An assessment of nutrient sources and water quality improvement measures in Hornsea Mere

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SUMMARY

Hornsea Mere is a large, shallow freshwater lake on the western edge of the town of Hornsea in East Yorkshire (TA190470). It has a surface area of about 130 ha and a mean depth of about 1.2 m. The Mere is surrounded by areas of fringing swamp, and its catchment includes grassland, woodland, agricultural land and parts of the town of Hornsea.

The Mere is a Site of Special Scientific Interest (SSSI) in recognition of its conservation interest, which includes aquatic plants, adjacent habitats and wintering and breeding bird populations. It is also a Special Protection Area (SPA) on account of it hosting the European Protected Species *Anas strepera*, the Gadwall (dabbling duck).

The lake is fed by several inflowing streams and dikes and discharges to a single outflow, Stream Dike. Discharge from this outflow is controlled by a sluice structure located at TA200472, which was installed to regulate the water level in the mere to around 3.7 m.a.o.d. (Popham, 2000). Beyond the sluice, the water flows a distance of 1.1 km and discharges directly into the North Sea at Hornsea.

Palaeolimnological evidence suggests that the lake has become increasingly eutrophic over the past century, with aquatic plant community structure shifting from charophytes to fine-leaved pondweed (Bennion et al., 2009). This conclusion is supported by the extremely high in-lake concentrations of orthophosphate (OP; up to 0.5 mg P l^{-1}) that were recorded at this site in the mid-1980s, and by the fact that a macrophyte survey carried out in 2006 found that many of the specimens of the characteristically large plant species were small, unhealthy and covered in filamentous algae. The lake is also reported to have a tendency to develop algal blooms, although documentary evidence to support these observations is sparse. It is important to improve water quality in the mere to meet water quality targets.that ensure the protection of conservation interests.

This project reviewed existing data and information on the mere and re-examined the evidence of eutrophication problems at the site with a view to making management recommendations for the future. The key findings of this study, including comments on the implication of these results for the future management of the mere, are outlined below.

Inferences can be made with respect to the apparent nutrient (i.e. nitrogen (N) or phosphorus (P)) limitation of the phytoplankton community using water column nutrient concentrations. P limitation was most likely in winter and spring, whereas N limitation was highly likely between April/May and October each year. So, it appears that OP levels remain high in summer because algal productivity, and therefore their ability to sequester OP, is limited by N availability over this period. If N became more available in summer, it is likely that this would result in serious algal blooms. So, limiting N use within the catchment and controlling discharges of sewage effluent are probably the best way to control algal growth and prevent water quality problems in the immediate future. The recent designation of part of this area as a nitrate vulnerable zone should help achieve this, although this is aimed at reducing N losses from agriculture and inputs from other sources should also be evaluated and controlled, where necessary.

The long term data suggest that chlorophyll *a* levels have been falling steadily in recent years. Although it is difficult to draw conclusions from these rather infrequent data, this may indicate a partial recovery of water quality following catchment

management action that has already been put in place, such as agri-environmental schemes and initiatives, and farm nutrient budgeting.

There is strong evidence that particulate material enters the western bay of the mere *via* Low Wood Drain under high flow conditions, i.e. following heavy rainfall. This causes at least local degradation in water quality and may also have wider ranging implications for the mere as a whole. The limited anecdotal information that exists suggests that erosion problems within the catchment that discharges to Low Wood Drain may need to be addressed.

Although there are only six small, consented discharges of sewage effluent within the catchment, it is clear that there are probably about 300 such discharges that are unconsented. Although individually small, in combination these discharges may be responsible for a considerable nutrient input to the mere, possibly similar in size to that of agricultural runoff in relation to P. These small discharges need to be located, assessed and controlled in relation to their nutrient export, especially that relating to P. Often, control of these discharges simply involves better maintenance and management of individual tanks by their owners, many of whom may be unaware of the need to empty and maintain their systems on a regular basis (May et al., 2010).

In addition to the main inflows, several small pipes discharge directly into the mere. It has been shown that at least one of these (near Cheyne Walk) can be linked to local impacts on water quality that are indicative of nutrient enrichment. The effect of others is unknown. Nutrient delivery to the mere from these sources needs to be evaluated and, where necessary, addressed.

It is well known that P concentrations in Hornsea Mere are exceptionally high in summer for this type of waterbody. As biological productivity within the mere is very low in winter and apparently N-limited in summer, open water P concentrations tend to reflect the processes of supply and dilution rather than biological uptake. So, winter P concentrations are mainly controlled by inputs from the catchment while summer concentrations are mainly driven by sediment release. The very high concentrations that are mainly responsible for failure to meet water quality targets occur in summer. For these levels to be reduced, the amount of P being released from the sediments needs to be reduced. In a lake of this size, sediment removal or capping is unlikely to be a practical or cost effective option. Instead, restoration needs to focus on reducing input from the catchment and maximising losses from the outflow in the first instance. The latter depends on the rate at which P is flushed from the lake *via* the outflow in summer when P concentrations are highest. The overall aim would be to ensure that losses from the outflow exceed those inputs from catchment sources, birds and rainfall. The current hydrological management regime for the mere may need to be reconsidered to achieve this.

Some issues have been raised in relation to the applicability of methods for setting water quality targets based on P and chlorophyll *a* concentrations to lakes that are N-limited. This is because most of the methods available, such as chlorophyll *a*/TP regression equations, lake models used to identify critical loads, and diatom-TP transfer functions, are all based on the assumption that shallow lakes are predominantly P-limited. This issue needs further investigation and is not specific to Hornsea Mere.

This study has found that there are relatively few data available on discharges from small sources of nutrients across the catchment or chemical concentrations and rates of flow in both inflows and outflow. For this reason, it is not possible to construct a meaningful nutrient budget for the mere. In addition, very little is known about the ecology of the mere itself and how the various biological components interact. More detailed information on fish populations, predation rates and zooplankton grazing are needed to gain a better understanding of how this ecosystem functions and to enable the effects of change to be predicted.

Future management of Hornsea Mere should focus on:

- Identifying and reducing nutrient inputs from the catchment, especially from small point sources

- Implementing in-lake measures to reduce internal phosphorus release from the sediment, increase phosphorus discharge into the outflow and improve ecosystem function through habitat improvement

- Monitoring and assessing changes in the phosphorus budget for the mere and in-lake responses

CONTENTS

1 Introduction and aims

Hornsea Mere is a large, shallow freshwater lake on the western edge of the town of Hornsea in East Yorkshire (TA190470). It has a surface area of about 130 ha and a mean depth of about 1.2 m. It is situated at about 3.5 m above sea level, and has a catchment area of about 1755 ha. The centre of the mere is 2.1 km from the North Sea, which lies to the east of the site.

The mere is surrounded by areas of fringing swamp, and its catchment includes grassland, woodland, agricultural land and parts of the town of Hornsea. It has been designated as a Site of Special Scientific Interest (SSSI) in recognition of its conservation interest, which includes aquatic plants, adjacent habitats and wintering and breeding bird populations. It is also a Special Protection Area (SPA) because it hosts the European Protect Species *Anas strepera*, the Gadwall (dabbling duck).

The mere is fed by several inflows that drain surrounding farmland and residential areas; it discharges to a single outflow, Stream Dike. The outflow is controlled by a sluice structure that was installed to regulate the water level in the mere to a more or less constant 3.7 m.a.o.d. (Popham, 2000). Beyond the sluice, the outflowing water travels a distance of 1.1 km before discharging directly into the North Sea at Hornsea.

Palaeolimnological evidence suggests that the lake has become increasingly eutrophic over the past century (Bennion et al., 2009). This conclusion appears to be supported by the extremely high in-lake orthophosphate (OP) concentrations that were recorded at this site in the mid-1980s (up to 0.5 mg P/L). In addition, a macrophyte survey carried out in 2006 found that many of the specimens of the larger plant species were small, unhealthy and covered in filamentous algae. There is also some anecdotal evidence that the mere has a tendency to develop algal blooms.

As with all SSSIs, Conservation Objectives have been written for Hornsea Mere. These included a target average total phosphorus (TP) concentration of 0.05 mg P/L, with values ranging between 0.035 mg P/L and 0.1 mg P/L (Coverdale, 2009). The targets are set using Common Standards Monitoring Guidance produced by English Nature (now Natural England) and the Joint Nature Conservation Committee (JNCC). Also, under the Water Framework Directive (WFD), the mere has been classified as a high alkalinity very shallow lake and, as such, has been assigned the upper boundary values for good/moderate and high/good status shown in Table 1.1. It should be noted, however, that these WFD values are not site specific, either, but simply reflect WFD water quality targets for this type of waterbody. Average annual TP concentrations of 0.28 mg P/L measured over the period 2008/2009 show that TP concentrations are currently well above these target concentrations. These very high P concentrations are likely to result from P entering the lake from its catchment and that being recycled within the lake itself.

As part of the restoration process, the catchment is now part of a Catchment Sensitive Farming Project. This aims to reduce nutrient inputs to the mere and its feeder streams from diffuse agricultural sources. As such, it does not address other possible sources of P within the catchment, such as small unconsented discharges, or internal nutrient loading from lake sediments. Neither does it take into account the possible influence of lake management activities, such as controlling water level/flushing rate, on the water quality of this system. These are all important factors that also need to be taken into account when developing a comprehensive management plan for the mere.

Table 1.1 WFD water quality status boundaries for a high alkalinity, very shallow lake.

Parameter	Good/moderate boundary	High/good boundary
Total phosphorus (TP) concentration	0.032 mg P/L	0.023 mg P/L
Chlorophyll *a* concentration	16.5 µg/L	8.6 µg/L

The main aim of this project was to assess the scale and nature of the water quality problems at Hornsea Mere using existing information and produce an action plan to inform future management of the site. The specific aims were as follows:

- To collate and review existing data and information on Hornsea Mere and its catchment in relation to eutrophication problems
- To locate and identify potential inputs from septic tanks within the catchment and assess their likely impact on water quality
- To carry out sediment sampling and analysis for up to three sediment cores taken from the mere
- To develop a nutrient budget for Hornsea Mere based on best available data
- To identify data gaps and provide guidance on how some of these can be addressed
- To produce an action plan for Hornsea Mere to enable a coordinated approach to improving water quality

This report summarises the results of these analyses and makes recommendations for the developing an effective management plan for improving water quality at the site.

2 Literature review

2.1 Conservation Objectives

The Conservation Objectives for Hornsea Mere, a Site of Special Scientific Interest (SSSI), are detailed by Coverdale (2009) and summarised below. These objectives define a desired state for the mere in terms of its designated features and require the site to be managed in such a way as to achieve 'favourable condition'. The mere is currently classed as `unfavourable' mainly due to the poor water quality and it's associated impacts on the plant communities. The Conservation Objectives were produced using Common Standard Monitoring Guidance produced by English Nature (now Natural England) and the Joint Nature Conservation Committee (JNCC)

In terms of the aquatic plant community, Coverdale (2009) indicates that this should comprise species that are characteristic of natural eutrophic lakes with *Magnopotamion* and *Hydrocharition* type vegetation. In this context, *Magnopotamion*, includes Lesser pondweed (*Potamogeton pusillus),* fan-leaved water-crowfoot (*Ranunculus circinatus*)*,* stonewort *Chara* spp. (*C. Globularis)* and associated species such as rigid hornwort (*Ceratophyllum demersum),* fennel pondweed (*P. Pectinatus*) and spiked water-milfoil (*Myriophyllum spicatum*)*.* Similarly, *Hydrocharition* spp. includes Duckweed *Lemna sp*. and the associated species, Yellow water-lily (*Nuphar lutea*). In addition to characteristic species being present, there is a requirement that there should be few or no non-native species present, and that the cover of benthic and filamentous algae should be less than 10%. Finally, the conservation objectives require the maximum growing depth of submerged vegetation not to fall by more than 20% of the depth measured in 2004, i.e. 2.25 m.

There is also a requirement for the site to have stable nutrient levels appropriate to its type. These are defined as an average annual TP concentration (based on at least quarterly values) of 0.05 mg P/L, and a range of 0.035 - 0.1 mg P/L. In addition, dissolved oxygen concentrations are required to be 'adequate for the health of characteristic fauna' and there should be no excessive growth of cyanobacteria or green algae. There is also an expectation that the hydrology of the site will be maintained according to a natural regime, without fluctuations in water level not being affected by abstraction from inflows, groundwater or the mere itself. The natural shoreline must also be maintained, together with a natural and characteristic substrate and a natural sediment load.

It should be noted that the Conservation Objectives were written based on information available at the time and are set for conditions suited for a eutrophic lake. As stated later in the report (2.2.1), Hornsea Mere has not always been a eutrophic lake and that changes started to occur in the early 1900s to create these high nutrient conditions.

In terms of the bird populations at the mere, the specific designated features are an internationally important wintering population of Gadwall and nationally important wintering populations of Gadwall (*Anas strepera*), Shoveler, Tufted Duck, Pochard and Goldeneye, and post breeding and moulting mute swans. Maintaining the site in favourable condition for these aquatic birds requires there to be no reduction in the extent of standing water at the mere. Targets have also been set for maintaining bird numbers. In terms of the internationally important Gadwall, the aim is to maintain the population at more than 50% of the population at the time of designation (i.e. at more than 50% of the 5 year average peak count of 210 for 1987-1992). In terms of the nationally important species, similar targets have been based on the following average peak counts: Shoveler (90), Tufted duck (500), Pochard (361) and Goldeneye (210). Reed warblers also need to be maintained at more than 75% of the population level at the time of designation, which was 800 breeding pairs.

Overall, the conservation interest requires any diffuse pollution issues to be resolved if they contribute to unfavourable condition within the mere. This includes managing any land within the catchment, but outside of the SSSI boundary, in a way that is compatible with the special interest of the mere.

2.2 Lake considerations

Hornsea Mere has a long history of eutrophication problems and it is generally believed that these have been worsening in recent decades. Increased algal blooms, more turbid water and negative impacts on wildlife have all been mentioned as evidence of this change. The documentary evidence of changes in the ecological status of the mere is reviewed below in relation to palaeoecological records, algal abundance, nutrient concentrations, fish populations and any management strategies that have previously been recommended to solve water quality problems at the site.

2.2.1 Palaeoecology

The most compelling evidence for a change in the ecological status of the lake over time is given by Bennion et al. (2009), who inferred historical changes in water quality from biological remains in different layers of the lake sediments. Although this palaeoecological technique is usually based on diatom frustules, this method was difficult to apply to sediment cores from Hornsea Mere due to problems with diatom preservation at depths below 40 cm (Johnes et al., 1998). Bennion et al. (2009) found that aquatic plant macrofossils (seeds, fruits, leaves, stems, spines, etc.) and zooplankton remains within the sediments were better indicators of changing historical conditions at this site than diatom remains.

Analysis of the aquatic plant macrofossils showed two zones within the time series of sediments studied. The first was pre-1920, when aquatic plants in the mere were dominated by *Chara* spp., a plant community that is characteristic of high alkalinity waterbodies in good condition. As time progessed, *Chara* spp. began to decline and *Zannichellia palustris* began to take its place. From 1925, onwards, the aquatic plant community was found to have shifted towards species that are more nutrient tolerant, such as *Zannichellia palustris* and fine-leaved *Potamogeton* spp.

The results of the analysis of zooplankton remains also showed two clear zonations over time. *Ceriodaphnia* spp. were dominant before about 1960, but these were progressively replaced by *Daphnia hyalina* and then *Daphnia magna* and *Simocephalus* after about 1960. These changes suggested an increase in pelagic species that that probably reflected greater food availability in the open water, probably due to an increase in planktonic algae as a result of eutrophication. Bennion et al. (2009) concluded that the changes that they had found indicated an on-going eutrophication problem at the mere that was probably gradual ("insidious") rather than event driven. Further palaeoecological studies of the mere, aiming to go back more than 10,000 years (Jane Reed, University of Hull, *pers. comm*.), may shed further light on the history of cultural and natural eutrophication processes at this site.

2.2.2 Water chemistry

Most of the concerns that have been raised about water quality at Hornsea Mere seem to focus on the very high concentrations of P that have been recorded at this site. Carvalho & Moss (1998), for example, report annual mean TP concentrations in the lake of about 0.36 mg P/L in 1984/1985, with individual values ranging from 0.1 mg P/L to 0.5 mg P/L. The authors compare this unfavourably with a water quality objective of 0.06 mg P/L, concluding that, according to the water quality definitions proposed by OECD (1968), this site would be classified as hypereutrophic. A few years later, Bailey (Planning Liaison Section, National Rivers Authority (NRA), *pers.*

comm.) recorded an average OP concentration of 0.78 mg P/L in the outflow (Stream Dike) between January and December 1995. In general, water quality in the outflow tends to reflect that of the lake from which it flows and is a good indicator of lake water quality where in-lake measurements are unavailable (Carvalho, et al., 2008).

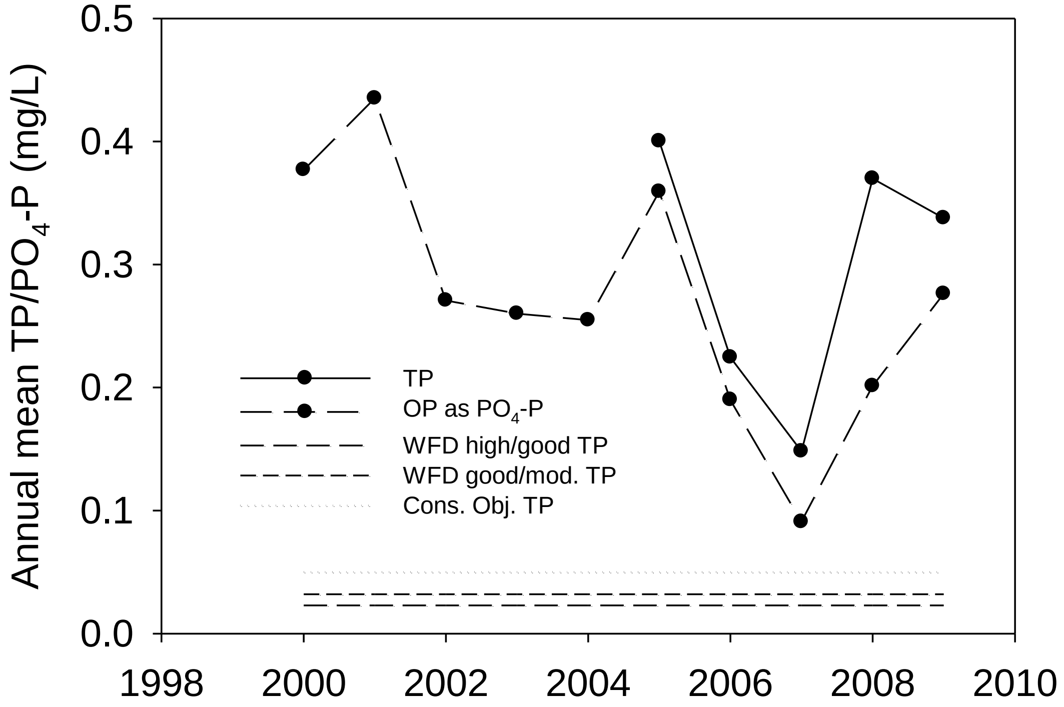


Figure 2.1 **Annual mean total phosphorus (TP) and orthophosphate (OP as PO_4-P) concentrations in Hornsea Mere, 2000 - 2009. Water Framework Directive (WFD) good/moderate and high/good upper boundary values for TP concentrations and the Conservation Objective (Cons. Obj.) target TP concentration for eutrophic lakes are shown.**

A range of Environment Agency (EA) water quality monitoring data collected between 2000 and 2009 was collated for this review. Annual mean TP and OP concentrations estimated from these data are shown in Figure 2.1. In general, OP concentrations declined between 1998 and 2007 and increased from 2007 to 2009. A similar trend is observed in the TP concentration data, although this has only been collected since 2005. It should be noted, however, that the particularly low value in 2007 may relate to heavy rainfall and particularly wet conditions in June 2007 and the subsequent period when there was localized flooding.

OP is the dominant form of P in the mere. As this is the soluble form of P that is usually considered to be bio-available, i.e. available to algae for growth, the very high concentrations regularly recorded at this site suggest that P is not the main factor limiting algal growth here. If it was, these high TP values would be associated with low OP values, because most of the TP would be in algal biomass not dissolved in the water. This situation is in contrast to many assumptions that have been made about how the mere works in the past (e.g. Yates, 2001) and raises questions about the water quality targets for this site, as many standard methods for defining targets make the assumption that lakes are P limited. For example, standard methods used by WFD and Common Standards Monitoring (CSM) for setting TP and chlorophyll *a* targets may not be appropriate for this type of lake because they are based on the assumption that the target lake is P-limited. It is also unclear whether the diatom/TP (DI-TP) transfer function (Bennion et al., 1994), which was used by Johnes et al. (1998) to hindcast in-lake TP concentrations at this site, is applicable to setting water quality targets in this type of lake. These issues require further investigation (Helen Bennion, ECRC University College London, *pers. comm*.). The role of P limitation in Hornsea Mere and the applicability of current water quality targets are also considered later in this report.

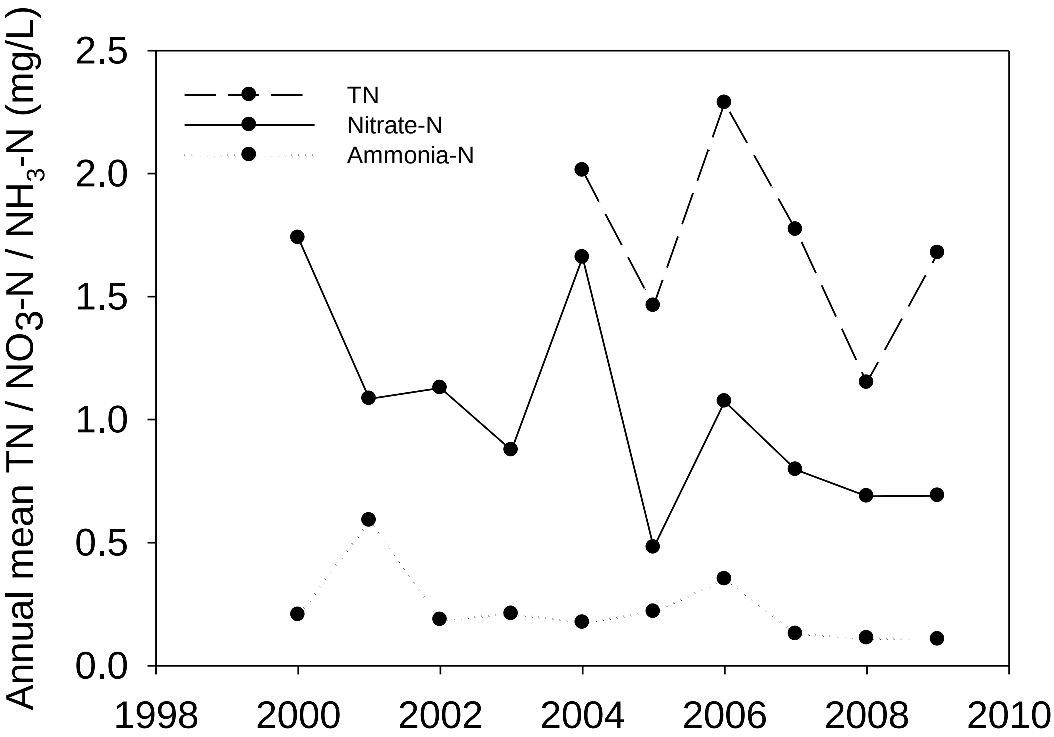


Figure 2.2 Annual total nitrogen (TN), mean nitrate (NO_3-N) and ammonia (NH_3-N) concentrations in Hornsea Mere, 2000 - 2009.

