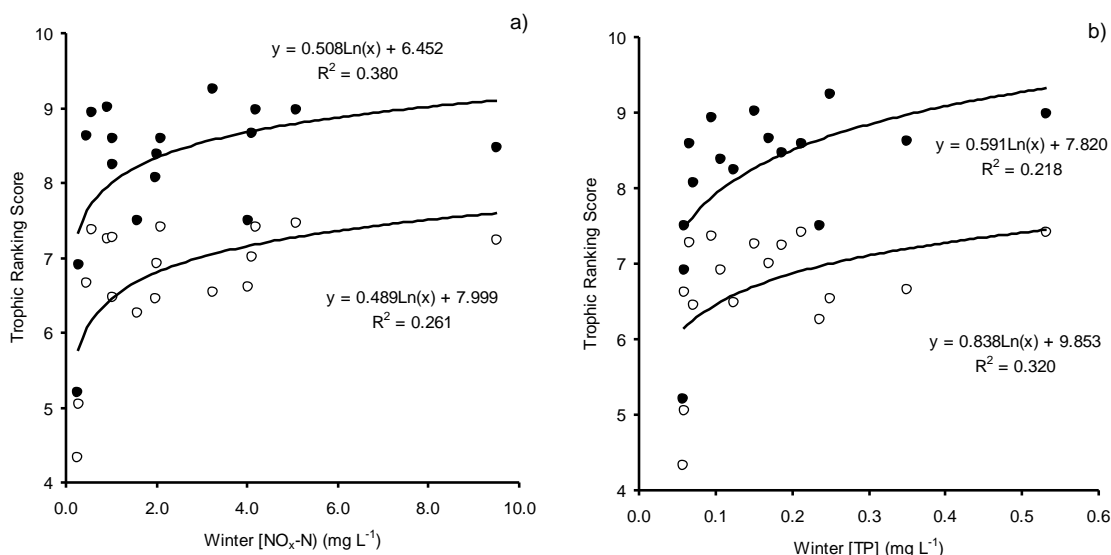
Figure 6.4. Relationship between Trophic Ranking Score according to Palmer et al. (1992), closed symbols and Willby (open symbols) against: a) concentration of winter NOx-N and b) concentration of winter total phosphorus.

6.4   N and P targets derived from WFD chlorophyll targets

Phytoplankton chlorophyll *a* is arguably the most sensitive and directly responding biological element to changing nutrient levels and influences the functioning of lake ecosystems, including light climate, deoxygenation at depth during stratification, and nutrient cycling and transfer of energy up the food-web to higher levels such as zooplankton and fish. The phytoplankton also interact with macrophytes and very shallow systems have a tendency to exist in either a turbid phytoplankton-dominated system or a clear-water macrophyte-dominated system. The Water Framework Directive (EC, 2000) prescribes the use of phytoplankton abundance as a key element of the ecological status assessment of European lakes. As part of WFD implementation a number of classification schemes for chlorophyll concentrations have been developed as a measure of phytoplankton abundance (e.g. Søndergaard et al. 2005; Carvalho et al. 2008; 2009) and status class boundaries have been agreed at an European level through the "Intercalibration" process (Table 6.5).

Table 6.5 WFD chlorophyll standards (µg L^{-1}) for lake types present in the meres (Modified from Carvalho et al. 2006.)

Lake Type	H/G Chl*a* target	G/M Chl*a* target
Low Alk VShallow	4.1	7.9
Mod Alk Shallow	4.7	7.2
Mod Alk VShallow	8.3	15.3
High Alk Shallow	4.6	7.5
High Alk Vshallow	8.6	16.5

The meres are no exception to this: chlorophyll *a* concentrations are widely seen as an important measure of nutrient enrichment which has major impacts on aquatic plant and invertebrate communities, and, therefore, the conservation status of the meres. For this reason, the WFD chlorophyll targets can be used as an ecological target for setting N & P targets. This can be carried out by inverting European regression equations relating total phosphorus or total nitrogen concentrations to chlorophyll *a* (Phillips et al. 2008) (Table 6.6 & 6.7)

Table 6.6 Regression equations relating chlorophyll a to total nitrogen concentrations (µg L^{-1}) for European lake types represented in the meres (Modified from Phillips et al. 2008).