Changes in nitrogen (N) concentrations in the mere have rarely been discussed in any of the water quality documents reviewed. However, N can be a key chemical driver of water quality in some shallow lakes. The possible role of N limitation in determining ecological water quality at this site will be assessed later in this report. In the meantime, an overview of the annual average concentrations of the various nitrogen species in the mere (total nitrogen [TN], nitrate [NO_3-N] and ammonia [NH_3-N]) are summarised in Figure 2.2. In outline, TN and NO_3-N concentrations showed similar trends across the years for which data were available, while NH_3-N concentrations have remained low throughout. There has been a steady decrease in NO_3-N concentrations since 2000, with the exception of 2004 (a “high” year) and 2005 (a “low” year). Overall, and on an annual basis, NO_3-N appears to be the dominant species of nitrogen in the mere.

2.2.3 Algae

When lakes become more nutrient enriched, they become more productive. As a result, algal productivity tends to increase and the water becomes more turbid. This restricts light penetration to under water plants, reducing their distribution and abundance (Scheffer, 1998; Jones et al., 2002). Increased growth of epiphytic algae on underwater plants may also have a similar effect (Phillips et al., 1978; Sand-Jensen, 1990) . In addition, algal communities change to species better able to compete at high nutrient concentrations with some, especially cyanobacteria (blue-green algae), becoming more abundant. Cyanobacteria are of particular concern because they can produce toxins that are hazardous to the health of people, birds, animals and fish. Because these types of algae often contain small gas vacuoles, they tend to accumulate on the surface of the water and are blown into sheltered bays by the wind. This can result in localized "surface scums" that, although very evident to local visitors, may not be reflect the overall water quality in the lake. For this reason, it is important to collect and analyse representative samples from across a waterbody when assessing changes in algal abundance due to eutrophication problems.

An examination of the documentary evidence of increasing algal blooms in Hornsea Mere, especially in relation to frequency and abundance of cyanobacteria, revealed little more than occasional records and anecdotal evidence from which few substantiated conclusions could be drawn. For example, Yates (2001) noted that toxic algal blooms of *Anabaena flos-aquae* and *Aphanizomenon flos-aquae* were found at the outlet of Hornsea Mere by the EA in August 2001, but there is no mention of densities recorded or whether a prevailing westerly wind was concentrating these algae in that particular part of the lake. The only quantitative study of cyanobacterial blooms was undertaken by the EA in 1990, when monthly surveys found *Aphanizomenon* to be present in May and *Anabaena* between June and August (E. Axford, NRA Yorkshire Region, *pers. comm*.). All of these records occurred when NO_3-N levels in the mere were below the detectable limit and OP concentrations were relatively high (Table 2.1). Axford (NRA Yorkshire Region, *pers. comm*.) suggested that the cyanobacteria recorded in the mere in 1990 may have been able to establish populations because they can "fix" N from the atmosphere when P levels in the water are high and N levels are very low, thus out-competing other species of algae. This hypothesis is in agreement with classical phytoplankton community succession hypotheses (Schindler, 1977). However, little is known about the biomass accrual capacity of N-fixing cyanobacteria under N-limited growth conditions.

Table 2.1 Data for Hornsea Mere collected during the monthly cyanobacteria (blue green algae) survey of 1990.

Determinand	Month (1990)					
	May	Jun	Jul	Aug	Sep	Oct
Nitrate concentration (mg/L)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Orthophosphate concentration (mg/L)	0.04	0.12	0.10	0.12	0.52	0.61
Anabaena concentration (colonies/mL)	0	15	22	603	2	0
Aphanizomenon concentration (filaments/mL)	21	0	0	0.5	0	0

An overall measure of the abundance of all phytoplankton species together is the amount of chlorophyll *a* that they contain. This information has been collected for Hornsea Mere as part of an EA routine monthly monitoring programme, albeit at a limited number of sites mainly located close to the outflow. These data have been collated and reviewed in terms of changes in annual mean chlorophyll *a* concentrations between 2004 and 2009 (Figure 2.3). The results suggest that water quality has been improving in recent years, with values moving from moderate water quality, through good water quality into high water quality when considered in relation to WFD water quality targets for lakes of this type.

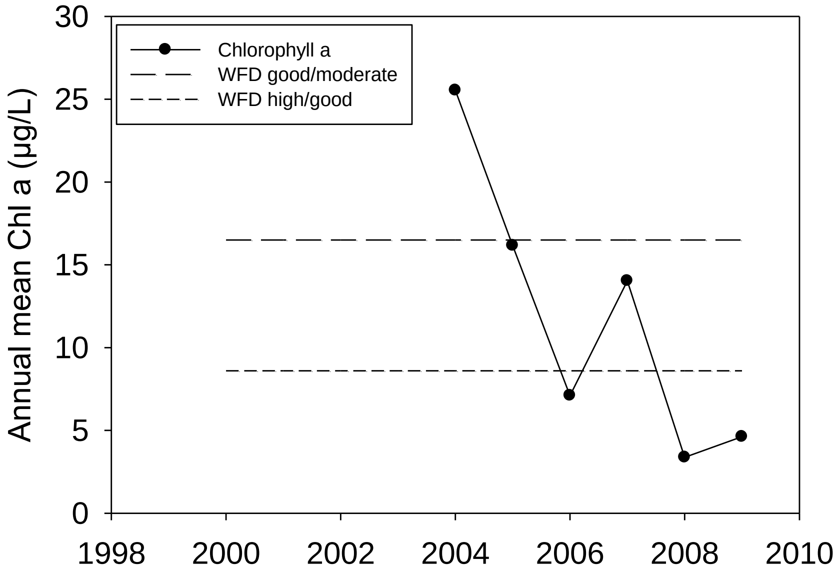


Figure 2.3 Annual mean chlorophyll *a* (Chl a) concentration in Hornsea Mere, 2004 - 2009. The upper broken line represents the good/moderate boundary and the lower broken line the high/good boundary for chlorophyll *a* concentrations in high alkalinity, very shallow lakes in accordance with the WFD.

Although the data suggest that chlorophyll *a* levels (and therefore algal abundance) have decreased in recent years, the reason for this change is unclear from these data alone. Such an effect could result from a decrease in nutrient supply to the water column (e.g. from catchment or sediments) or a change in the ecosystem structure of the lake. If, for example, the number of zooplanktivorous fish (e.g. roach or perch) had decreased over this period, the number of zooplankton feeding on the algae would have increased and the standing crop of algae (chlorophyll *a*) would have fallen because they were being heavily grazed. The overall effect on algal biomass would have been similar to that resulting from decreased productivity resulting from lower nutrient availability. There are insufficient supporting data on the biological components of Hornsea Mere to allow the possible drivers of this change to be explored and identified in detail.

2.2.4 Fish

The status of the fish population in Hornsea Mere, and its impact on the ecology of the waterbody, is unclear, as few surveys have been completed or records kept. The earliest quantitative record of fish stocks appears to be that of Bolam (1913), who documented a catch of 1800 pike in a single year in the late 1800s, but noted that numbers had dwindled to only a few large fish by 1911. The author also comments that roach are “common” and perch “frequent” in the early 1900s, describing the mere as “plentifully stocked with pike, perch, roach and eels”. Although he also suggested stocking with trout as a “good paying investment”, this recommendation does not seem to have been followed up immediately. Instead, stocking with rudd, bream, roach and carp continued into the early 1990s, with about 100 rainbow trout being introduced on a single occasion in the spring of 1988.

In 1993, Fryer (1993) noted that eel and pike were abundant in the mere while conducting a survey of freshwater Crustacea at the site, although no numbers were given. A few years later the importance of having more information on the fish populations of the mere was recognised and, in 1998, the EA fisheries section requested that Hornsea Mere be added to a 3-year rolling programme aimed at assessing the structure and health of fish in standing waters (Caroline Essery, EA, *pers. comm*.). There is, however, no evidence that this proposal was ever implemented. Two individual fish surveys were, however, subsequently undertaken by Harvey (2000) in late 1998 and early 1999 who reported that the resultant fish catches were generally low and comprised a small number of roach and bream. The exception to this was a relatively large number of perch and roach caught beneath the boating pontoon at the eastern end of the mere where, it was suggested, they were probably seeking refuge from predatory birds such as cormorants. From the limited information collected, Harvey (2000) concluded from his study that the fish in the mere were generally fast growing, indicating that there was no shortage of food available to them. Harvey (2000) goes on to recommend that better information on the condition of fish stocks and the quality and location of spawning areas should be collected in future. He also suggests that better records should be kept of angling catches and fishing effort. Finally, he proposes that better information on food availability is gathered through the measurement of primary and secondary productivity within the mere to identify bottle necks that may influence fish dynamics. While this is essentially true, it should be noted that the data that Harvey (2000) suggests collecting (e.g. chlorophyll *a* concentrations and invertebrate densities) will provide only a measure of standing crop (i.e. abundance), not productivity (i.e. population growth/turnover) as such.

Finally, Alan Mullinger (Fisheries Management Officer, EA, *pers. comm*.) notes that, in 2000, cyanobacteria were abundant in the mere for a long period of time and that this may have caused low numbers of fish deaths. He then goes on to request a discussion with Natural England (NE) over the installation of brushwood ‘reefs’ to improve fish habitat because “the clear water of the Mere offers little or no cover to fish”. Mullinger (*pers. comm*.) also comments that fish caught in 2000 were mainly “very thin emaciated pike” which, according to the University of Hull International Fisheries Institute (HIFI), indicated heavy predation on the population by fish eating birds.

The impact of the management of this fishery on water quality and the ecology of the lake is unclear. However, Carvalho & Moss (1998) suggested that the introduction of bream and carp to the lake may have exacerbated any nutrient enrichment problems. This is because these species disturb the lake sediments while feeding, which may increase the turbidity of the water causing a corresponding increase in internal nutrient cycling.

2.2.5 Water level

The water level of the mere may be an important consideration in relation to its response to eutrophication pressures because water level affects flushing rate, a key driver of P relinquishment following changes in catchment management (Bailey-Watts, 1992). This is because, in simple terms, lakes that flush more quickly are less likely to develop algal blooms than those that flush more slowly. Historical records suggest that, although Hornsea Mere was much larger and deeper in the 1600s than it is now (Stephenson, 1848; Popham, 2000), and was reportedly (16 feet) deep at the end of the 18^{th} century (Jane Reed, University of Hull, *pers. comm*.). By the early 1800s the water level had fallen to a level that is close to that of today. As the water level has changed very little since then, it is unlikely that any of the changes in nutrient concentrations that have been observed over the last few years have occurred as a result of variations in annual flushing rate.

The mere has a single outflow that discharges eastwards into the sea. In terms of current water level management, the volume of water that discharges into the outflow is controlled by a sluice gate located at NGR TA200472. This is operated by Yorkshire Water according to an agreement that was reached between Hornsea Urban District Council (HUDC) and the Strickland Constable Estate in 1969, when HUDC were planning to build a surface water sewer that would discharge into the mere. The agreement states that the level of the mere should be maintained at an average of 12 feet (about 3.7 m) above sea level under normal conditions. Although originally controlled manually, the level of the mere is now controlled by an electric penstock on the outflow that was installed in 1979. This is operated by Yorkshire Water. In terms of its impact on water quality, it is possible that the management regime that is now in force may have resulted in flushing rates being reduced sufficiently to prevent P being flushed from the mere into the outflow during critical periods in summer when concentrations are high. If so, this will have resulted in an internal accumulation of P in the sediments that may have significantly slowed recovery times.

Concerns have been raised about the mere silting up and the possible effect of this on the water level. These concerns are unfounded because, although silting up will affect the depth of the mere, it is unlikely to affect the water level because this is regulated by the height of the sluice, which is generally operated like an overflow to maintain a particular level. That said, when heavy rainfall and high tides coincide, the outflow, Stream Dike, cannot discharge to the sea and flooding may occur. It has been suggested that the water level should be dropped below 3.7 m.a.o.d. in winter to increase storage capacity during heavy rainfall events and reduce downstream flooding, but there are concerns about the impact that this would have on the conservation interest and on the amenity value of the mere. A Water Level Management Plan is required; such plans aim to “provide a means by which the water level requirements for a range of activities …, including agriculture, flood defence and conservation, can be balanced and integrated” by taking into account all stakeholder interests.

The relationship between groundwater movement and the hydrology of the mere and its associated inflows/outflow is unclear. Initial results from a drift mapping project being undertaken for the EA by the British Geological Survey suggest that the mere is effectively sitting in a bowl of alluvium over gravel beneath which is a layer of sand and gravel, then clayey till, then the chalk. The layer of clay undulates between the mere and the coast and it is believed that this could influence water movement, with the different layers slowing down or speeding up groundwater movement at different rates. It is hoped that the project will provide further insight into the impact of groundwater movement on the hydrology of the mere as work progresses (Helen Sharp, EA, *pers. comm*.).

2.3 Catchment considerations

The nutrients in a lake are derived from the catchment, roosting birds and rain falling directly onto the surface of the lake. The level of the nutrient supply from external sources (the ‘input’ or ‘load’) affects the water quality of the lake, with higher nutrient inputs being more likely to cause eutrophication problems such as an increase in toxin producing algae and a decrease in underwater plants. These effects may pose a health hazard to people, animals and fish, and reduce the amenity value of the lake in terms of conservation, recreation and, in some cases, water supply. Where water quality has become degraded by excessive nutrient inputs, restoration measures need to identify and address the main sources of the problem within the catchment, first, before considering in-lake restoration measures. This is because the success of in-lake restoration measures may be short-lived if high levels of nutrients continue to enter the lake from external sources. Even when catchment measures are effective at reducing external inputs, however, internal recycling of nutrients that have accumulated in the sediments over time may delay the subsequent recovery of the system for many years.

Hornsea Mere is fed by a large number, probably about 15, streams and drains that carry nutrients from the catchment into the lake (Hornsea catchment drainage survey, East Riding of Yorkshire Council). The three largest of these are Foss Dike, Springfield Wood Drain and Low Wood Drain. A large pipe near Cheyne walk (built in the 1980s on the north side of the mere) also channels runoff from urban areas into the lake; in addition this pipe is also believed to carry some grey water from washing machines that have been plumbed incorrectly upstream of this point (Bedworth et al., 2005). This supposition is supported by casual observations that water in this drain sometimes develops “soap-like” foam on the surface (McLachlan, *pers. comm*.). There is also evidence that this discharge has at least a local impact on water quality within the mere, with diatom assemblages around the outlet indicative of relatively high P loads entering the mere at this point (Yates, 2001).

Nutrient concentrations and loads in the inflows to the mere have rarely been measured and any studies that have been carried out in the past have focused on the three or four main inflows, only. These, together, probably drain about 70% of the catchment. The limited data that have been collected clearly show that the P concentrations in these streams, which drain intensively farmed agricultural land, allotments and a golf course, and receive inputs from many small point sources such as septic tanks and small sewage treatment plants, are exceptionally high. This is in spite of the fact that some of these problems, such as effluent from a piggery draining into Croftings Dike, have been resolved (Carvalho & Moss, 1998).

In 1990, Axford (NRA Yorkshire Region, *pers. comm*.) surveyed the biological and chemical water quality of two of the inflows, Foss Dike and Decoy stream. Axford (NRA Yorkshire Region, *pers. comm*.) found the biological quality of both streams to be poor. Alongside the biological survey, Axford (NRA Yorkshire Region, *pers. comm*.) recorded OP levels of 1.47 mg P/L in Foss Dike and 1.67 mg P/L in Decoy stream on the day of sampling (16/10/90), noting that discharges from septic tanks were a potential problem at Foss Dike. Five years later, Bailey (Planning Liaison Section, NRA, *pers. comm*.) reported the results of a ‘prevention of pollution’ survey at the mere that was carried out between July and November 1995. This recorded average OP concentrations of 0.47 mg P/L in Foss Dike at Lelley Bridge and 0.26 mg P/L in Low Wood Drain. In 1998, it was recommended that better monitoring of inflows and the outflow at monthly intervals was needed and that all small point sources within the catchment should be located and assessed (Caroline Essery, EA, *pers. comm*.). This recommendation was followed up, at least in part, in 2002/2003 when monthly measurements of nutrient concentrations in the main inflows (i.e. Foss Dike, Springfield Drain and Low Wood Drain) were undertaken and the possible impacts of *consented* point source discharges on water quality were assessed during the Habitats Directive Review of Consents (RoC) process. At Stage 3 of the RoC process, it was concluded that, on the basis of modelling evidence alone, that the small number of consented discharges identified had no adverse effect on the 'sole European interest feature at the mere', i.e. the Gadwall, either directly or through their impact on water quality at the site. This only, however, assessed the impact to features for which the Special Protected Area (SPA) was designated (the bird assemblage), rather than the lake habitat itself which is a SSSI feature. It should also be noted that there are probably about 700 people living within the catchment of the mere (Johnes, et al., 1998), which does not include the town of Hornsea as this is downstream of the mere. Assuming that there is an average of 2.3 people living in each household, this suggests that about 300 unconsented discharges from septic tanks in this area that were not taken into account during the RoC process. The value of 2.3 was estimated by dividing the number of residents in Hornsea Urban Area by the number of households using the 2001 Census summary data which is available at http://www.eastriding.gov.uk/corp-docs/researchgroup/Reports/HornseaUAP.pdf.

Table 2.2 Summary results from the water quality survey conducted by the EA in 2002/2003 (after Bedworth et al., 2005).

Inflow	Mean OP conc. (mg L^{-1})	Mean flow (cumecs)	OP Load to mere	
			(kg d^{-1})	(t y^{-1})
Foss Dyke	0.807	0.038	2.65	0.97
Springfield Drain	0.272	0.043	1.01	0.37
Low Wood Drain	0.247	0.051	1.09	0.40
Total			4.75	1.74

The results from the 2002/2003 water quality survey comprised monthly water chemistry measurements on the three main inflows (Foss Dike, Springfield Drain and Low Wood Drain) and on the outflow (Stream Dike). However, corresponding measurements of flow were made "only when flows permitted", which resulted in measurements on only six occasions. The meaning of this statement is unclear. The resulting data were analysed in relation to nutrient loads to the lake by Bedworth et al. (2005). It should be noted, however, that such infrequent sampling of stream discharges makes it very difficult to convert monthly in-stream nutrient concentrations to annual loads to the mere. Given the limited data available, the authors concluded that about 1.74 t P y^{-1} was entering the mere from these sources. They also found that average P concentration in Foss Dike (mean = 0.8 mg P/L) was especially high in comparison to Springfield Drain (0.27 mg P/L) and Low Wood Drain (0.25 mg P/L). Bedworth et al. (2005) estimated that Foss Dike delivered about 0.97 t P y^{-1} to the mere, while Springfield Drain and Low Wood Drain each delivered about 0.4 t P y^{-1}. These results are summarised in Table 2.2. The authors also suggested that P losses from the outflow amounted to about 36.12 kg P d^{-1}, or 13.18 t P y^{-1}. However, this value seems to be the result of an arithmetical error, with the actual discharge based on these figures being about 13.4 kg P d^{-1}, or 4.9 t P y^{-1}, an error that was corrected in the final version of the EA's Appropriate Assessment (Final Appendix 21) for Hornsea Mere Special Protection Area, which forms part of the Habitats Directive RoC for 2005 (Liz Chalk, EA, *pers. comm*.). Bedworth et al. (2005) also calculated that the P input to the mere from birds was less than 0.464 kg P d^{-1} (0.17 t P y^{-1}) and that from consented discharges was about 0.15 kg d^{-1} (0.06 t P y^{-1}). The total P load to the mere from these sources was estimated to amounted to 1.96 t y^{-1}, a value that is very similar to that derived using an export coefficient approach by Johnes et al. (1998), i.e. 2.3 t y^{-1}. Although at first sight, these values suggest that Hornsea Mere is in recovery (i.e. the amount of P entering the system, 1.96 t P y^{-1}, is less than that leaving *via* the outflow, 4.9 t P y^{-1}, there is too much uncertainty in these values for this conclusion to be drawn.

Bedworth et al. (2005) also used the equation of Vollenweider (OECD, 1982) to estimate the "maximum permissible" P load to the mere that would result in a target in-lake annual average P concentration of about 0.1 mg P/L being met. They concluded that this value was about 396 mg P m^{-2} y^{-1}. However, there appears to be a mathematical error in the calculations as documented in the report (see Equation 2) and, using the values given, we believe the correct result from this calculation to be somewhat lower, i.e. about 276 mg P m^{-2} y^{-1}.

In 2002, a survey was undertaken to evaluate diffuse pollution problems within the catchment (Phillips, 2002). This comprised visits to 12 farms and the development of nutrient budgets for nine of these, based on information provided by the farmers. The report concluded that farmers within the catchment demonstrated good agricultural practice with, for example, many earlier problems associated with nutrient leaching from stored manures already having been addressed. However, it was noted that ploughing of arable land could result in soil erosion under heavy rainfall conditions and subsequent sediment delivery to the mere in some areas. This is consistent with the observations of Bennion et al. (2009) who, when sampling the mere on 21/1/08, found the water very turbid after recent heavy rainfall and those of the present study, which recorded a noticeable influx of sediment to the mere from the Low Wood Drain under high flow conditions on 1/12/09 (see Section 5.2). Phillips (2002) also concluded that the nutrient budgets for each farm indicated that there was no major problem in relation to P losses from farmland, as the annual P surplus on each farm was less than 20 kg ha^{-1}. It should be noted, however, that if this level of loss is converted to a runoff concentration by dividing it by the volume of rainfall that runs off each hectare of land in this area (i.e. about 2.55×10^3 m^3 y^{-1}), these values suggest that runoff concentrations of about 6 mg P/L could be produced from this source, a concentration that is only slightly lower than that of treated sewage effluent. Although the P surplus seems relatively small compared to the amount of P used on each farm, it is always important to remember that a small loss to land can be a big gain to water, potentially causing serious ecological problems downstream.

Further evidence of occasional but serious water quality problems in the inflows to the mere is provided by the fish kill that occurred in Low Wood Drain in 1998. It is estimated that about 10,000 fish died suddenly, here, as a result of a pollution incident in the drain, but the exact cause of this problem was never identified (Environment Protection Willerby, 1998) Although there was some evidence of a degradation in biological water quality in the drainage water downstream of an emergency overflow from the Seaton sewage pumping station, this was not thought to be sufficient to have caused such a massive fish kill and there was no evidence that pollution from the storm overflow from this site or a septic tank upstream of this location had caused this problem (Bond, 1999).

2.4 Previous management recommendations

There is considerable documentary evidence of water quality problems within Hornsea Mere and the inflows that drain into it. Diffuse pollution from agricultural sources has been, and is currently being, addressed through various means including an ADAS farm pollution prevention campaign in North Holderness (Caroline Essery, EA, *pers. comm*.), the use of agri-environment schemes such as, Wildlife Enhancement Scheme, Countryside Stewardship Scheme and more recently Higher Level Stewardship and Entry Level Stewardship, together with the introduction of a Catchment Sensitive Farming project (Bennion, et al., 2009) and the recent declaration of this area as a nitrate vulnerable zone (NVZ). However, diffuse pollution from about 300 small discharges of sewage effluent (e.g. from septic tanks) across the catchment has received little attention, with the exception of the evaluation of potential discharges from the six consented small discharges as part of the RoC process.

Carvalho & Moss (1998) suggested that some of Hornsea Mere's eutrophication problem might be solved by fish manipulation (i.e. removal of carp & bream). This was because these introduced species could be disturbing the sediments when feeding, increasing the turbidity of the water and promoting the release of nutrients from the sediments. However, in the absence of any reliable information on fish stocks, it is difficult assess the likely size or extent of this problem. In addition, occasional observations suggest that at least some of the mere's turbidity problems may be caused by sediment delivery from the catchment (Bennion et al., 2009; Section 5.2), indicating that changes in farming practice, such as the introduction of buffer zones or changes in ploughing activities, within the catchment might better resolve this problem (Phillips, 2002).

Many authors have commented that chlorophyll *a* concentrations in the mere are remarkably low given the very high summer concentrations of OP that have been recorded in the open water. Various explanations have been suggested, such as high zooplankton grazing rates (Beddell, 2002) or light limitation due to high turbidity (Bedworth et al., 2005), possibly related to the disturbance of sediments by bottom feeding fish (Carvalho & Moss, 1998) or wind induced mixing. Analysis of the existing data has led the current authors to conclude that N-limitation is more likely to be the most important factor keeping observed chlorophyll *a* concentrations low. The evidence for this is outlined below (see Section 5.1) and the consequences for future management of Hornsea Mere and its eutrophication problems are discussed in Section 6.

3 Overview of data sources

3.1 Temporal data

Rainfall data for the period 2000 to 2008 were provided by the EA. These data comprised daily rainfall values (mm) from a tipping bucket rain gauge located at Great Culvert (TA 145 554), about 6 km north of the mere.

Monthly bird counts for the period 2003 to 2007 were provided by the British Trust for Ornithology. These data gave information on 73 species that had been recorded at the site over this period. Of these, only 17 species had an average annual population density of more than 20 birds per day. The remainder were mainly occasional visitors whose P input to the lake would probably be small. So, these were excluded from the P loading calculations.

Water chemistry and flow monitoring data for the period 2000 to 2009 for the mere, its inflows and outflow were provided by the EA. The EA sampling points are shown in Figure 3.1.

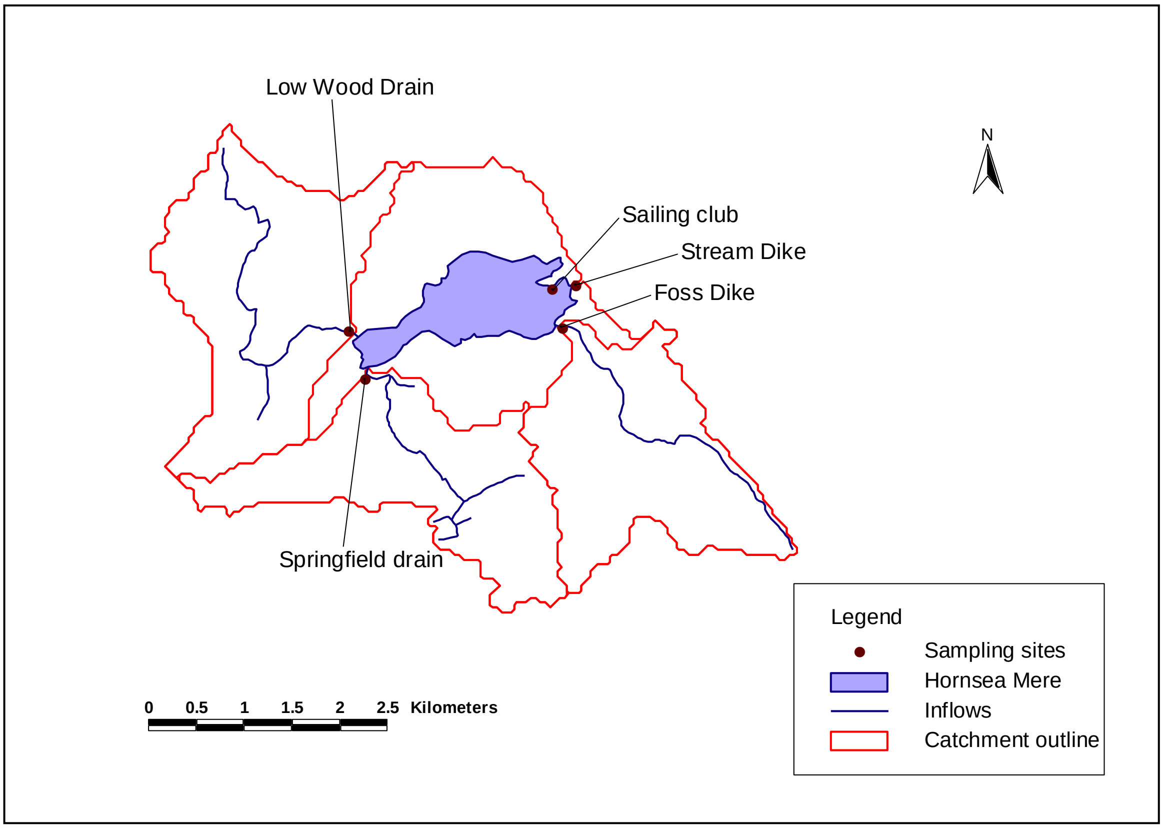


Figure 3.1 Catchment of Hornsea Mere showing inflows and EA water quality sampling points.

3.2 Spatial data

Inflow and lake shoreline data were from OS 1:50,000 resolution map data provided under licence by CEH.

The catchment boundary was derived from a 5 m resolution digital terrain model (DTM), reflecting the land surface draining to the outflow (Stream Dike). Subcatchments for the main inflows were derived similarly and defined to be the surface water catchments that drained to their confluence with the lake. Catchment and subcatchment outflow points are shown in Table 3.1 and Figure 3.1.

The land cover data comprised Level 2 vector data from the digital Land Cover Map of Great Britain 2000 (LCM2000). LCM2000 is derived from a computer classification of satellite scenes, obtained mainly from Landsat satellites. LCM2000 is a vector database that is registered to the Ordnance Survey grid reference system and shows areas of land as 'parcels' or polygons. Each land parcel has an associated list of attributes that includes land cover class, parcel area, length of boundary, processing history, knowledge-based correction and identification of the original satellite scene. More detailed information on this dataset can be found at (http://www.ceh.ac.uk/sci_programmes/BioGeoChem/LandCoverMap2000.html).

Information on the location and size of consented discharges within the catchment was provided by the EA.

Table 3.1 Outflow points and upstream areas of the catchments and subcatchments draining to Hornsea Mere.

Catchment/subcatchment	Outflow location	Area (km^2)
Foss Dike	TA 19900 46700	4.23
Springfield drain	TA 17870 46300	4.13
Low Wood Drain	TA 17600 46700	5.09
Hornsea Mere catchment to outflow (Stream Dike)	TA 20000 47200	18.85

4 Methods

4.1 Assessment of seasonal variation in water quality

Variation in average monthly values of key water quality variables was assessed in Hornsea Mere (1) to determine seasonal and long-term changes in water quality in relation to water quality targets and (2) to develop our understanding of the key processes that drive these changes.

Where appropriate (i.e. for TP and chlorophyll *a* concentrations), changes in water quality variables were compared to WFD targets for high alkalinity, very shallow lakes and Common Standards Monitoring (CSM) targets for naturally eutrophic lakes. All water quality data used for this assessment correspond to EA sampling site 4900082 (Hornsea Mere at the Sailing Club). All water quality values were determined by the EA using standard analytical methods.

Monthly average TP, PO_4-P, NO_3-N, NH_3-N, TN, SiO_2, chlorophyll *a*, suspended sediments and dissolved oxygen concentrations were derived from data provided by the EA (see Section 3.1). The temporal resolution of the data supplied is given in Table 4.1.

Table 4.1 Number of values included in annual and monthly averages for EA water quality data, where TP = total phosphorus; PO_4-P = orthophosphate; TN = total nitrogen; NO_3-N = nitrate-nitrogen; NH_3-N = ammonia-nitrogen; SiO_2 = silicate; Chl a = chlorophyll *a*; SS = suspended solids; DO = dissolved oxygen.

	TP	PO_4-P	TN	NO_3-N	NH_3-N	SiO_2	Chl a	SS	DO
Year									
2000		12		12	12		12	12	
2001		7		7	7		7	7	
2002		12		12	12		12	12	
2003		12		12	12		12	12	
2004		11	7	11	11		11	11	
2005	11	12	11	12	12		12	12	
2006	10	12	11	12	12		12	12	
2007	7	12	8	12	12		9	12	
2008	8	12	8	12	12		8	12	
2009	9	9	9	9	9		9	9	
Month									
Jan	3	7	2	7	7	1	6	7	7
Feb	2	9	4	9	9	2	8	9	9
March	6	13	6	13	13	3	12	13	13
Apr	4	9	4	9	9	2	8	9	9
May		5	1	5	5	1	5	5	5
Jun	8	12	8	12	12	3	12	12	12
Jul	5	9	7	9	9	3	9	9	9
Aug	3	7	3	7	7	1	7	7	7
Sep	5	10	6	10	10	3	10	10	10
Oct	5	12	7	12	12	4	11	12	12
Nov	2	12	3	12	12	3	11	12	12
Dec	2	6	3	6	6	3	5	6	6

4.2 Estimation of external P loads and sources

4.2.1 Export coefficient modelling

An initial examination of the catchment and location of Hornsea Mere suggested that the main external sources of P inputs were probably runoff from land, domestic waste, rainfall and roosting birds. Although groundwater may also be a source or sink of P, there was insufficient data available for this to be investigated. The inputs (loads) from the remaining sources were estimated using an export coefficient approach; this is based on P inputs to the lake *per* unit area of land for runoff or *per capita* for inputs from human and bird excreta.

4.2.1.1 Inputs from runoff

In order to estimate the TP input to the mere from surface runoff, the catchment draining to the lake was defined using a 50m resolution digital terrain model and this was subdivided into three subcatchments draining to the main inflows, i.e. Foss Dike, Springfield Stream and Low Wood Drain (Figure 5.10). The areal extent (A_i, hectares) of each land cover type (*i*, 1 to n) within these areas was then determined from land cover data provided by CEH (see Section 3.2). Each areal value was then multiplied by a corresponding nutrient export coefficient (E_i, kg ha^{-1}y^{-1}) obtained from the literature to give an estimated annual nutrient loss from each land-cover type to water. Finally, these individual loss rates were summed to give the predicted annual load to the lake from runoff over the whole surface-water catchment ($Load_{runoff}$), as follows:

$$Load_{runoff} = \sum_{i=1}^{n} (A_i \times E_i)$$

The TP export coefficients used in these calculations are shown in Table 4.2.

Table 4.2 Land-cover types in the surface-water catchment of Hornsea Mere and their associated annual total phosphorus (TP) export coefficients.

Land-cover type	TP export coefficient (kg ha^{-1}y^{-1})	Reference
Improved grassland	0.38	May et al. (1996)
Unimproved grassland	0.07	Cooke & Williams (1973)
Dwarf shrub heath	0.1	Harper & Stewart (1987)
Broad leaved/mixed	0.15	Dillon & Kirchner (1975)
Coniferous forest	0.15	May et al. (1996)
Arable/bare ground	0.25	Cooke & Williams (1973)
Urban/rural development (runoff only)	0.83	Bailey-Watts et al. (1987)
Fen, marsh, swamp	0.01	This study

4.2.1.2 Inputs from sewage

Nutrient inputs from waste water treatment works discharging to drainage channels within the catchment could not be calculated due to lack of data. Also, the number of septic tanks within the catchment was unknown. So, inputs from sewage related sources ($Load_{sewage}$) were calculated from the estimated number of people living in the catchment (i.e. about 700, after Johnes et al., 1998), making the assumption that all of these were living in properties served by septic tanks. The likely *per capita* P export from these systems was estimated using the method described by May et al. (2010). In outline, this value is calculated as the average *per capita* volume of water used each day within the UK (i.e. 150 litres – www.defra.gov.uk) multiplied by the most commonly reported concentration of P in septic tank effluent (i.e. about 10 mg/L). This equates to an annual *per capita* P export from each tank of about 0.54 kg y^{-1}.

4.2.1.3 Inputs from rainfall

The external P input from rain falling directly onto the surface of the lake was calculated from the mean annual rainfall for the area and the estimated P concentration in freshly fallen rain, i.e. 0.2 kg m^{-3} (Bailey-Watts & Kirika, 1991). The size of this input ($Load_{rain}$) was then estimated as:

$$Load_{rain} = R \times A_{lake} \times P_{conc}$$

where R is the mean annual rainfall (m), A_{lake} is the surface area of the lake (m^2) and P_{conc} is the concentration of P in fresh rainwater (kg m^{-3}).

4.2.1.4 Inputs from birds

Of the 17 dominant bird species recorded at Hornsea Mere, only 7 species (Table 4.3) were considered to import P from feeding grounds beyond the lake, such as the surrounding catchment (e.g. geese, swans) and the sea (e.g. cormorants, gulls). The remainder were judged more likely to feed within the lake itself (Maria Bogdanova, CEH, *pers. comm.*), which would recycle nutrients within the system. The exception to this was the mute swan, which was judged to feed both in the lake and in the catchment.

Per capita P loss coefficients were gathered from the published literature for each of the 7 bird species listed in Table 4.3. For the purposes of the present study, the published coefficient for swans was reduced by 50% to reflect its bimodal feeding activity.

These coefficients were used to estimate the P input to the mere from birds ($Load_{bird}$, kg y^{-1}), as follows:

$$Load_{bird} = \sum_{=1}^{n} \left(N_{bird_i} \times E_{bird_i} \times 365 \right)$$

where:

i = the i th species of bird that contributes P to the lake

N_{birdi} = the average number of the i th bird species on the mere each day

E_{birdi} = the daily *per capita* P input to the lake from the i th bird species

Table 4.3 Most important bird species in terms of P input to the lake and their estimated daily *per capita* P loss.

Bird species	Estimated P input to mere (g/*capita*/d)	Reference
Barnacle goose	0.211	Hancock, 1982
Canada goose	0.211	Hancock, 1982
Cormorant	2.6	Hahn et al., 2007
Greylag goose	0.211	Hancock, 1982
Little gull	0.15	Hahn et al., 2007
Mute swan	0.23 x 50%	Mitchell & Wass, 1994

4.2.1.5 Inputs from other sources

Insufficient information was available to estimate nutrient inputs from other sources ($Load_{other}$), such as fish stocking e*tc*. So, this input was assumed to be negligible.

4.2.1.6 Total external load

The total external TP load to the lake ($Load_{total}$, kg y^{-1}) was calculated as the sum of the individual loads estimated above, i.e.

$$Load_{total} = Load_{runoff} + Load_{sewage} + Load_{rain} + Load_{bird} + Load_{other}$$

4.2.2 Spatial survey of P source 'hotspots'

A spatial survey of OP concentrations in drains and streams across the catchment was undertaken between 12/10/09 and 10/12/09 to identify OP source 'hotspots' (Grant Robinson, University of Hull, *pers. comm*.). In total, 26 sites were visited over the period of study (i.e. 6 sites on 12/10/09; 1 site on 26/10/09; 5 sites on 9/11/09; 2 sites on 19/11/09; 3 sites on 23/11/09; 9 sites on 10/12/09). The locations of the sampling sites are shown in Table 4.4 and Figure 4.1. Orthophosphate determinations were performed by the EA, using Method A of the Standing Committee of Analysts (1981).

Table 4.4 Sampling sites visited during the spatial survey of P source 'hotspots'

Site description	Distance upstream of mere (km)	Date	Location
Adjacent Springs Close	2.92	12-Oct-09	TA 16739 47626
Adjacent Common Farm	2.43	12-Oct-09	TA 16561 47097
B @ Stone Bridge	1.8	12-Oct-09	TA 16680 46692
Croftings Drain adjacent Low Wood	0.78	12-Oct-09	TA 17124 46638
Low Wood Drain	0.74	12-Oct-09	TA 17122 46670
Field Drain adj Snipe Grounds		26-Oct-09	TA 18700 46400
Lelley Bridge	0.09	09-Nov-09	TA 19900 46800
Trib utary@ Hornsea Freeport	0.8	09-Nov-09	TA 20400 46300
Trib utary@ Strawberry Gardens	1.06	09-Nov-09	TA 20600 46100
Trib utary@ Golf Course	1.5	09-Nov-09	TA 20500 45500
Willow Garth Drain	2.56	09-Nov-09	TA 21500 45500
Field Drain		19-Nov-09	TA 20600 45500
Field Drain		19-Nov-09	TA 20200 44700
B1244 Junction		23-Nov-09	TA 18800 47600
Hornsea Mere		23-Nov-09	TA 19400 47500
Foss Dyke @ Lelley Bridge	0.09	10-Dec-09	TA 19900 46600
Foss Dyke @ Freeport	0.8	10-Dec-09	TA 20400 46400
Foss Dyke @ Strawberry Gardens	1.06	10-Dec-09	TA 20500 46100
Adjacent Willow Garth	2.56	10-Dec-09	TA 21300 45600
Junction adjacent Springs Close	2.92	10-Dec-09	TA 16600 47500
Adjacent Common Farm	2.43	10-Dec-09	TA 16500 47200
Stream Dyke @ Stone Bridge	1.8	10-Dec-09	TA 16500 46700
Low Wood Drain	0.74	10-Dec-09	TA 17200 46600
Low Wood @ Bridge		10-Dec-09	TA 17400 46800

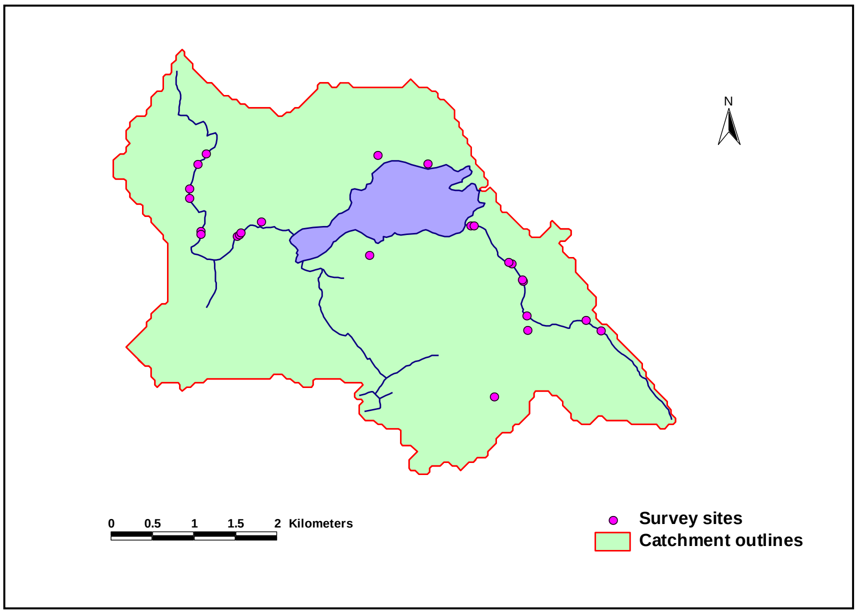


Figure 4.1 **Sites sampled during the survey of drainage water 'hotspots' with high OP concentrations across the catchment of Hornsea Mere, 12/10/09 to 10/12/09.**

4.3 Estimating in-lake P concentrations, loads and sources

4.3.1 Total phosphorus

To examine spatial variation in water quality across the mere, water samples were collected from 43 locations (Figure 4.2) on 1/12/09 and analysed to determine their TP content. The samples were chilled (4^{o}C) on return to the laboratory and TP concentrations were determined using a sulphuric acid-potassium persulphate digestion on unfiltered samples, followed by colorimetric analysis based on the molybdenum-blue method described by Wetzel and Likens (2000).

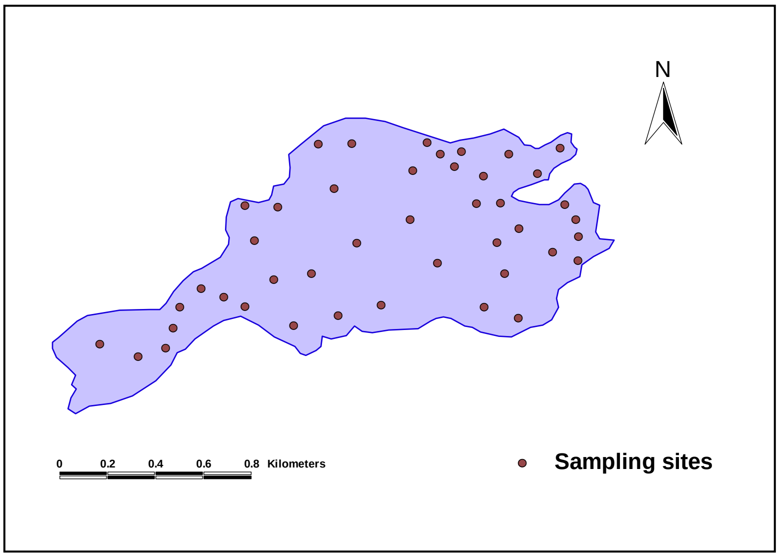


Figure 4.2 **Location of 43 sites sampled across the mere for TP analyses on 1/12/09.**

4.3.2 Sediment-P pools

Spatial variation in sediment pools of P were determined from single sediment cores collected from 9 open water sites (Figure 4.3; Table 4.5) on 1/12/09, using a Pylonex HTH gravity corer (Pylonex Termokonsult, Sweden). Water overlying the sediment surface was carefully siphoned off and the upper 3 cm of the sediment itself was collected in a polythene bag. Each sample was homogenised, chilled and stored at 4^{o}C on return to the laboratory. Subsamples of the stored sediment were retained for subsequent analysis of water content and pore water soluble reactive P (SRP; as PO_4-P), total soluble P (TSP) and releasable sediment P, and total sediment P concentrations.