Lake Type	Chl-TN Equation
LAVS	$\text{Log10 Chl} = -3.904(\pm 0.36) + 1.812(\pm 0.13)\ \text{Log10 TN}$
MAS	$\text{Log10 Chl} = -2.158(\pm 0.19) + 1.091(\pm 0.07)\ \text{Log10 TN}$
MAVS	$\text{Log10 Chl} = -3.189(\pm 0.40) + 1.538(\pm 0.14)\ \text{Log10 TN}$
HAS	$\text{Log10 Chl} = -2.177(\pm 0.35) + 1.096(\pm 0.12)\ \text{Log10 TN}$
HAVS	$\text{Log10 Chl} = -2.575(\pm 0.87) + 1.205(\pm 0.30)\ \text{Log10 TN}$

Table 6.7 Regression equations relating chlorophyll a to total phosphorus concentrations (µg L^{-1}) for European lake types represented in the meres (Modified from Phillips et al. 2008).

Lake Type	Chl-TP Equation
LAS	
LAVS	
MAS	$\text{Log}_{10}\text{Chl} = -0.528 + 1.108\ \text{Log}_{10}\text{TP}$
MAVS	
HAS	
HAVS	$\text{Log}_{10}\text{Chl} = -0.306 + 0.868\ \text{Log}_{10}\text{TP}$

The resultant N and P targets (Table 6.8) can be compared with the current status of the meres and the distance to target calculated (Table 6.8). This indicates that the meres are

failing chlorophyll and nutrient targets, with only one exception to this – the chlorophyll target at Cop Mere. On a more positive note, many sites are not too far from the N target and may even pass if site-specific chlorophyll targets were applied, as recommended by Carvalho et al. (2009). In terms of TP targets, many of the meres fail by a long distance and would generally be classified as bad status. Although these high TP concentrations may be partly natural, derived from apatite deposits (Reynolds 1979) they probably mainly result from phosphorus inputs that have accumulated over many years (Kilinc & Moss 2002) and so to get these sites to meet the good status TP target may be almost impossible to achieve in the short-term.

An important point to note is that passing the N target and failing the P target should not mean that management of N sources to the mere should be ignored, almost counter-intuitively it means that N control could lead to more immediate benefits in reducing chlorophyll *a* concentrations further.

Table 6.8 A comparison of current status of the meres with site-specific WFD targets (Chl and TP µg L^{-1}; TN mg L^{-1}). The "difference" representing distance to target. Green highlighting indicates current status is below target (i.e. site is at least good status), amber is relatively close to target ("moderate-poor" status) and red is far from target (>100 µg L^{-1} TP, >2.0 mg L^{-1} TN difference).

Lake	Current Status Chl	TP	TN	WFD G/M target Chl	TP	TN	Difference Chl	TP	TN
Aqualate Mere	25	245	7.6	16.5	57	1.4	9	188	6.2
Berrington Pool	20	182	1.7	7.5	35	0.6	13	147	1.1
Betley Mere	74	479		16.5	57	1.4	58	422	
Betton Pool	11	56	1.3	7.5	37	0.6	4	19	0.7
Bomere Pool	23	42	1.8	7.2	27	0.6	15	15	1.2
Chapel Mere	25	305		16.5	56	1.4	9	249	
Cole Mere	25	127	1.1	7.5	37	0.6	18	90	0.5
Comber Mere	31	186	1.8	7.5	38	0.6	24	148	1.2
Cop Mere	9			16.5	52	1.4	-7		
Crose Mere	25	108	3.2	7.5	40	0.6	17	68	2.6
Hatch Mere	44	70		16.5	48	1.4	27	22	
Oak Mere	29	76	0.9	7.9	21	0.4	21	55	0.5
Rostherne Mere	30	181	1.6	7.5	33	0.6	23	148	0.9
Tabley Mere	92	355	3.4	16.5	56	1.4	75	299	2.0
Tatton Mere	17	155	0.8	7.5	40	0.6	10	115	0.2
The Mere, Mere	28	73	1.9	16.5	41	1.4	11	32	0.5
White Mere	32	471	1.2	7.5	34	0.6	25	437	0.6