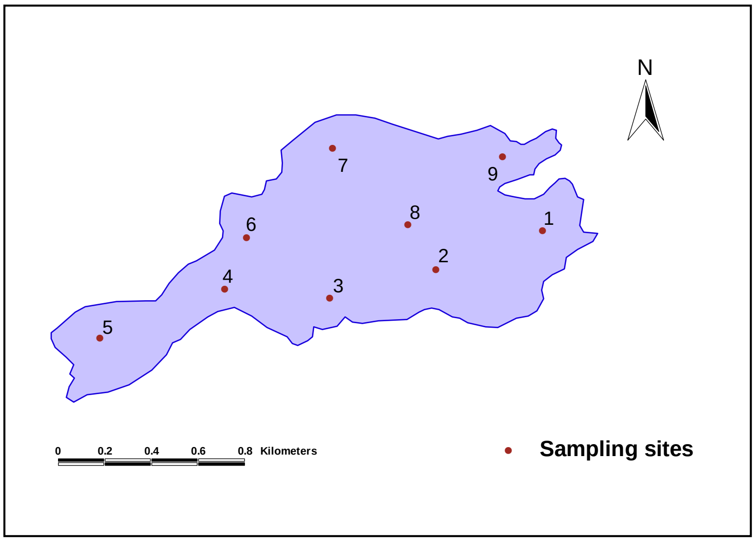


Figure 4.3 **Location of 9 open water sediment coring sites sampled across the mere on 1/12/09.**

For the analysis of sediment water content, subsamples (5 g wet weight) of sediment were weighed into pre-weighed aluminium trays and oven dried at 40°C for 24 hours. The trays and dried sediment were then re-weighed, placed back into the oven for 1 hour and then weighed again. Constant weights returned at 24 and 25 hours of drying indicated that the drying process was complete.

Pore water was separated from bulk sediment by pouring sediment subsamples (20 g wet weight) into tubes and centrifuging them at 3,800 revolutions per minute for 5 minutes. The supernatants were then filtered (Whatman® GF/C grade filter) and analysed for pore water SRP and TSP content. TSP analyses were conducted as outlined in Section 4.3.1 for TP, while SRP analyses were conducted in the same way but without the acid-persulphate digestion stage.

Table 4.5. Supporting data from sediment coring sites, 1/12/09.Con. = conductivity; DO = dissolved oxygen; Temp = water temperature; '>' followed by lake depth in metres = Secchi disk visible on lake bed.

Site no.	Latitude (Degrees)	Longitude (Degrees)	Depth (m)	pH	Con. (µs/cm)	DO (mg/L)	Temp (°C)	Secchi depth (m)
1	-0.17719	53.90569	2.20	7.81	0.494	13.00	4.37	2.00
2	-0.18417	53.90428	2.30	7.91	0.491	13.53	4.50	1.90
3	-0.19139	53.90361	1.60	7.91	0.492	12.64	4.45	1.63
4	-0.19797	53.90375	1.30	7.90	0.493	13.60	4.41	1.45
5	-0.20617	53.90200	1.30	7.36	0.588	8.69	5.10	0.40
6	-0.19644	53.90572	1.40	7.90	0.495	12.22	4.30	> 1.4
7	-0.19069	53.90908	1.60	7.95	0.494	12.36	4.43	> 1.6
8	-0.18594	53.90606	2.00	7.98	0.493	12.39	4.52	2.00
9	-0.17967	53.90858	1.40	7.96	0.494	12.34	4.28	> 1.4

Duplicate subsamples of sediment (1 g wet weight) were weighed into 50 ml capacity centrifuge tubes prior to sequential extraction of sediment P pools, following the procedure outlined below (after Hupfer et al., 1995). A modified extraction procedure was used, as follows: two sub-samples of homogenised sediment from each site were subject to (1) extraction in 1 M NH_4Cl for 30 minutes [repeated for 5 minutes] after which TSP was quantified on the filtered supernatant [labile P]; (2) extraction with 0.11 M $NaHCO_3$/0.11 M $Na_2S_2O_4$ for 1 h [repeated for 5 minutes] after which TSP was quantified on the filtered supernatant [reductant-soluble P]; (3) digestion with 30% v/v H_2SO_4 and 8% $K_2S_2O_4$ at 121°C for 30 minutes followed by the analysis of TSP on the filtered supernatant (metal-bound/organic/residual ("remaining") P). Sediment TP was estimated as the sum of all fractions in the extraction procedure. Sediments and extraction solutions were continually shaken in 50 ml centrifuge tubes throughout each extraction. Supernatants were collected following centrifugation

(3,800 revolutions per minute for 5 minutes) and filtration (Whatman® GF/C grade filter) at the end of each extraction step.

This technique provides an estimate of the sediment P that may be released under specific environmental conditions. The forms of P included in this study are those considered to be the most sensitive to release, i.e.:

1. *Labile P* (e.g. PO_4-P)

Labile/loosely bound P is that fraction of the sediment P that can be released across diffusive concentration gradients. Release of this P fraction may increase as a result of sediment resuspension. It includes easily mobilised adsorbed P and P contained in pore water.

2. *Reductant-soluble P* (e.g. $FePO_4$, $Fe_3(PO_4)_28H_2O$)

Reductant-soluble P is that fraction of the sediment P that can be mobilised under conditions of anoxia. This pool represents P that is mainly bound to iron and manganese hydroxides.

4.4 Lake sensitivity factors

A key factor affecting the sensitivity of a lake to nutrient load is its flushing rate. In outline, lakes that flush more quickly are less likely to develop algal blooms than those that flush more slowly. Estimating flushing rate requires information on the hydraulic load to the lake and the volume of the lake. A lake's sensitivity to nutrient loads is also affected by its mean depth. As none of these data were available for Hornsea Mere, they were derived as follows.

4.4.1 Hydraulic load

As very few flow measurements were available for the inflows to, or outflow from, the mere, it was not possible to estimate the volume of water entering the lake (hydraulic load) using data from this source. So, the volume of water entering the lake was estimated from the difference between the average annual rainfall over the catchment and the corresponding annual evaporation rate. More specifically, this value (commonly known as hydrologically effective rainfall, or HER) was estimated from daily rainfall data collected between 2000 and 2008 and an average annual evaporation rate for the area provided by Eleanor Blyth (CEH, *pers. comm*.).

4.4.2 Lake volume and mean depth

The volume of the lake was estimated from a bathymetric survey undertaken on 1/12/09. During this survey, Geo-referenced bathymetric data were collected using a Lowrance® LCx-37c SONAR/GPS chart logger with a dual beam vertical transducer. The logger recorded depth data at a rate of 5 times per second and positional data once per second along a "zig-zag" shaped transect, as shown in Figure 4.4. This procedure collected more than 13,500 geo-referenced depth values that were processed to provide depth measurements in metres and locations in UK National Grid Reference (NGR) units.

The transformed data were used to generate a bathymetric map (Figure 4.5) using the geographical information system, ArcGIS, using the OS digital lake shoreline as the 0 m depth contour. This was used to estimate the volume of the mere. Its mean depth was then calculated by dividing the estimated volume of the mere by the surface area enclosed by the OS digital lake shoreline.

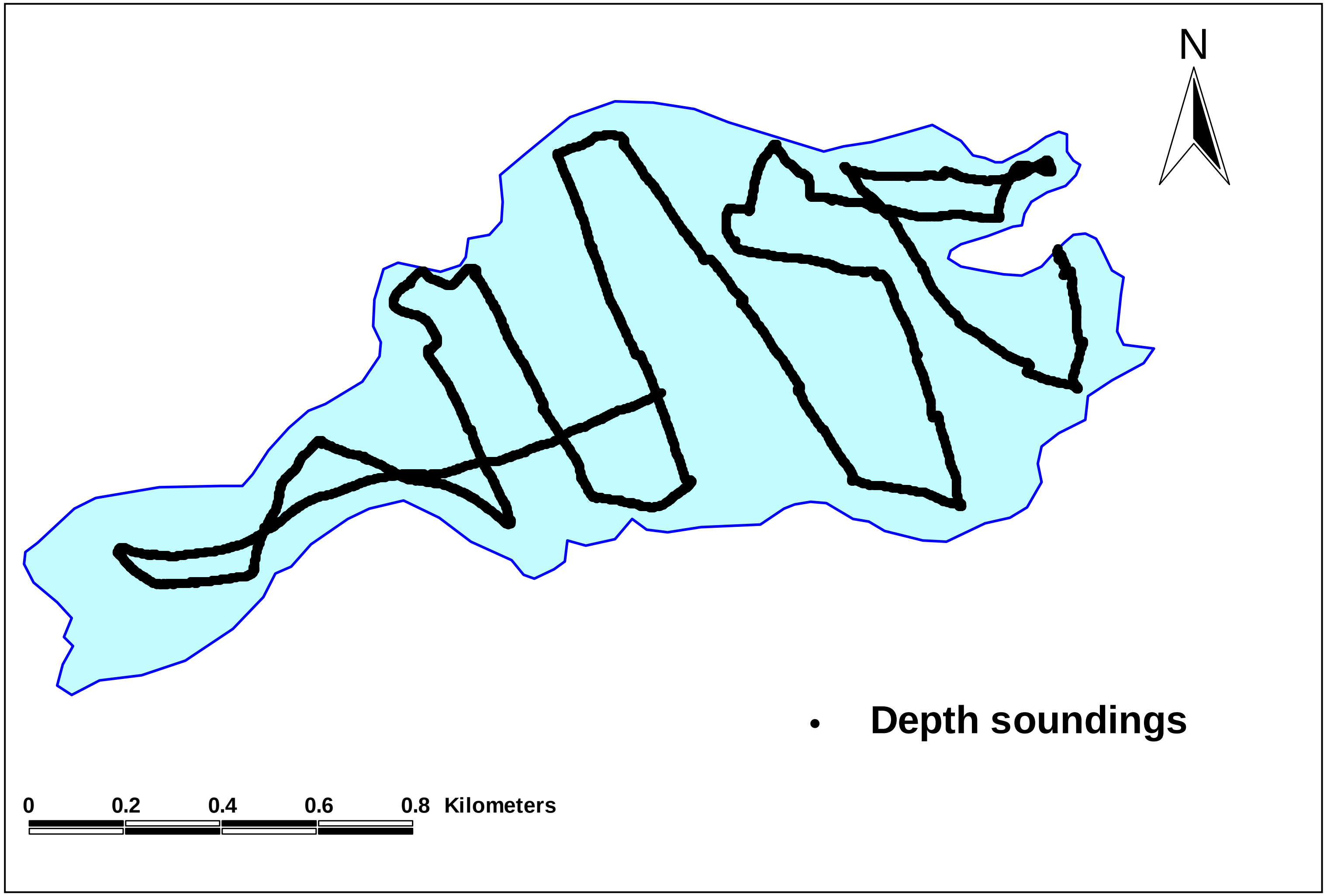


Figure 4.4 Depth sounding locations for the bathymetric survey undertaken on 1/12/09.

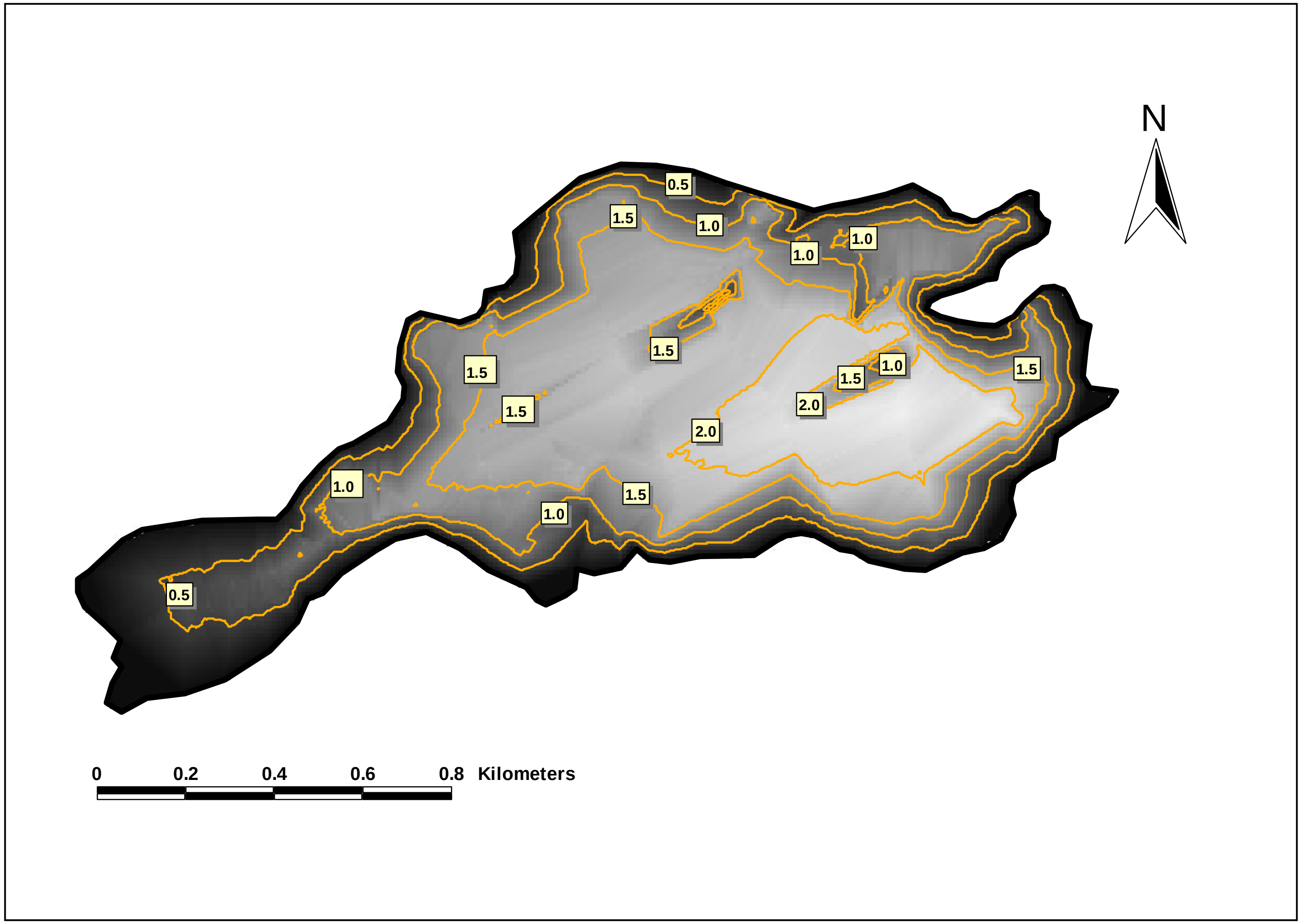


Figure 4.5 **Bathymetric map of Hornsea Mere showing depth contours in metres.**

4.5 Expected lake response to external nutrient load

The expected mean annual open-water TP concentration for Hornsea Mere, based on the external TP load estimated above (see Section 4.2.1), was calculated using the methods described below. It should be noted, however, that this method may not be applicable to a waterbody where chlorophyll *a* concentrations are predominantly nitrogen limited in summer, because many of these equations assume P limitation on algal growth. This is especially true of the equations that predict mean and maximum chlorophyll *a* concentrations from mean annual P concentration in the lake.

First, the TP retention coefficient of the mere (P_R) was determined from the areal water loading (q_s) using the method of Kirchner & Dillon (1975):

$$q_s = \frac{V_{in}}{A_{lake}}$$

$$P_R = 0.426e^{-0.271q_s} + 0.574e^{-0.00949q_s}$$

where V_{in} is the annual hydraulic load to the mere (m^3) and A_{lake} is the surface area of the lake (m^2).

The expected mean annual in-lake TP concentration (P_{lake}, mg m^{-3}) was then estimated from the flushing rate (ρ, loch volumes y^{-1}) and the external TP load (P_{load}) using the equations of Dillon & Rigler (1974), as follows:

$$\rho = \frac{V_{in}}{V_{lake}}$$

where V_{in} is the annual hydraulic load to the lake (m^3) and V_{lake} is the volume of the lake (m^3).

$$L = \frac{P_{load}}{A_{lake}}$$

where L = areal P load (mg m^{-2} y^{-1}), and

$$P_{lake} = \frac{L(1 - P_R)}{z \times \rho}$$

where P_{lake} is the mean annual TP concentration in the lake (mg m^{-3}) and z is the mean depth of the lake (m).

The expected annual mean and maximum open-water chlorophyll *a* concentrations based on the mean annual TP concentration predicted, above, were estimated using the following relationships derived for shallow lakes by OECD (1982):

$$chl_{mean} = 0.48 P_{lake}{}^{0.97}$$

$$chl_{\max} = 0.74 P_{lake}{}^{0.97}$$

where chl_{mean}, chl_{max} are the annual mean and maximum in-lake *a* concentrations, respectively, and P_{lake} is the mean in-lake TP concentration derived above (mg m^{-3}).

5 Results

5.1 Seasonal variations in water quality within the mere

The average monthly TP concentrations across all of the years for which data were available are shown in Figure 5.1a. In general, TP concentrations in the mere are relatively low in winter, decreasing through to spring, and then increasing towards late summer where the main annual peak occurs. Peak TP concentrations then decline again towards the end of the year. Average monthly TP concentrations are above the WFD good/moderate boundary in all months, especially during the summer. A similar trend is observed for OP concentrations (Figure 5.1b), with OP being the main form of TP throughout the year.

Average monthly concentrations of total nitrogen (TN) across all of the years for which data were available are shown in Figure 5.1c. TN concentrations in the mere are relatively high in winter, decreasing through spring. TN concentrations remain low until late summer, when concentrations increase towards the end of the year. A similar trend is observed in NO_3-N concentration (Figure 5.2a), which appears be the main form of TN. However, NO_3-N concentration is reduced to near zero values in spring and summer. In contrast, NH_3-N (Figure 5.2b) concentrations are low throughout the year, although slightly higher in winter than in summer.

Average monthly concentrations of SiO_2 across all years are shown in Figure 5.2c. SiO_2 concentrations are relatively high in winter, decreasing through spring to summer where concentrations peak. A decrease in SiO_2 concentration is observed between late summer and late autumn after which concentrations increase towards the end of the year.

Annual monthly chlorophyll *a* concentrations (Figure 5.3a) are low in winter and early summer, with peaks being observed in early spring and late summer/early autumn. In relation to WFD targets, chlorophyll *a* concentrations range between “high” and “moderate”.

Annual monthly suspended solid (SS) concentrations (Figure 5.3b) tend to be high in winter and late-summer/early autumn and low at other times of the year. Although there are insufficient data to examine the reasons for this in detail, it might be hypothesised that high winter levels of SS are unlikely to be caused by sediment disturbance by fish, as proposed by Carvalho and Moss (1998), because there will be limited fish feeding activity at this time of year. It seems more likely that these high values are caused either by sediment being washed into the mere from the catchment after high rainfall events or by the resuspension of sediment within the mere as a result of wind induced mixing events.

Annual monthly DO concentrations (Figure 5.3c) decrease from winter through to early summer. A significant drop in DO is observed in August, after which concentrations recover for the remainder of the year.