This approach deriving N & P targets from WFD chlorophyll targets assumes that both the chlorophyll targets and the regression equations are appropriate for the meres. As has been shown earlier (section 5.3) many of the meres do not conform to the European regressions relating nutrients to chlorophyll, and so the latter is certainly not true. Regression equations specific to the meres, or at least to the type of low-flushing lake present in the meres, should be developed. In particular meres with limited flushing (i.e. no outflow) may be expected to have higher chlorophyll concentrations as loss rates through the outflow will be non-existent. Similarly Moss et al. (1994) has shown that in many of the very shallow meres, grazing appears to be the most significant driving variable of chlorophyll concentrations and zooplanktivorous fish communities may be very important in this respect.

6.5   Conclusions

Table 6.9 provides a summary of all the targets outlined in this report. Except for the palaeolimnological targets, the approaches outlined above represent a "lake population" approach and are not ideal for representing the individuality of many of the meres and the complexity of the multitude of factors that affect macrophyte and phytoplankton communities. Where possible we would recommend meres-specific or site-specific approaches. The final suggested targets for TP are based on the UK TAG (2008) site-specific G/M boundary where this can be calculated and the Phillips et al. (2008) type-specific targets for a few sites where they cannot be calculated. The final suggested targets for TN are based on Phillips et al. (2008). Where a site has been identified as co-limited by N and P, both TN and TP targets are recommended to be set. While it is probably not true that all the meres are naturally rich in phosphorus, they have had a long-history of nutrient enrichment and, as Table 6.4 demonstrates, achieving these targets in order to reduce phytoplankton chlorophyll *a* will require careful management of nutrient sources within the catchment.

Table 6.9 Summary of nutrient targets for the meres. Grey areas show sites where data is not available, '-' indicates not applicable.

| Lake | Target nutrient | JNCC (2005) | UK TAG (2008) Type-specific | | UK TAG (2008) Site-specific | | Phillips et al. (2008) Chl-TP | Palaeo-limnology | James et al (2005) | Phillips et al. (2008) Chl-TN | Final targets | |
| | | | | | | | | NO₃-N (mg L⁻¹) | | TN (mg L⁻¹) | | |
			H/G	G/M	H/G	G/M	G/M			G/M	TP (µg L⁻¹)	TN (mg L⁻¹)
Aqualate Mere	N&P	50	35	49	44	57	57		1.5	1.4	**57**	**1.4**
Berrington Pool	N&P	35	25	35	25	35	35		1.5	0.6	**35**	**0.6**
Betley Mere	N&P	50	35	49	44	57	57		1.5	1.4	**57**	**1.4**
Black Mere												
Bomere Pool	N&P	15	11	16	18	27	18	50		0.6	**27**	**0.6**
Shomere Pool	N&P	20	15	22	13	20	35			0.7	**20**	**0.7**
Betton Pool	N&P	35	25	35	27	37	35	51	1.5	0.6	**37**	**0.6**
Brown Moss												
Chapel Mere	N&P	50	35	49	44	56	57		1.5	1.4	**56**	**1.4**
Cole Mere	N	35	25	35	27	37	35		1.5	0.6	**-**	**0.6**
Comber Mere	N	35	25	35	29	38	35		1.5	0.6	**-**	**0.6**
Cop Mere	P	50	35	49	39	52	57		1.5	1.4	**52**	**-**
Fenemere	P	50	35	49	45	57	57		1.5	1.4	**57**	**-**
Hatch Mere	P	50	35	49	35	48	57		1.5	1.4	**48**	**-**
Maer Pool	N	50	35	49			57		1.5	1.4	**-**	**1.4**
Marton Pool, Chirbury	N&P	50	35	49			57		1.5	1.4	**57**	**1.4**
Oak Mere	N&P	10	9	14	14	21	19			0.4	**21**	**0.4**
Oss Mere	P	50	35	49	39	51	57		1.5	1.4	**51**	**-**
Quoisley Big Mere	N	50	35	49	45	57	57		1.5	1.4	**-**	**1.4**
Quoisley Little Mere	N	50	35	49	46	56	57		1.5	1.4	**-**	**1.4**
Rostherne Mere	N&P	35	25	35	23	33	35		1.5	0.6	**33**	**0.6**
Sweat Mere												
Crose Mere	N&P	35	25	35	30	40	35	31	1.5	0.6	**40**	**0.6**
Tabley Mere	N&P	50	35	49	41	56	57		1.5	1.4	**56**	**1.4**
Tatton Mere	N	35	25	35	30	40	35		1.5	0.6	**-**	**0.6**
The Mere, Mere	P	50	35	49	30	41	57		1.5	1.4	**41**	**-**
White Mere	N	35	25	35	25	34	35	40	1.5	0.6	**-**	**0.6**

7. ASSESSMENT OF GAPS IN DATA AND UNDERSTANDING & RECOMMENDATIONS FOR FUTURE RESEARCH

This section considers the gaps in data, understanding and future research needed to manage the conservation and water quality of the meres more effectively.

Data gaps and survey

- There are gaps in basic data for some of the meres, some of which were reviewed in this report. Table 4.24 summarises the key features for the meres reviewed here which highlights these gaps: mean depth and retention time are not known for many of the meres. Mean depth could be measured by survey- possibly using hydroacoustics and this would also be a prerequisite for estimating retention time. Some sites, such as Black Mere, Marton Pool and Shomere have very little water chemistry. Information on key nutrients are also not complete for other meres such as Brown Moss and Maer Pool although in the case of the former a paper on early online giving a detailed nutrient budget (Chaichana et al. 2010) became available as this report was being completed. For these sites, a monthly survey extending over a year would provide this minimal data needed to manage these meres effectively by allowing mere-specific targets to be produced.

- More widespread measurements of groundwater chemistry are needed to establish the likelihood of achieving N & P targets.

- More accurate hydrological budgets are needed to assess the likely lags in response to catchment nutrient reductions.

- Greater knowledge on nutrient inputs from small non-sewered settlements (e.g. Cop Mere, Black Mere).

- Internal loading of phosphorus was indicated by the analysis of seasonal changes in concentration of phosphorus. It is probably important to be able to estimate the magnitude of this, otherwise, unaccounted for phosphorus-load.

Understanding and future research

- A key issue is to determine the 'baseline' concentration of phytoplankton chlorophyll *a*. This could be tackled using modelling approaches. For example:

1) Use estimates of baseline nutrient concentrations and develop meres-specific TP-chl*a* or TN-chl*a* relationships that reflect low flushing rates and a balanced fish community (healthy zooplankton community). Similar low flushing reference-condition sites could be sought across Europe (e.g. Polish kettle lakes) to validate chlorophyll targets.

2) Use historical macrophyte records (and macrophyte species responses in relation to light climate) to model target chlorophyll *a* concentrations (Maberly unpublished)

3) Use analogue sites across Europe where macrophytes from meres' historical past are still present – examine what chlorophyll and nutrient concentrations 'support' them.

- Where it is important to determine the prime nutrient limiting productivity, direct bioassays could be undertaken. As a minimum these should be undertaken on several occasions during the growing season as nutrient-limitation varies seasonally. More modern approaches based on physiological status or molecular methods might also be beneficial.

- It is unclear exactly why there is not a clear relationship between macrophyte species richness and nutrient availability. Future research could include experimental studies, for example in mesocosms, to investigate macrophyte survival and diversity and nutrient concentration.

- Examine whether cyanobacterial blooms are enhanced by N-limitation or whether just a response to high alkalinities – requires increased sampling of summer phytoplankton community across N- and P-limitation gradients in meres.

- Greater knowledge of fish community biomass, particularly benthivorous fish which are known to be highly damaging to submerged macrophyte communities.

- Better understanding of trophic webs in meres – is high fish biomass linked to elevated nutrient status, regular stocking, or unbalanced food-webs (e.g. lack of piscivorous fish, toxic cyanobacteria)

- Greater clarity on what value meres provide. Is it simply conservation interest? What is their value to fisheries? Can the fishery value be enhanced alongside conservation interests? What is their wider role in ecological services such as denitirification and C storage? Other roles? Tourism and recreation?

8. ACKNOWLEDGEMENTS

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