(a)

(b)

(c)

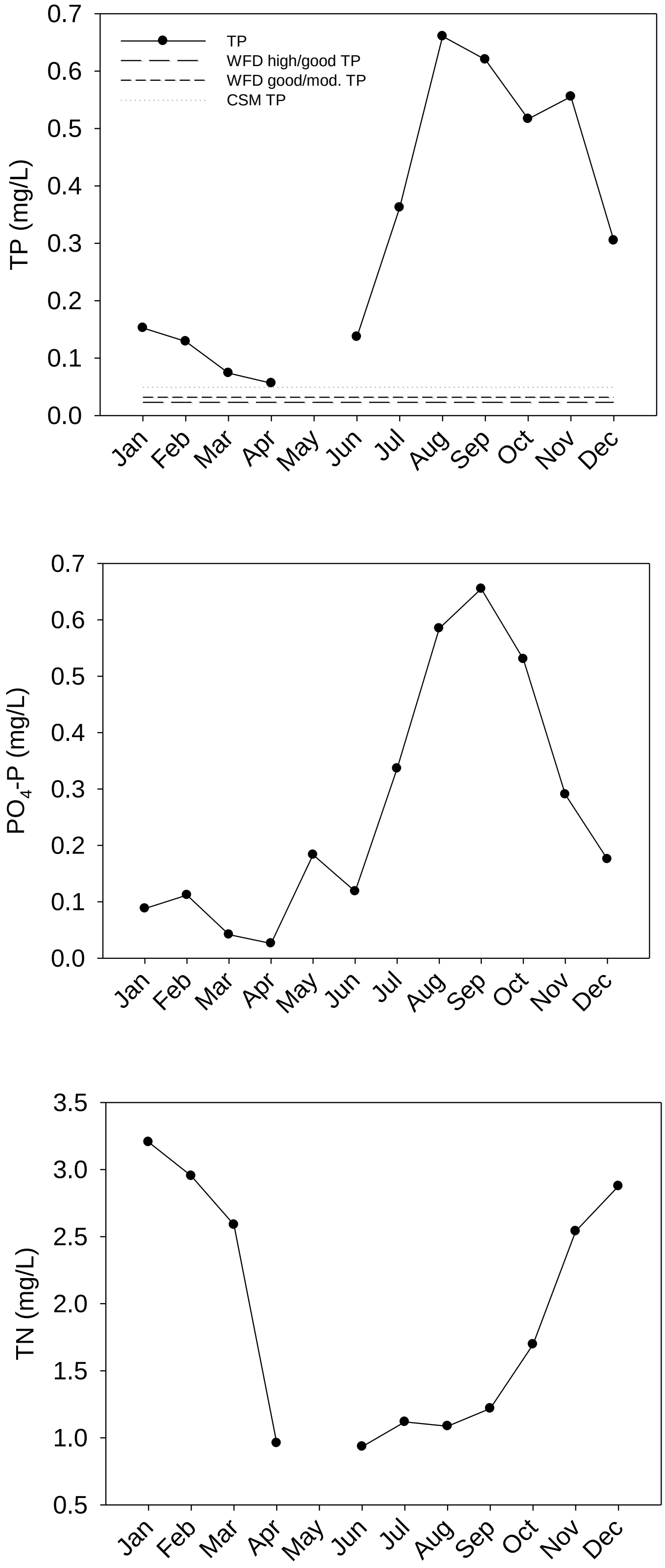
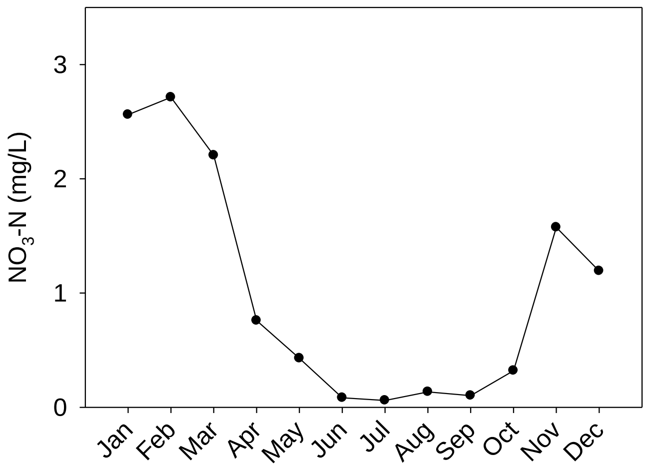
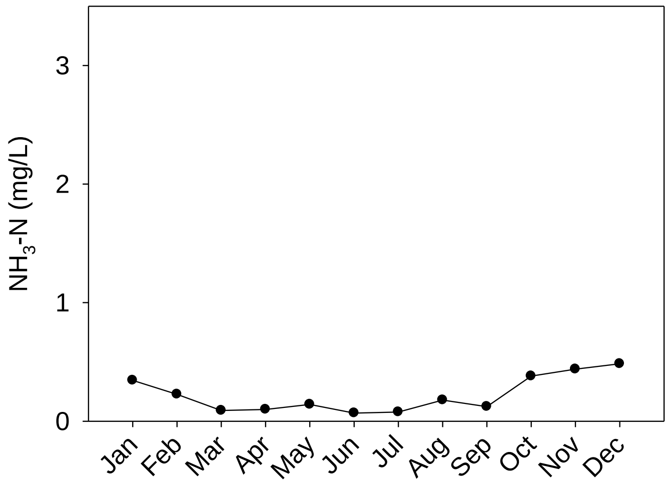


Figure 5.1 **Mean monthly (a) total phosphorus (TP), (b) orthophosphate (PO_4-P) and (c) total nitrogen (TN) concentrations averaged over all available years for Hornsea Mere. WFD and CSM target TP concentrations are shown in panel (a).**

(a)



(b)



(c)

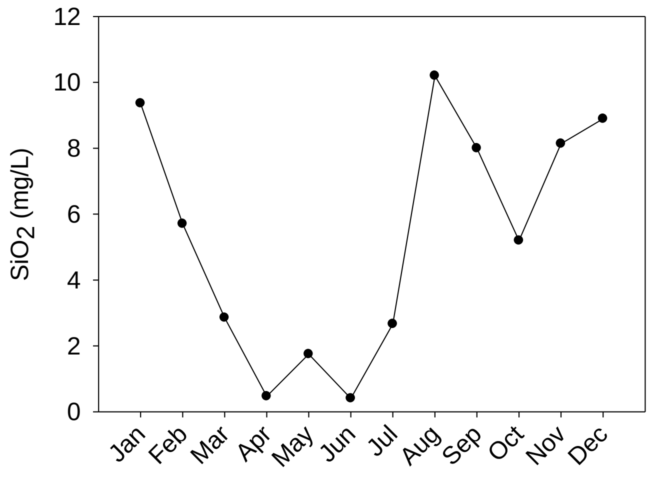


Figure 5.2 **Mean monthly (a) nitrate (NO_3-N), (b) ammonia (NH_3-N) and (c) silicate (SiO_2) concentrations averaged over all available years for Hornsea Mere.**

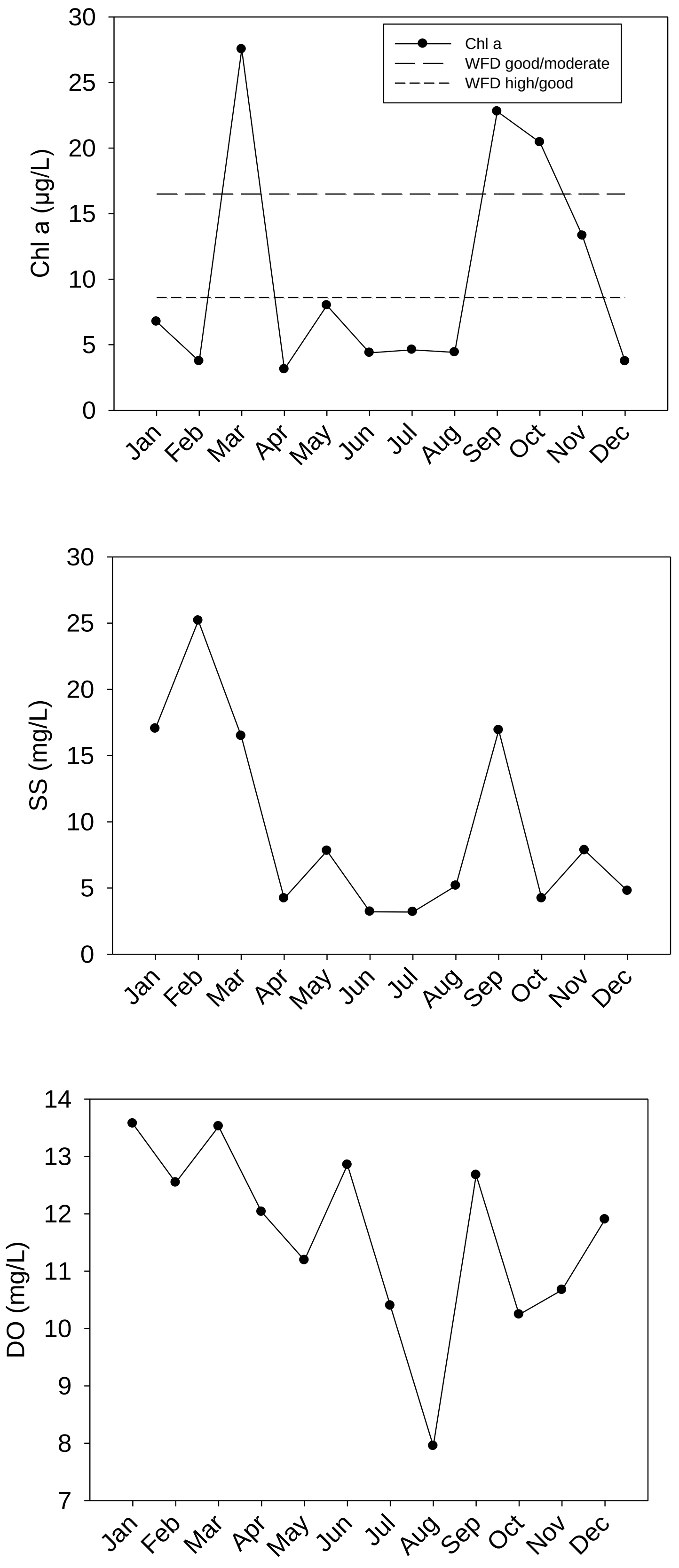


Figure 5.3 **Mean monthly (a) chlorophyll *a* (Chl a), (b) suspended solids (SS) and (c) dissolved oxygen (DO) concentration averaged over all available years for Hornsea Mere.**

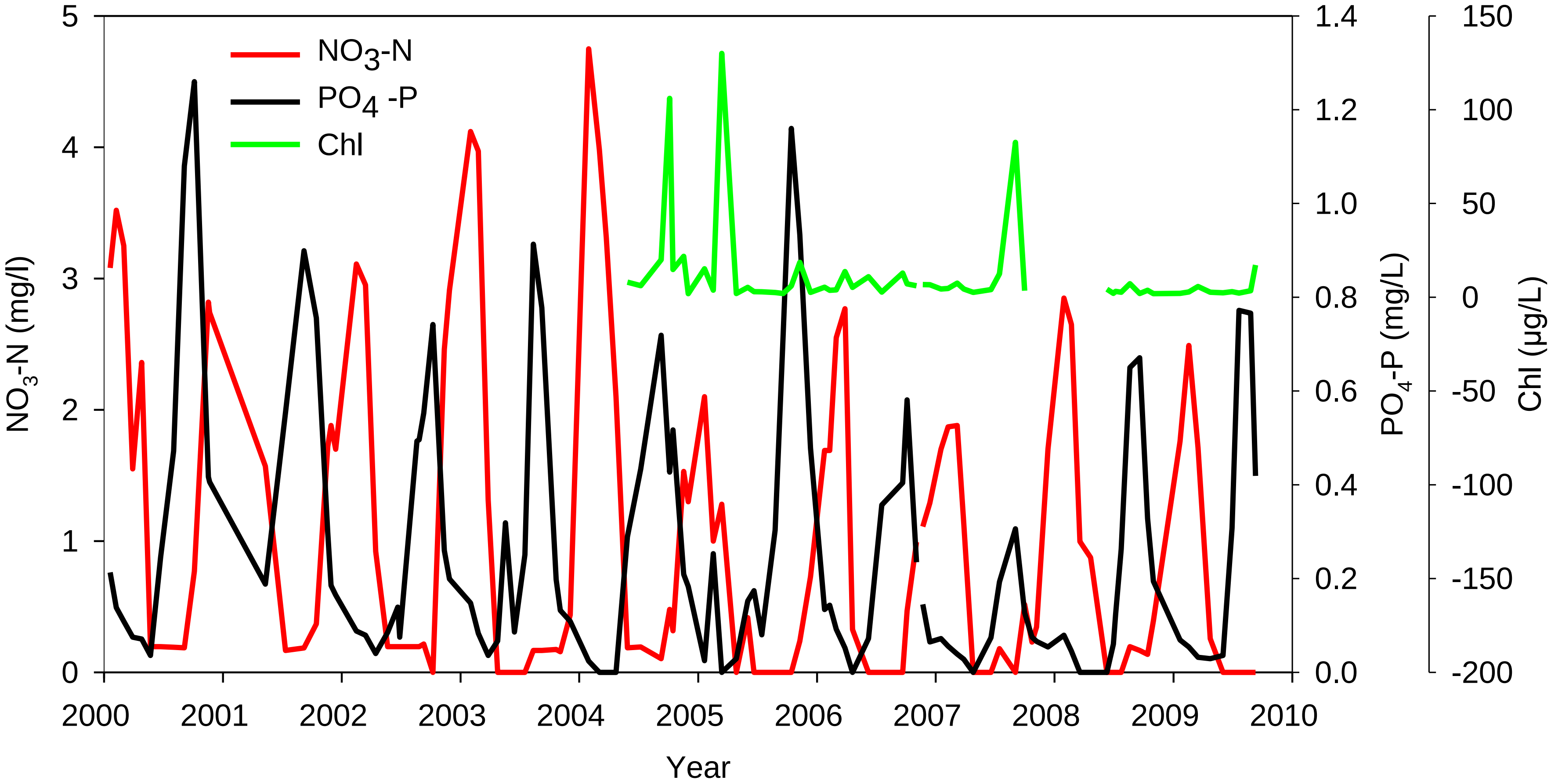


Figure 5.4 **Long-term variation in nitrate (NO_3-N), orthophosphate (PO_4-P) and chlorophyll *a* (Chl) concentrations in Hornsea Mere.**

Long-term trends in OP, NO_3-N and chlorophyll *a* concentrations are shown in Figure 5.4. NO_3-N and OP are the most common forms of N and P, respectively (Figure 5.1 and 5.2) and so, by assessing relative changes in their concentrations over time, we can make inferences about nutrient limitation within the mere. Seasonal switching between P-limiting and N-limiting conditions seems to occur in spring and autumn, with P-limitation being more likely in winter/spring and N-limitation being more prevalent in summer. Three large peaks in chlorophyll *a* concentration were observed in 2004, 2005 and 2007, during periods when both P and N were available for algal growth. In 2004 and 2007, this occurred during the switchover between periods of N- and P-limitation, when concentrations of both NO_3-N and OP were high. In contrast, the peak in chlorophyll *a* concentration in 2005 appears to have occurred as a result of an anomalous increase in OP concentration during winter.

Table 5.1. Estimated mass of N responsible for changes in water column concentrations between winter and summer in Hornsea Mere, 2004 - 2009.

Year	Rate of TN loss (t y^{-1})
2004	1.13
2005	2.25
2006	3.92
2007	3.50
2008	insufficient data
2009	4.36

The decrease in NO_3-N concentration is likely to be the result of both biological (e.g. macrophyte and phytoplankton) uptake and denitrification. However, the low phytoplankton biomass (Figure 5.3a) and the apparent poor condition of the macrophyte community suggest that denitrification is probably the key process responsible for the loss of N from the water during the summer months. The level of N loss occurring within the mere over the summer months can be estimated by calculating the mass of N responsible for the observed changes in open water N concentrations between winter and summer. The results of these calculations for 2004 to 2008 (Table 5.1) suggest that N loss rates vary between 1.13 t y^{-1} and 4.36 t y^{-1}.

Denitrification is clearly an important driver of water quality in Hornsea Mere and is probably the key environmental factor that prevents the very high concentrations of OP that are characteristic of this site being converted into phytoplankton biomass (chlorophyll *a*). Denitrification rates have been shown to be positively related to temperature (Seitzinger, 1988; Saunders & Kalff, 2001), with temperature explaining about 66% of the variation in denitrification rates in some lakes (Saunders & Kalff, 2001) This is because temperature is an important factor in the regulation of microbial activity. The relationship between changes in this water temperature and NO_3-N concentration was explored for Hornsea Mere. The results show that NO_3-N concentrations tend to decrease as water temperatures rise, with NO_3-N being almost completely lost from the system when the temperatures of more than 20^oC are reached (Figure 5.5). Although it is difficult to identify the exact processes that are responsible for this loss without further research, the mere appears to be capable of scrubbing NO_3-N efficiently from the system at temperatures above about 17^oC.

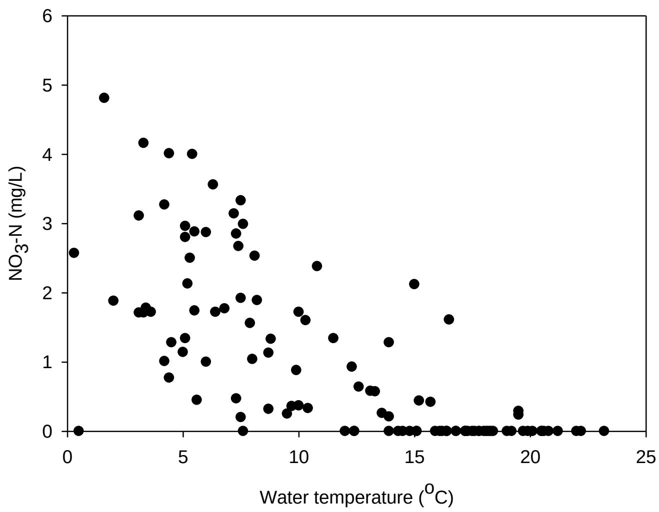


Figure 5.5 Water temperature *vs*. nitrate (NO_3-N) concentration for all available data from Hornsea Mere.

5.2 Spatial variation in water quality within the mere

A spatial survey of water quality across the mere was undertaken on 1/12/09. The aim of this survey was to assess the level of spatial variation in water temperature, water clarity (measured as Secchi disk transparency), DO, TP and SS concentrations across the mere on that date. As the date of sampling followed a period of heavy rain, it was hoped that the results would also provide useful information on important discharges to the lake under high runoff conditions.

The survey found that TP concentrations were generally higher towards the western end of the mere (Figure 5.6), while transparency was much reduced (Figure 5.7). This suggested that, under high flow conditions, water quality at the west end of the mere was being reduced by material entering the lake from Low Wood Drain. The corresponding elevation in water temperature (Figure 5.8) and depression in DO concentration (Figure 5.9), here, appear to provide further evidence of an impact on water quality in this area. However, it should be noted that the water is particularly shallow (<0.5m depth) in this sheltered bay and that the elevation in temperature may have been a local response to changes in air temperature or incident solar radiation; this is unlikely, however, in early December. The reduction in transparency associated with these observations is consistent with the transport of eroded soil particles to the lake by the Low Wood drain under high flow conditions. It was also noted that a plume of turbid water could clearly be seen entering the mere from this drain on the day of sampling. These results seem to indicate that some areas of the upstream catchment draining into Low Wood Drain have erosion problems that need to be addressed. Although aerial photography of the area shows that there are many arable fields within the immediate catchment that may be a source of eroded material, many roads in the area are narrow and their margins are disturbed by passing traffic. This may also create an important source of eroded material that is transported into the mere under heavy rainfall conditions.

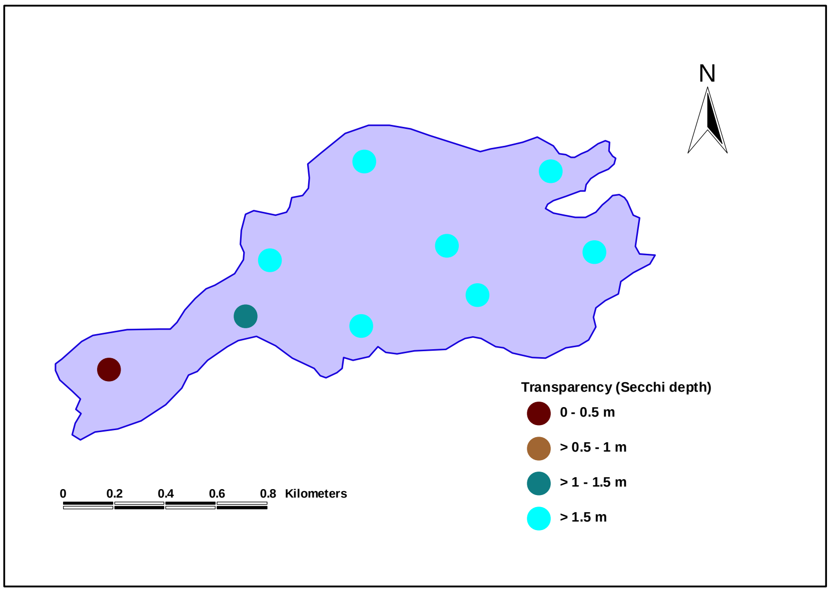


Figure 5.6 Spatial variation in water clarity (Secchi disk transparency) on 1/12/09.

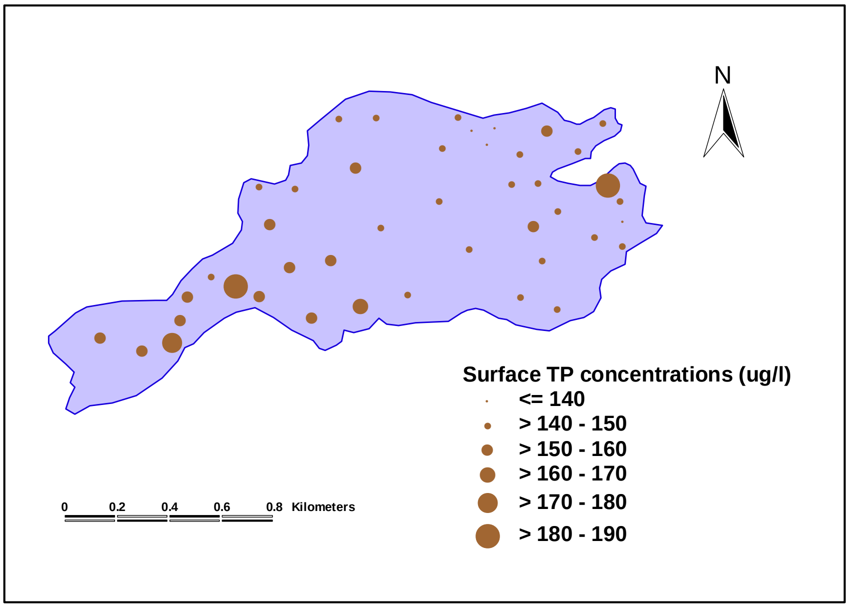


Figure 5.7 Spatial variation in surface water TP concentrations on 1/12/09.

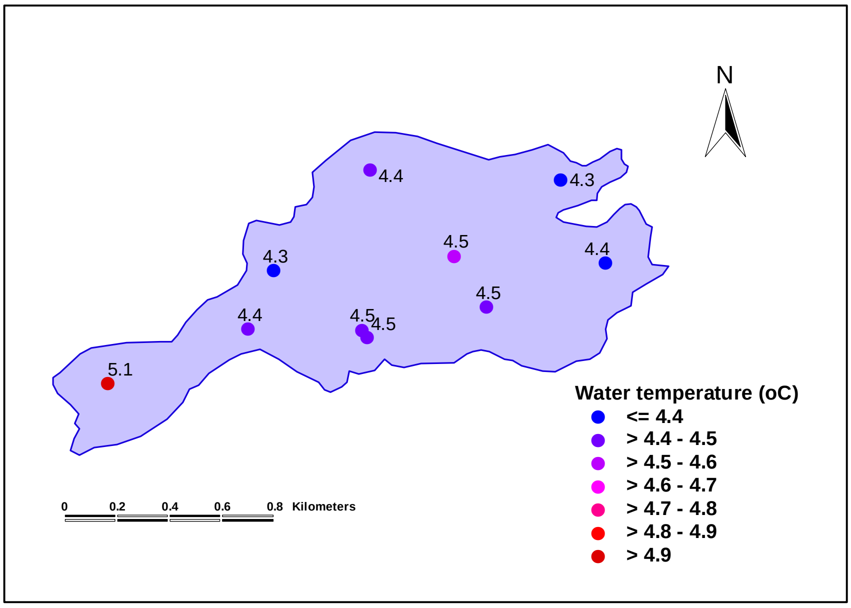


Figure 5.8 **Spatial variation in surface water temperatures within the mere on 1/12/09**

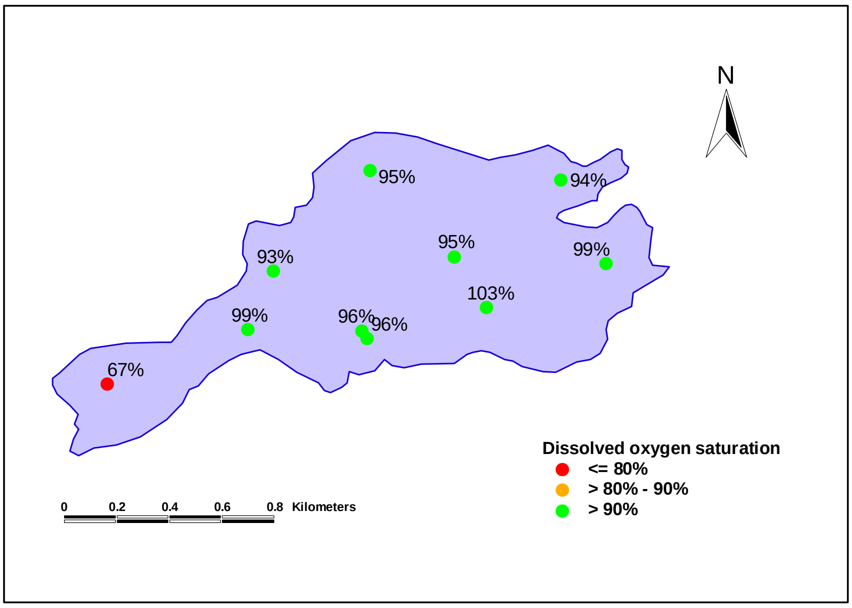


Figure 5.9 **Spatial variation in dissolved oxygen concentration within the mere on 1/12/09**

5.3 External P load to the mere

5.3.1 Export coefficient approach

5.3.1.1 Runoff

A land cover map of the catchment compiled from satellite data collected in 2000 is shown in Figure 5.10. More than half of the catchment at this time was arable land, while much of the remainder was improved or unimproved grassland (Table 5.2). It is unlikely that the situation will have changed significantly since then.

Table 5.2 Areal coverage and TP export of different land cover types within the Hornsea Mere catchment.

Land cover type	**Area (ha)**	**Area (%)**	**P export (kg/y)**	**P export (%)**
Broad leaved/mixed woodland	112	6%	17	3%
Coniferous forest	14	1%	2	0%
Arable/bare ground	941	53%	235	47%
Improved grassland	296	17%	112	23%
Unimproved grassland	268	15%	19	4%
Dwarf shrub heath	4	0%	0	0%
Fen, marsh, swamp	4	0%	0	0%
Urban/rural development (runoff only)	134	8%	111	22%
Total	**1773**	**100%**	**497**	**100%**

Most of the P loss to surface water from land cover sources within the catchment probably comes from areas that are intensively farmed, such as arable land, and from areas of improved grassland. The export coefficient approach suggests that about 70% of P laden runoff probably comes from these areas (Table 5.2). Figure 5.11 shows the estimated P loss rates for different parts of the catchment, indicating areas where these rates of loss are likely to be particularly high. The largest of these is runoff from areas of rural development. Overall, it seems likely that P losses associated with land use within the catchment are about 0.5 tonnes y^{-1} (Table 5.2).

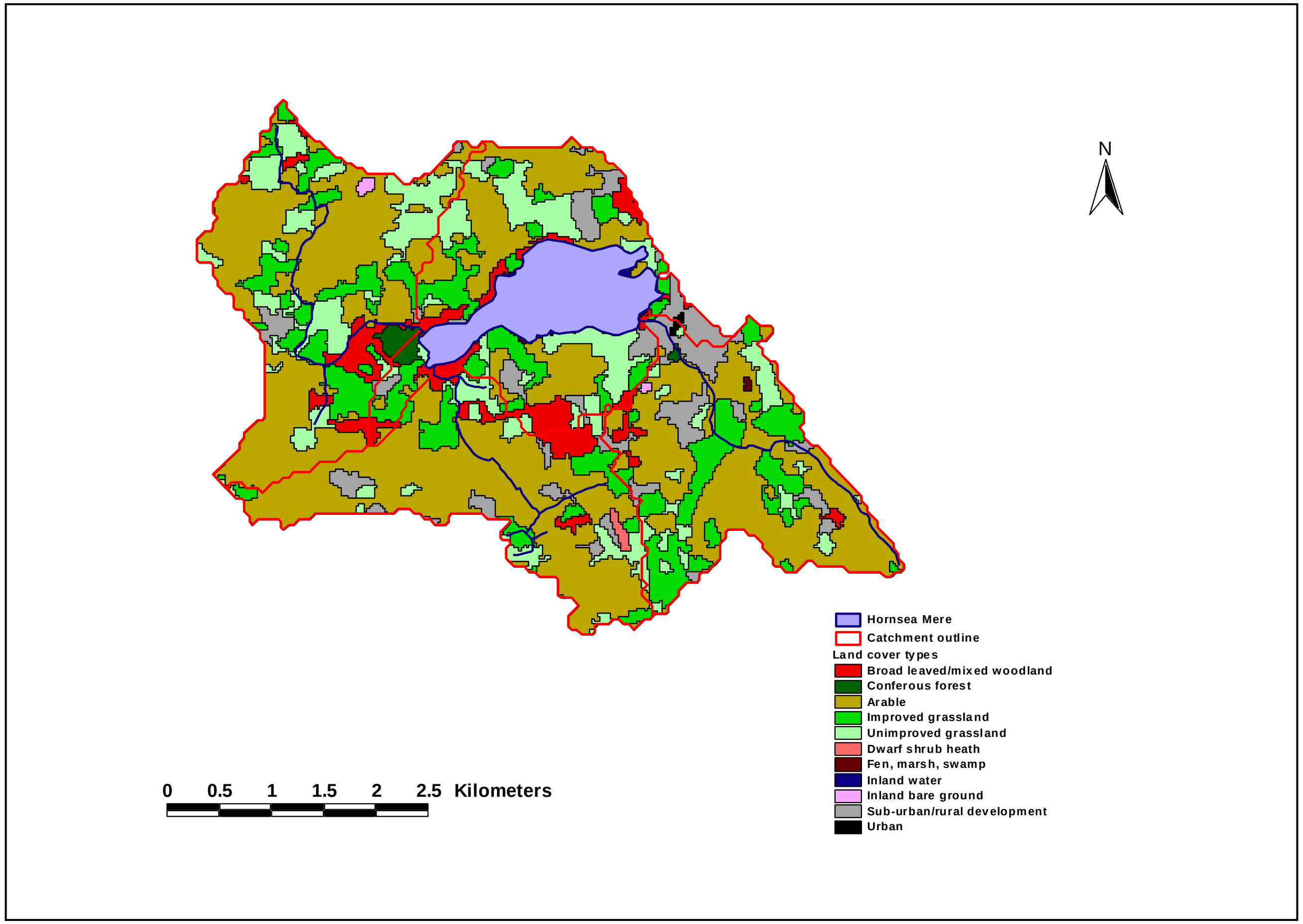


Figure 5.10 Land cover map of the surface water catchment of Hornsea Mere, showing subcatchment boundaries corresponding to each of the three main inflows.

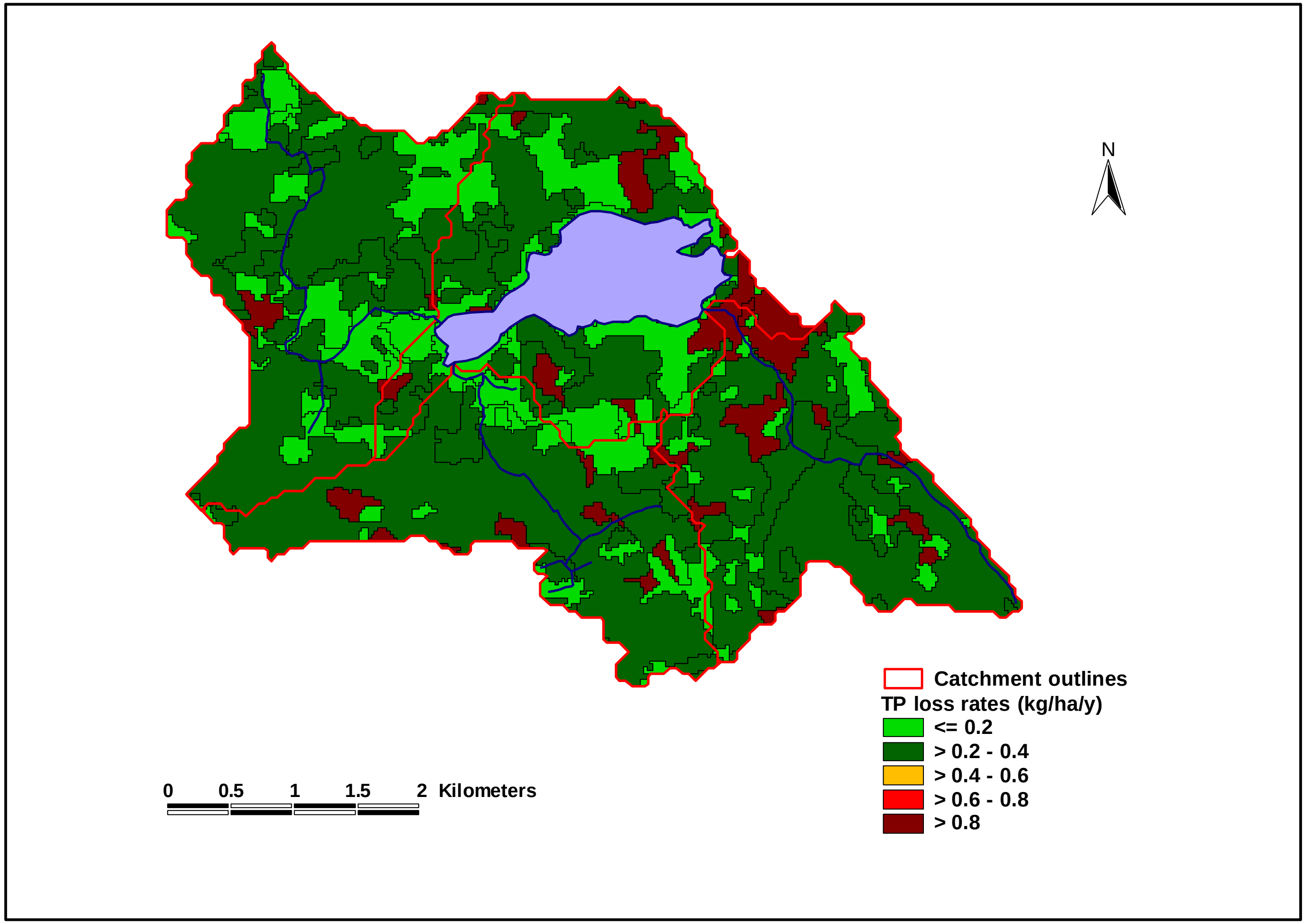


Figure 5.11 Map of TP loss rates for the surface water catchment of Hornsea Mere, showing subcatchments boundaries corresponding to each of the three main inflows.

5.3.1.2 Rainfall

The average annual rainfall over the mere and its catchment was estimated to be about 0.66 m y^{-1}. Given that the surface area of the mere is about 130 ha., the volume of rain falling directly onto its surface appears to be about 871,150 m^3. Assuming that the P content of freshly fallen rain is about 2×10^{-2} mg/L (Bailey-Watts & Kirika, 1991), this suggests that the P load to the lake from direct rainfall is about 17 kg y^{-1}.

5.3.1.3 Birds

The likely P load to the mere from roosting birds is shown in Table 5.3. Cormorants appear to be the biggest source of P input from this source, probably contributing about 82 kg y^{-1}. Greylag geese probably contribute a further 19 kg y^{-1}, while input from the remaining bird species is relatively low. In total, it was estimated that the P load to the mere from its bird population was probably about 124 kg P y^{-1}.

Table 5.3 Estimated P load to the mere from roosting bird populations.

Bird species	Average daily count	P load (kg/y)
Barnacle goose	26	2.00
Canada goose	102	7.86
Cormorant	86	81.61
Greylag goose	247	19.02
Little gull	139	7.61
Mute swan	130	5.46
Total P input to lake		123.56

5.3.1.4 Sewage

In the absence of more accurate data, it was assumed that the resident population of the catchment was about 700 people (Johnes et al., 1998). When multiplied by a *per capita* P export coefficient of 0.54 kg y^{-1}, this suggests that the annual P load to the mere from rural sewage sources is probably about 378 kg y^{-1}.

Given an average household size of 2.3 people in this area (Office for National Statistics, Census 2001), it can also be estimated that there are about 300 households in this area whose dwellings will be served by septic tanks or small private sewage works. It is interesting to note that only 6 of these (i.e. about 2%) have consented discharges (Figure 5.12). Although, cumulatively, an important source of P in rural areas (May et al., 2010), discharges from individual septic tanks in this area have so far been considered too be too small to have a significant impact on water quality (Bedworth et al., 2009).

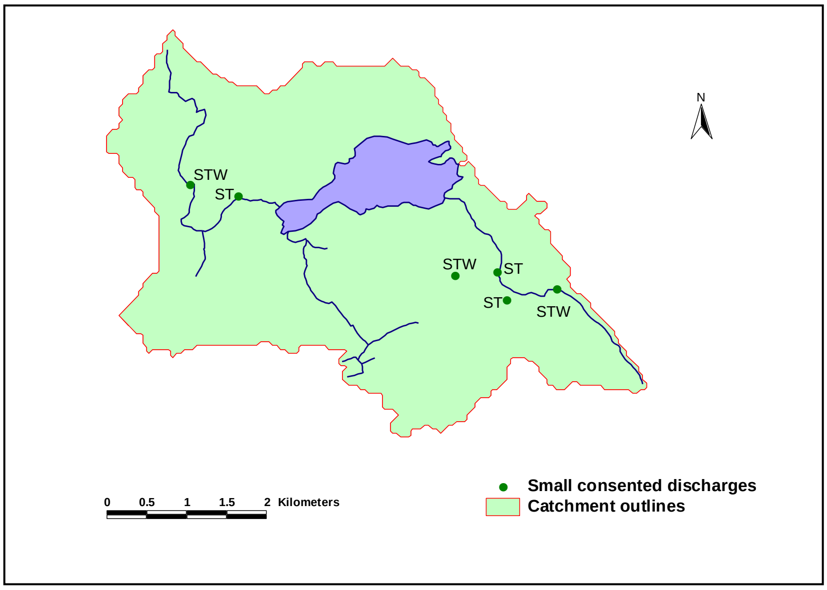


Figure 5.12 **Map of small consented discharges of sewage effluent within the catchment of Hornsea Mere (ST = septic tank; STW = private sewage treatment works).**

5.3.1.5 Total

The total external nutrient load to the lake ($Load_{total}$, kg TP y^{-1}) was calculated as the sum of the individual loads estimated above, i.e.

$$Load_{total} = Load_{runoff} + Load_{sewage} + Load_{rain} + Load_{bird} + Load_{other}$$

where:

$Load_{runoff}$ = 500 kg y^{-1}

$Load_{sewage}$ = 378 kg y^{-1}

$Load_{rain}$ = 17 kg y^{-1}

$Load_{bird}$ = 124 kg y^{-1}

$Load_{other}$ = unknown, assumed negligible

The total contribution of TP to the mere from the catchment sources explored above is, therefore, estimated to be about 1 t y^{-1}. Although it is impossible to estimate the external P load to the lake exactly using this method, the relative importance of the different sources is probably reflected quite well in the results summarised in Figure 5.13.

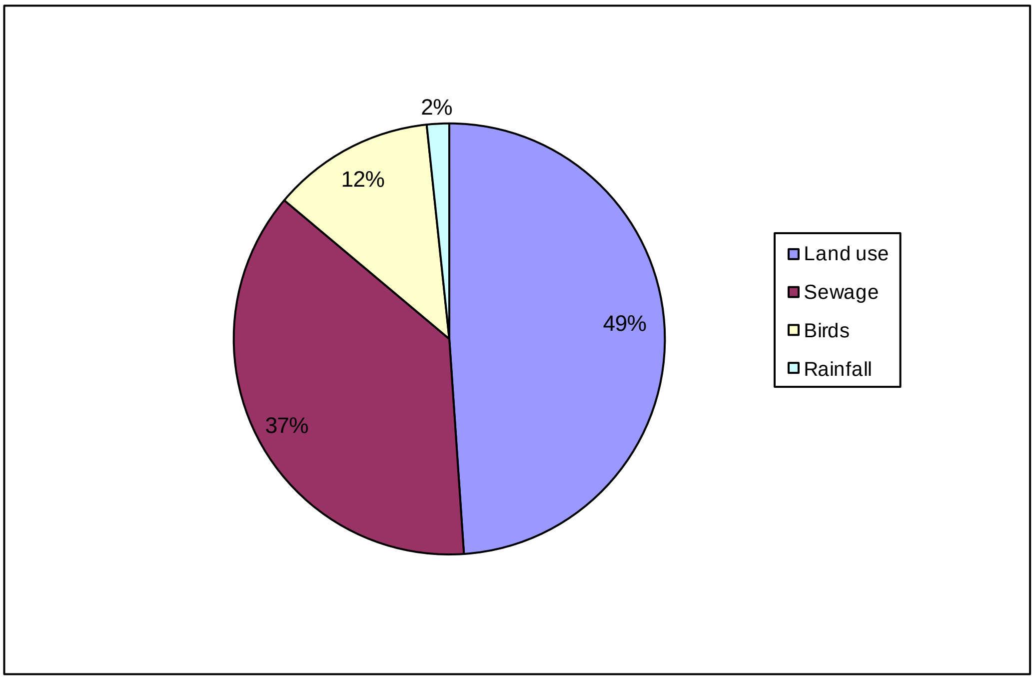


Figure 5.13. Estimated relative importance of catchment sources of P to the total load to Hornsea Mere.

It should be noted, however, that these values are based on TP. If based on bioavailable P (OP), the relative contribution from sewage sources could be much higher because runoff is usually only 30-50% OP while sewage sources are generally about 90% OP.

5.3.2 Spatial survey of P 'hotspots' within the catchment

A series of spatial surveys of water quality in drainage systems across the catchment were carried out by the EA between 12/10/09 and 10/12/09, with spot samples being collected for water chemistry analyses. Only those results pertaining to OP concentrations are reported here. The full dataset from this survey is held by the EA.

Spatial variation in OP concentrations in dikes and ditches on individual sampling dates is shown in Figure 5.14. The data are summarised across all sites in Figure 5.15. OP concentrations were found to be very high in many of the waters sampled, with an exceptionally high value of more than 2 mg P/L being recorded just downstream of a septic tank system close to a dog kennels (Figure 5.14). Values of 0.2 - 0.3 mg P/L were commonly recorded across much of the catchment.

Streamwalks were carried out along both Low Wood Drain and Foss Dike on each of two occasions to look at the effects of small discharges on downstream P concentrations. Sudden increases in concentration downstream of a particular point were taken to indicate a point source discharge. The results of these surveys are plotted against upstream distance from the mere along these inflows in Figure 5.16. High upstream OP concentrations were recorded in both Foss Dike and Low Wood Drain in October and November 2009 in areas where these streams passed consented point discharges, but this was not the case in December 2009. Although flows were not measured, it seems likely that the earlier measurements were associated with low flows/less dilution while those in December 2009 were associated with higher flows/greater dilution. This hypothesis is supported by the rainfall data for this period, with the 5-day antecedent rainfall values for 12/10/09 and 9/11/09 amounting to 5.4 mm and 4.8 mm, respectively, while that corresponding to 10/12/09 was much higher, i.e. 20.4 mm.

Overall, this study suggests that there may be about 300 small discharges of P within the catchment of Hornsea Mere. Together, many of these have been shown to cause a serious degradation in downstream water quality within drainage network. Only about 2% of these are consented. The remainder comprises unconsented small point sources, which probably account for about 98% of the sewage-related P that enters the mere from its catchment. Overall, the combined input of P from these sources may have a significant impact on water quality in the mere.

5.4 Internal P load to the mere

As with most shallow lakes, Hornsea Mere appears to have a high internal release of P to the water column over the summer months. This is evident in the summer peaks observed in mean monthly TP concentrations (Section 5.1). The potential size of this release was investigated by estimating the mass of TP required to raise/lower the water column concentrations by the levels observed and by investigating the amount of P that is contained within the sediments and associated pore water, especially that considered to be release sensitive.

Table 5.4. Estimated mass of TP responsible for observed changes in the water column concentration between summer and autumn, 2005 to 2009.

Year	Mass of TP (t y^{-1})
2005	1.63
2006	0.93
2007	0.66
2008	1.26
2009	1.28

Estimated annual internal P loads for the years 2005 to 2009 are summarised in Table 5.4. The results suggest that internal P load varied between 0.66 t y^{-1} and 1.63 t y^{-1} TP per year. This is similar to the annual external P load estimated above. However, in contrast to the external load, which is delivered over a 12 month period, the internal P load is delivered over just a few months.

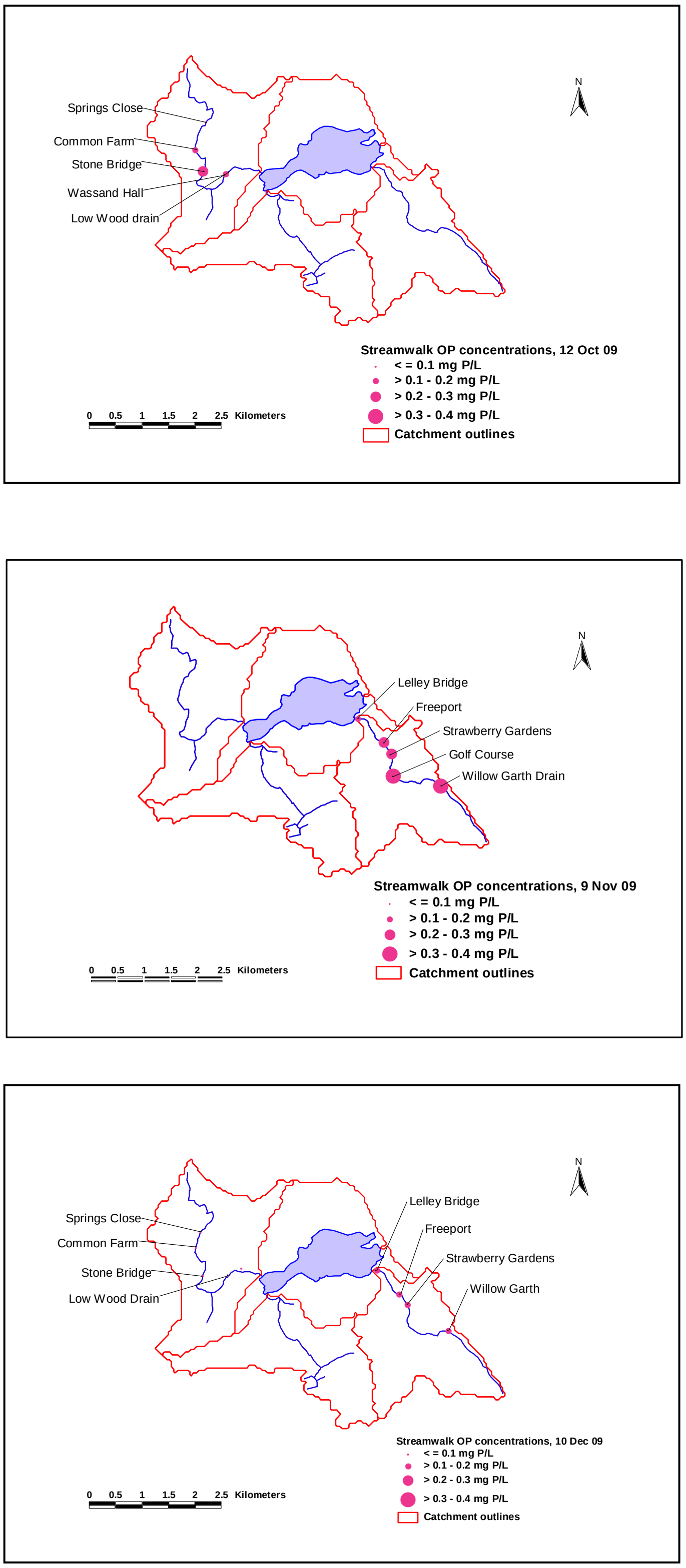


Figure 5.14 OP concentrations recorded along inflows to the mere and in neighbouring drains on three separate sampling occasions, i.e. 12/10/09, 8/11/09 and 10/12/09.

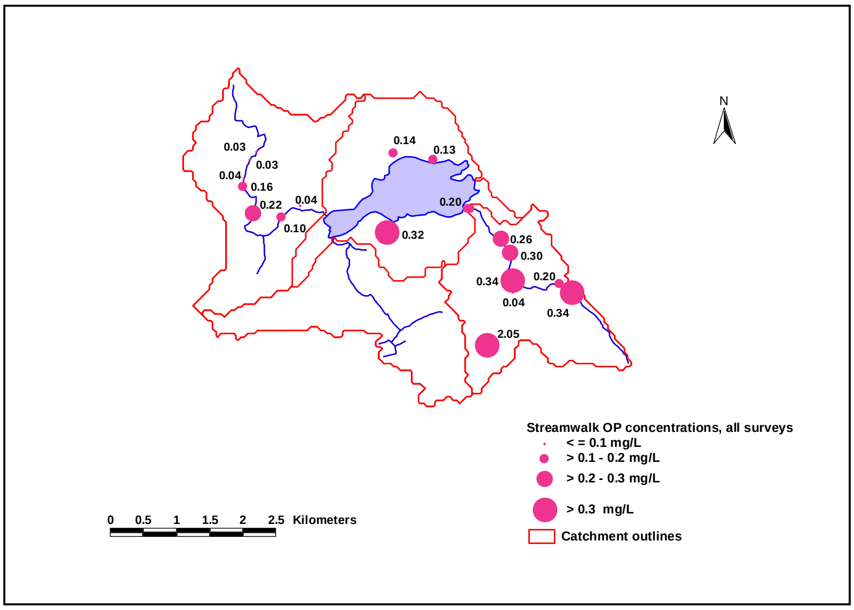


Figure 5.15 **Individual OP concentrations recorded along inflows to the mere and in neighbouring drains between 12/10/09 and 10/12/09.**

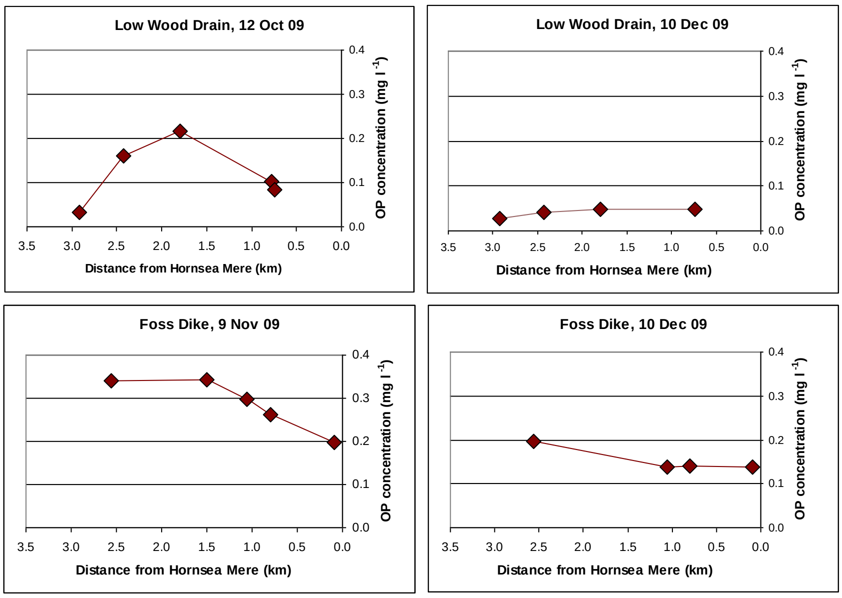


Figure 5.16 **OP concentrations (mg P/L) measured along inflows to the mere within the catchment of Hornsea Mere, 12/10/09 to 10/12/09.**

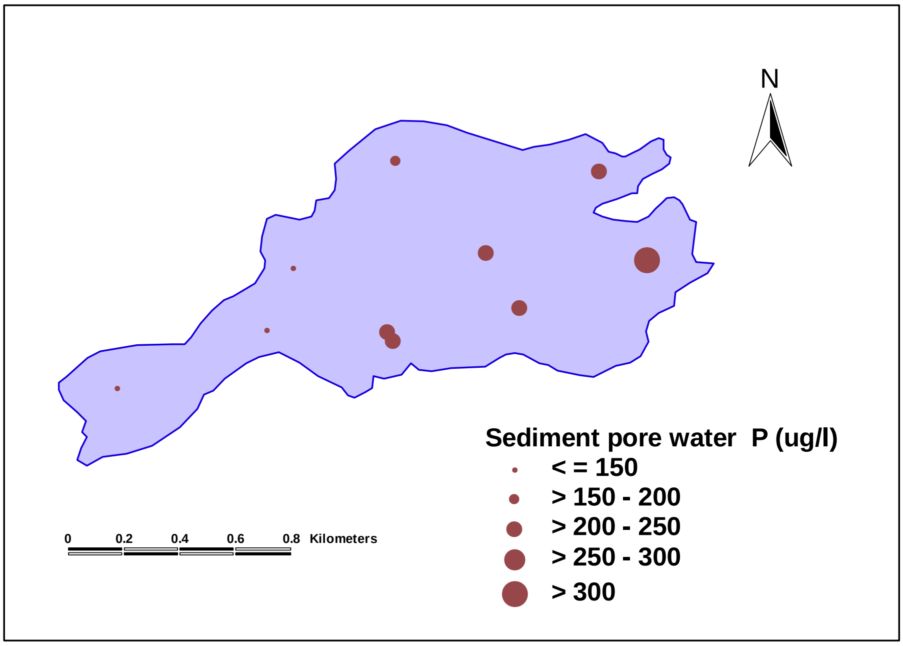


Figure 5.17 Spatial variation in pore water P concentrations in the sediment of Hornsea Mere on 1/12/09.

Concentrations of sediment and pore water P fractions were determined from the sediment cores collected across the mere. The results are shown in Figure 5.17. Pore water OP and TSP concentrations were found to be higher than surface water TP concentrations at Sites 1-3 and 7-9, suggesting diffusive sediment P release across the sediment water interface at these locations. In contrast, pore water OP concentrations were similar to surface water TP concentrations at Sites 4-6, although total soluble phosphorus (TSP) concentrations were above surface water TP concentrations at these sites. The results suggest that, at the time of sampling, diffusive sediment P release potential was higher within the main part of the mere than in the smaller western bay (Figure 5.18).

Labile-P concentrations were highest at Sites 2 and 6 and relatively low at all other sites. The release of this P fraction may be increased by sediment disturbance. Reductant-soluble P concentrations were high at Site 2, low at Site 3 and similar at all other sites. Release of reductant-soluble P is triggered by anoxia and this is the fraction of P that is usually responsible for the summer internal loading events that are common in shallow lakes (Spears et al., 2007).

In summary, sediment TP concentrations were low at Site 3, moderate at Sites 1 and 7, and high at all other sites. Overall, between 34% and 66% of the TP within the sediments was found to be reductant-soluble (release sensitive) P, highlighting the large pool of releasable P that is present within the surface sediments of this mere (Figure 5.19).

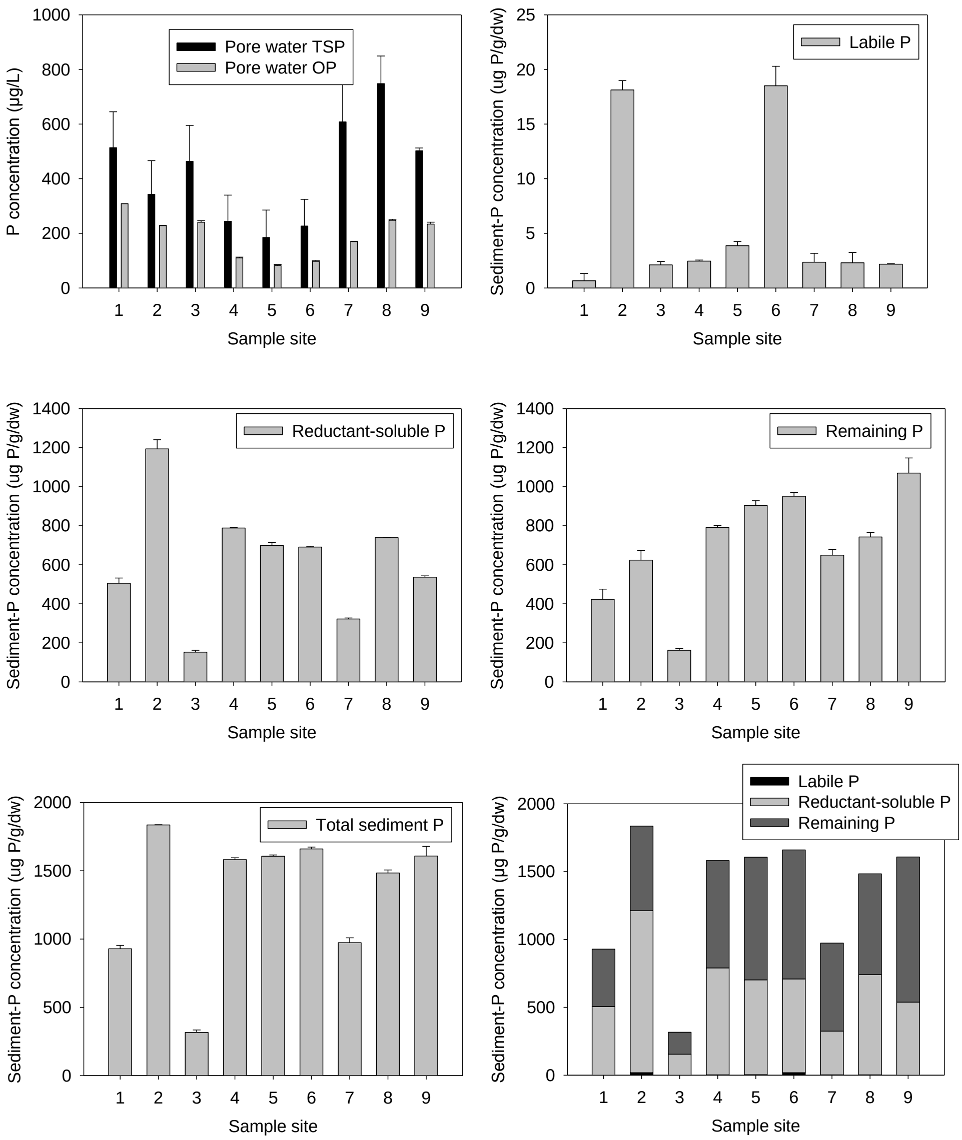


Figure 5.18 Concentrations of sediment and pore water P fractions across 9 sampling sites on 1/12/09.

When averaged over the upper 3 cm of sediment and across the whole lake, the TP and release sensitive P (i.e. labile + reductant soluble P) pools equated to 8.6 t and 4.0 t of P, respectively. The estimated store of TP in surface sediments is higher than the actual mass of P estimated to have been responsible for the observed summer water column TP peak between 2005 and 2009 (i.e. 0.66 to 1.63 t TP; Section 5.4). As such, the actual P release from sediments within the mere appears to be less than about 40% of the sediment-P store that has "release potential" (i.e. 1.63 t *cf*. 4.0 t). Conditions that may result in the release of this P pool include reducing conditions (deoxygenation) at the sediment water interface and disturbance by wind or bottom feeding fish species.

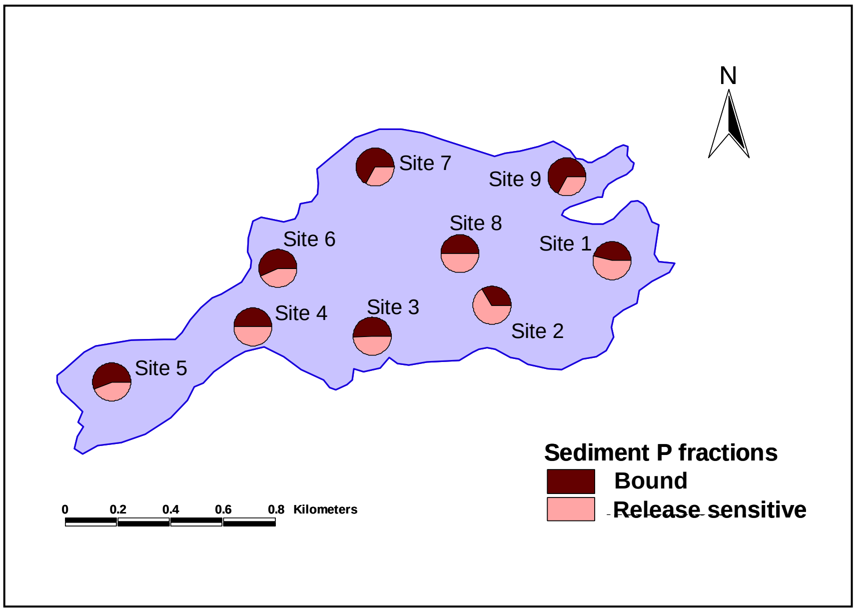


Figure 5.19 Spatial variation in the proportion of bound and release sensitive P fractions in the sediments of Hornsea Mere on 1/12/09.

The summer peak in SiO_2 may also be attributable to sediment release. These peaks are commonly explained by release in late summer following the dissolution of planktonic diatom frustules that have accumulated at the bottom of the lake during spring and summer deposition (Bailey-Watts, 1976a and b; Gibson *et al.,* 2000). This process has also been linked with bacterial mediation (Bidle *et al.,* 2003) and which increases with temperature (Spears et al., 2008).

5.5 Impact of climate change on lake response

The role of climate in driving water quality is evident in many case studies of temperate shallow lakes (Mooij et al., 2007; Spears et al., 2010a). Although wind-induced wave mixing (Spears et al., 2010b) and annual precipitation (Jeppesen et al., 2009) have been identified as important climate change drivers in shallow lakes, the data available for the present study only allows an assessment of the effects of temperature. Following an initial screening of the data, it was apparent that water temperature played an important role in regulating NO_3-N concentrations in Hornsea Mere (see Section 5.1).

It should also be noted that, although temperature has been identified as a key driver of sediment P release, initial screening of the data did not return a similar result to that shown for NO_3-N. Other studies have, however, identified significant relationships between internal P loading and combinations of climate drivers (e.g. wind, summer temperature and water clarity), showing that this process is not necessarily controlled by single drivers (Spears et al., 2010a). However, it is generally accepted within the scientific community that the potential for high magnitude sediment P release events will increase with rising summer temperatures (Jeppesen et al., 2003; Spears et al., 2009).

Overall, it seems likely that increasing summer temperatures in this geographical area as a result of climate change would be expected to increase both denitrification and P release from the sediments within Hornsea Mere. This would probably result in increased N limitation and higher P concentrations in summer, causing an apparent degradation in water quality. This is in contrast to the situation in some P limited shallow lakes, where increasing water temperatures can result in apparent improvements in water quality due to greater zooplankton grazing activity (Ferguson et al., 2009).

5.6 Likely impact on water quality

The likely impact of the estimated 1.07 t y^{-1} input of phosphorus to Hornsea Mere on its water quality was estimated using the equations outlined in Section 4.5. The site specific values used in the calculations are detailed in Table 5.5. It should be noted, however, that this method of calculation may have limited applicability to a waterbody where chlorophyll *a* concentrations are predominantly limited by nitrogen availability in summer. This is because many of these equations assume that P availability is limiting algal growth. This is especially true of the equations that predict mean and maximum chlorophyll *a* concentrations from mean annual in-lake P concentration. Also, the equations assume a more or less natural flushing regime, whereas flushing at Hornsea Mere is artificially controlled by a weir that is managed to maintain high water levels in summer by reducing discharge at the outflow. In practice, this means that flushing rates are artificially low in summer when in-lake P concentrations are high due to high levels of P release from the sediments.

Hornsea Mere was found to have a natural flushing rate of about 3 lake volumes per year. This value represents the amount of runoff from the catchment that flows through the mere over an annual rainfall cycle. However, as the outflow is controlled by a weir, it is likely that within year flushing does not follow a natural seasonal cycle. This is because the weir is managed in such a way as to retain water in the summer months (when P concentrations in the water are high) and discharge water during the winter months (when P concentrations are low). This will have the effect of retaining P in the mere during a period when the model will assume that it is being discharged under a natural flushing regime. For this reason, it is unlikely that the predicted P retention coefficient for this waterbody, i.e. 0.7, accurately reflects the way that the mere functions in reality.

That said, it is a useful exercise to compare the predicted TP and chlorophyll *a* concentrations in this waterbody with those measured between October 2008 and September 2009. The calculated mean in-lake TP concentration of about 0.056 mg/L, although close to the conservation target concentration, is very much lower than the measured value of 0.36 mg/L. Much of this difference is likely to be due to the lack of flushing in the summer, which will increase the P retention coefficient, and the fact any available P from internal and external sources remains unused due to N limitation of algal growth from May to September each year. In addition, it is likely that the conservation target was set using equations similar to those used in the present study that assume that the mere is P limited.

Table 5.5 Site specific values for each of the variables required for calculating expected TP and chlorophyll *a* concentrations from TP load to the mere

Variable	Value	Units
Average annual rainfall (a)	0.655	m
Average annual evaporation (b)	0.4	m
Hydrologically effective rainfall (a - b)	0.255[1]	m
Catchment area	17,730,000	m^2
Lake area	1,330,000	m^2
Lake volume	1,585,939	m^3
Lake mean depth	1.2	m
Total phosphorus load	1.070	tonnes y^{-1}

On the basis of the predicted in-lake TP concentrations, the calculations further predict in-lake annual mean and maximum chlorophyll *a* concentrations of about 27 µg/L and 41 µg/L, respectively. These are much greater than the corresponding measured values of 4.7 µg/L and 17.2 µg/L even though, in reality, P availability is greater than the calculations predict. This is almost certainly due to the fact that algal growth and biomass accumulation is being limited by N rather than P over the summer months at this site. If the same calculations are performed using the measured, rather than predicted, in-lake P concentration of 0.36 mg/L, annual mean and maximum chlorophyll *a* concentrations of 145 µg/L and 223 µg/L, respectively are predicted. These values probably reflect the potential for Hornsea Mere to produce algal blooms in summer if, for any reason, N became more available. Although the processes that cause N limitation in summer at this site are unclear, it can be hypothesised that if N became more available, e.g. through an increase in N-laden runoff from the catchment, algal blooms could become a serious problem at the site. It is, therefore, important to control N delivery to the mere from all sources within the catchment until the very high P levels that accumulate in summer have been controlled.

It should also be noted that the current trophic cascade within the system, i.e. predatory birds (Cormorants) that feed on zooplanktivorous fish, thus facilitating an increase in zooplankton grazing on algae (Ian Cowx, HiFi, *pers. comm*.), may also play an important role in the control of potential algal blooms at this site.

6 Summary results and their implications for management of the mere

The key results from this study are outlined below with comments on their implications for the future management of the mere.

6.1 Nitrogen availability limits algal growth in summer

The mere seems to be strongly N limited from April/May to October each year, which explains why chlorophyll *a* levels remain low even though OP levels are exceptionally high. So, limiting N applications to agricultural land within the catchment and controlling N-laden discharges from human sewage and animal waste are probably the best way to control algal blooms at this site in the short term. The recent designation of parts of this area as a nitrate vulnerable zone (NVZ, see Figure 6.1) should contribute to this process, but management of NVZs is aimed, primarily, at reducing losses from agricultural activity within the catchment. So, inputs from other sources, such as sewage effluent, may also need to be evaluated and addressed.

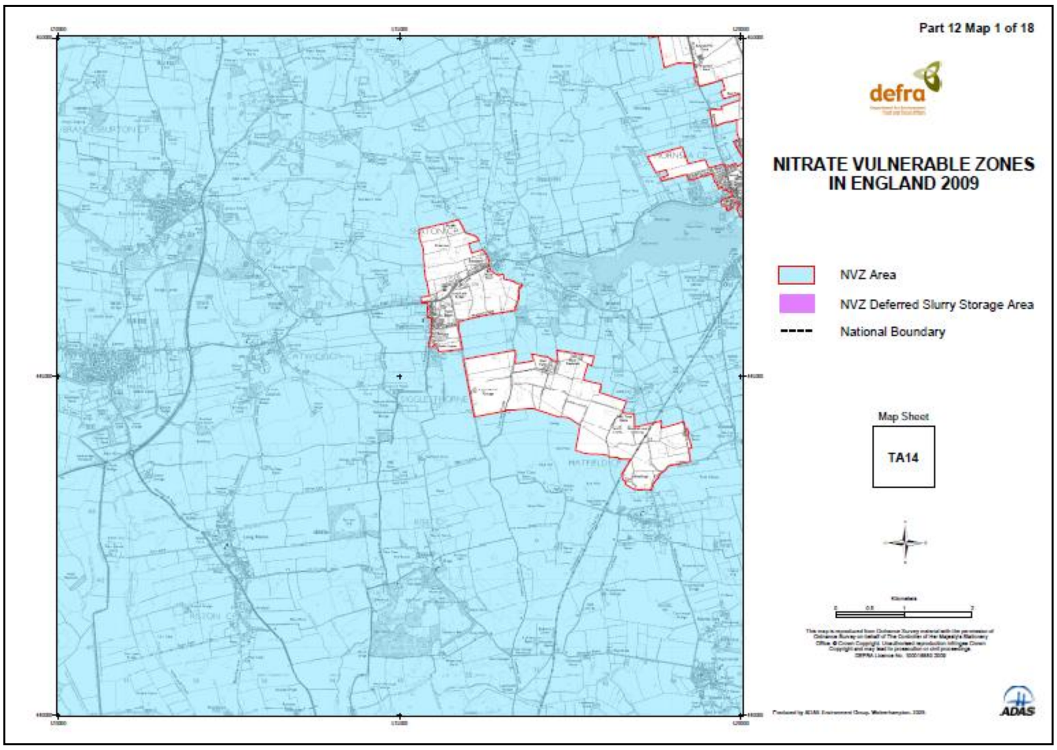


Figure 6.1. Area around Hornsea Mere recently designated as a NVZ. (Source: http://web.adas.co.uk/defra/parts/parts/pdfs/Part12_PDF/Part12_Part%2012%20Map%201%20of%2018.pdf

6.2 Phosphorus inputs need to be controlled to reduce open water P concentrations

As biological productivity within the mere is very low in winter and N limited in summer, open water P concentrations tend to reflect the processes of supply and dilution rather than biological uptake. So, in winter, P concentrations are mainly controlled by inputs from the catchment whereas, in summer, they are mainly driven by sediment release. The very high concentrations that are responsible for the mere failing to meet the JNCC water quality target of 0.5 mg/L mainly occur in summer. For these levels to fall, the amount of P being released from the sediments needs to be reduced. For a lake of this size, sediment removal or capping to reduce internal recycling of P within the mere may not be a practical or cost effective solution. In the first instance, restoration should focus on reducing inputs from the catchment and maximizing losses from the outflow to reduce P availability. Losses from the outflow depend on the rate at which P is flushed from the lake. The overall aim would be to ensure that losses from the outflow exceed inputs from catchment sources, birds and rainfall. To do this, consideration should be given to changing the flushing regime to flush more water from the lake when P concentrations in the water column are highest, i.e. midsummer to autumn.

6.3 Small, unconsented discharges of sewage effluent may be important sources of P

Although there are only six small, consented discharges of sewage effluent within the catchment, there are probably about 300 unconsented discharges of this type in this area. In the past, P discharge from these small sources has been considered negligible in comparison to P losses from agriculture (Bedworth et al., 2005). The present study has shown that, although individually small, when considered together, 300 small consented (2%) and unconsented (98%) discharges may be responsible for a P input to the mere that is similar in size to that of agricultural runoff. In terms of biological response, discharges from these small sources may have a much greater biological impact than losses from agricultural sources because the proportion of biologically available (soluble) P in this effluent (about 90%) is much greater than that in agricultural runoff (30-50%). The number of unconsented septic tanks, their location and the operational status of the systems should be quantified.

The survey of pollution 'hotspots' conducted as part of this study clearly demonstrated the presence of very high P concentrations in streams and drains across the catchment as a result of discharges from small point sources (Figure 5.14). These small discharges need to be located, assessed and controlled, to reduce P inputs to the mere from these sources. Often, this simply involves better maintenance and management of individual tanks by their owners, many of whom are often unaware of the need to empty their systems on a regular basis and keep them in a good state of repair (May et al., 2010).

In addition to P discharges from small point sources, which enter the mere *via* the streams and drains, several small pipes that collect runoff from urban areas discharge directly into the mere itself. These may also be important sources of P. At least one of these pipes, which enters the mere near Chenye Walk, has been shown to cause local changes in the diatom community of the mere that are consistent with nutrient enrichment. Nutrient delivery to the mere from this and other small pipes that discharge directly into the mere needs to be evaluated and addressed, where necessary.

6.4 Sediment delivery is high from some parts of the catchment

There is strong evidence of particulate material entering the western bay of the mere *via* Low Wood Drain under high flow conditions, i.e. following periods of heavy rainfall. This causes at least local degradation in water quality and may have wider implications for the mere as a whole. Of particular concern is potential loss of amenity value due to a reduction in the volume/depth of the mere as a result of silt accumulation. The area around Low Wood Drain comprises mainly arable land, which is probably very susceptible to soil erosion and transport during periods of heavy rainfall. However, vehicular damage to roadside verges in the area may also cause soil erosion problems.

Although the results suggest that the area around Low Wood Drain probably has a particular problem with soil erosion, similar problems may also occur in other areas of the catchment. Fields, paths and roads across these areas need to be managed in such a way as to minimise soil erosion and transport to drainage waters.

6.5 Accepted methods of setting water quality targets may not be applicable to N limited systems

The results of this study have raised issues about the general applicability to N limited systems of methods that are generally available for setting water quality targets for lakes. This is because most of these methods (including chlorophyll *a*/P regression equations developed for implementing the WFD, lake models used to identify critical loads, and diatom-phosphorus transfer functions), are all based on the assumption that shallow lakes are P limited. These issues need further investigation. The results of a separate study that CEH is currently involved in, and which is being funded by NE (project manager Helen Wake), may provide some useful information on this problem. The study is investigating ways of setting realistic nutrient targets for meres in the Midlands (i.e. Shropshire, Staffordshire and Cheshire) which are also N, rather than P, limited. In particular, this project aims to make recommendations on which nutrient targets, i.e. N and/or P, would be the most appropriate for the effective management of these systems.

6.6 Chlorophyll *a* levels are falling

Chlorophyll *a* levels seem to have been falling steadily in recent years, suggesting that water quality in this mere is improving. If so, this is probably a result of catchment management actions that have already been put in place recently, such as agri-environmental schemes and farm nutrient budgeting. Consideration should be given to providing feedback to stakeholders where their actions may have resulted in positive outcomes for the mere, such as the decreasing trends in P and N concentrations shown in Figures 2.1 and 2.2 (see Section 2.2.2) .

6.7 Data availability is limited

This study has collated all available monitoring data on the mere and its catchment. Although water samples have been collected from the mere at roughly monthly intervals since 2000 and analysed for chemical (e.g. TP, PO_4-P, TN, NO_3-N, NH_3-N, SiO_2, DO, etc.), suspended solids and chlorophyll *a* concentrations, monitoring and assessment of nutrient sources within the catchment, especially in the inflows or outflow, have been occasional and sporadic. In particular, there are relatively few data available on rates of flow into or out of the mere, which makes constructing a nutrient budget almost impossible. It is therefore, essential, that better monitoring of water levels and rates of flow is implemented in future, alongside better monitoring of nutrient concentrations in the feeder streams and drains. In 2009 the EA started to record water levels from a gauge board installed in the mere.

In addition, to the above, it was found that very little was known about the ecology of the mere and how the various biological components interact. More detailed information on the effects of piscivorous birds (e.g. Cormorant) on fish populations, and on zooplankton predation rates and their impact on algal biomass, are needed to provide a better understanding of how this ecosystem functions and to enable the ecological effects of environmental change to be predicted and responses to management action assessed.

7 Management Plan

The overall process involved in restoring an impacted lake is summarised in Figure 7.1. First, the water quality targets for the site must be defined and compared to existing conditions. Then, causes of any degradation in water quality must be identified. Finally, appropriate management options must be selected and implemented. In lake water quality needs to be monitored throughout this process to track recovery and determine the ecological responses to that recovery. It is important that lake response is constantly monitored and compared to water quality and conservation targets so that progress can be assessed and documented.

Although target P concentrations have already been set for Hornsea Mere, it is possible that N targets may also need to be set as algal growth in this waterbody is N limited in summer. This issue requires further investigation and may benefit from the results of a parallel study which is assessing the need to set P and/or N targets for meres in the Midlands, which are also N limited in summer. In addition, it is unclear whether diatom transfer coefficients can be used to set baseline P concentrations in N limited lakes in general, although it should be noted that this method has not been used to set restoration targets for this particular waterbody.

The main driver of water quality problems at Hornsea Mere is nutrient enrichment. So, the first priority, in terms of improving water quality and promoting sustainable recovery, is to identify and control nutrient inputs from the catchment. These include inputs of both nitrogen (N) and phosphorus (P). As algal growth within the mere is strongly limited by N availability during the summer, the highest priority in the short term is to focus on controlling N inputs because as any increase in N availability when P concentrations are high could result in the development of significant algal blooms.

It is also important to reduce the delivery of P and sediments to the mere from the catchment, as these will continue to drive high levels of P in the water column through direct supply and through the recycling of P from the sediments in summer. It is important to recognise, however, that nutrient and sediment delivery are closely linked, with agricultural sediments often providing a transport mechanism through which P is delivered to waterbodies under high flow conditions. So, it is not possible, or even desirable, to address N, P and sediment delivery issues separately. For this reason, the action plan outlined below takes a practical approach to solving these problems by addressing these pollutants by source rather than addressing each pollutant separately.

Reducing external inputs is only part of the solution to water quality problems in Hornsea Mere. In parallel to the identification and control of external inputs, internal recycling of P must also be addressed to reduce the very high open water concentrations of P that develop over the summer months. Although it is theoretically feasible to remove P laden sediment from the bottom of the mere by dredging or to prevent P release by capping the sediments, these solutions are very expensive to apply to a relatively large waterbody such as Hornsea Mere. They may also be potentially damaging to the conservation interest of the mere, especially with respect to the macrophyte community. In addition, any improvements in water quality as a result of these activities will not be sustainable in the long term unless external inputs have been reduced. For this reason, it is recommended that, in the short term, the possibility of manipulating the flushing regime of the mere to increase the flushing rate in summer, when P concentrations are high, should be explored in the first instance.

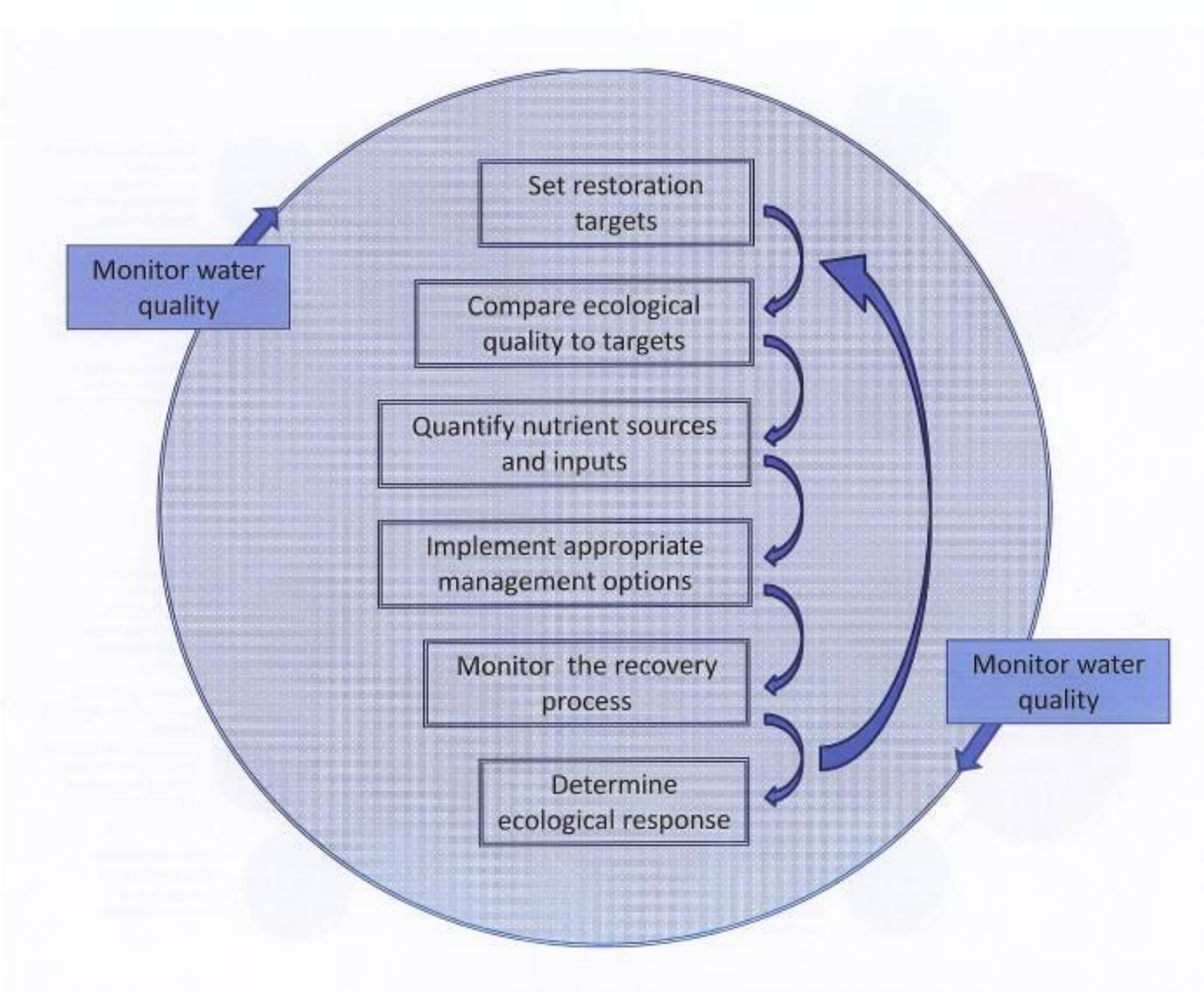


Figure 7.1 **Process involved in restoring an impacted lake.**

The aim of decreasing inputs of nutrients from the catchment and increasing losses *via* the outflow is to achieve an overall loss of nutrients from the system. Once this has been achieved, the lake will begin to recover, with mean annual open water P concentrations falling over time. It may, however, take many years for the mere to achieve mean annual in-lake P concentrations that approach the target values that have been set.

Although there is clearly a need for more ecological monitoring of the mere to gain a better understanding of how this system functions and to track its recovery, this is much less of a priority for management purposes in the immediate future than reducing inputs and increasing outputs of nutrients. This is because concerns about water quality in this system are currently driven by water chemistry problems (i.e. exceptionally high OP concentrations in summer) rather than biological interactions at the present time. Nevertheless, it should be noted that the current trophic cascade within the system, i.e. predatory birds (Cormorants) that remove zooplanktivorous fish thereby facilitating an increase in zooplankton grazing on algae (Ian Cowx, HiFi, *pers. comm*.), may also play an important role in the control of potential algal blooms at this site.

7.1 Specific Actions

The specific actions required to manage the mere and improve its water quality are outlined below and summarized in Figure 7.2 and Table 7.1.

7.1.1 Set management targets

7.1.1.1 Nutrient concentrations

The current water quality target for Hornsea Mere is an annual average TP concentration of 0.05 mg P/L (Coverdale, 2009). However, it is unclear whether accepted methods for setting nutrient concentration targets for lakes, such as paleolimnological and modelling methods, are applicable to N limited systems such as this. Further research is needed to address this issue. A joint project between University College London (Helen Bennion, ECRC University College London) and CEH (Linda May/Bryan Spears) is planned to investigate whether the diatom/TP transfer function, which is commonly used to determine baseline TP concentrations in lakes, is applicable to N limited systems. The applicability of the method will be tested on data from a wide range of N limited systems. Also, the outcome of a NE funded project on the Midlands Meres should provide some useful information on setting nutrient concentration targets in these systems. In the longer term, nutrient concentration targets for Hornsea Mere should be reviewed, and revised if necessary, as better methods of setting targets are developed for application to systems in which N limitation is important.

7.1.1.2 Aquatic birds

Management targets for aquatic bird populations and aquatic plant species at Hornsea Mere are given by Coverdale (2009). In terms of the internationally important Gadwall, the aim is to maintain the population at more than 50% of the population at the time of designation (i.e. at more than 50% of the 5 year average peak count of 210 for 1987-1992). Similar targets have also been set for nationally important species, based on the following average peak counts: Shoveler (90), Tufted duck (500), Pochard (361) and Goldeneye (210). Reed warblers also need to be maintained at more than 75% of the population level at the time of designation, i.e. 800 breeding pairs.

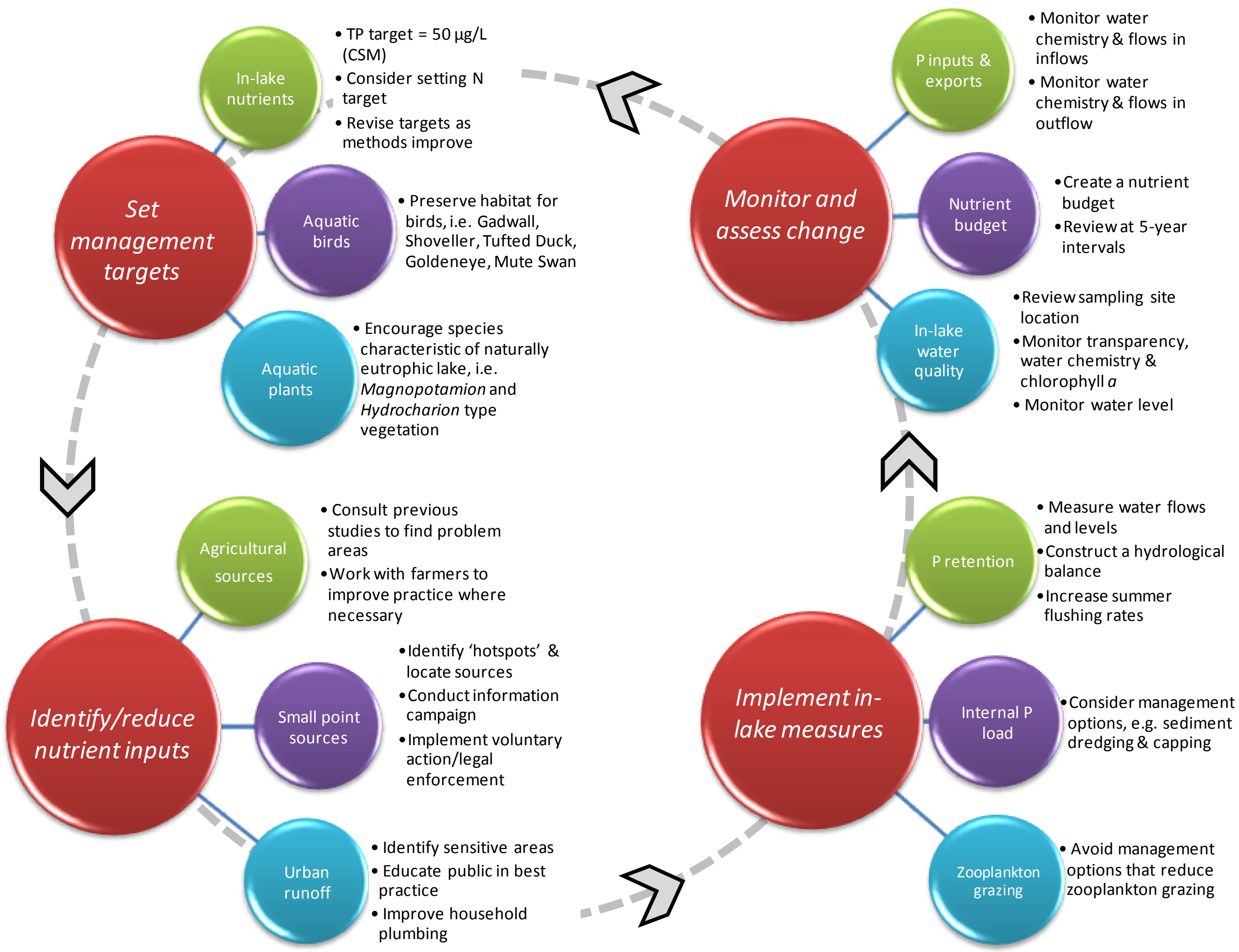


Figure 7.2 **Overview of specific actions required to manage the mere and improve its water quality.**

7.1.1.3 Aquatic plants

In relation to aquatic plant species, the conservation objectives aim to maintain a community that is characteristic of natural eutrophic lakes with *Magnopotamion* and *Hydrocharition* type vegetation. In this context, *Magnopotamion*, includes Lesser pondweed (*Potamogeton pusillus),* fan-leaved water-crowfoot (*Ranunculus circinatus*)*,* stonewort *Chara* spp. (*C. Globularis)* and associated species such as rigid hornwort (*Ceratophyllum demersum),* fennel pondweed (*P. pectinatus*) and spiked water-milfoil (*Myriophyllum spicatum*)*.* Similarly, *Hydrocharition* spp. includes Duckweed *Lemna sp*. and the associated species, Yellow water-lily (*Nuphar lutea*). In addition to characteristic species being present, there is a requirement that there should be few or no non-native species present, and that the cover of benthic and filamentous algae should be less than 10%. Finally, the conservation objectives require the maximum growing depth of submerged vegetation not to fall by more than 20% of the depth measured in 2004, i.e. 2.25 m.

7.1.2 Identify/reduce nutrient inputs

The main sources of nutrients within the catchment of Hornsea Mere are agricultural land, small sewage treatment facilities (mainly septic tanks) and runoff from urban areas and roads. Recommendations for reducing inputs from these sources are outlined below.

7.1.2.1 Agricultural sources

Every farm within the catchment should be encouraged to manage their nutrient budgets carefully to keep N and P surpluses to a minimum to reduce nutrient laden runoff. If sewage sludge is spread on land within the catchment, this should be included in the nutrient budget.

Farmers should also be encouraged to implement best farming practices (Environment Agency, 2008), many of which are specifically aimed at reducing contamination of water courses within the catchment. These include:

- Keeping animals away from watercourses
- Managing farm drainage effectively
- Creating ponds, reed beds and buffer strips to trap nutrients and eroded soils transported by runoff
- Ploughing along contours in steep areas and using minimum tillage where possible
- Growing cover crops on autumn harvested land that is destined for spring cultivation
- Establishing permanent grass or woodland on slopes that are greater than 11 degrees
- Storing slurry and manure safely, only spreading at appropriate times and under favourable weather conditions
- Measuring soil P content to enable fertiliser applications to be focused on areas where there is a P deficit

Many of these recommendations have been, or are being, addressed within the catchment under a catchment sensitive farming (CSF) initiative that is promoting best farming practice to reduce diffuse water pollution, such as the Entry Level Stewardship (ELS) and Higher Level Stewardship (HLS) agri-environmental schemes. Careful management of nutrient budgets is also required as part of the recent designation of much of the area as a nitrate vulnerable zone. It is also likely that recent increases in fertiliser costs, especially in relation to P, will also reduce fertilizer application rates within the catchment.

Although likely to come from a range of sources, monitoring data from this study clearly shows that some areas of the catchment, especially areas around Low Wood Drain, still have soil erosion problems that need to be addressed. It is important that any agricultural sources of sediment are identified and controlled quickly. In addition to reducing nutrient and sediment losses at source, wetlands and reed beds could be used to trap suspended sediments within the drainage system and prevent nutrients and eroded material from entering the mere.

7.1.2.2 Small point sources

Up to 50% of the P that is entering the mere may be coming from small discharges of effluent associated with private sewage treatment works and septic tanks. Most of these are not consented. Discharges from these sources need to be identified and controlled. In many cases, discharges from these systems are high because they are badly maintained and/or managed. In particular, there is a widely held belief across the UK that septic tanks do not need to be emptied if they are working properly. As a result, many are full of accumulated sludge and overflow into nearby watercourses causing pollution problems (May et al., 2010). It is estimated that there are about 300 septic tanks or private sewage treatment facilities within the catchment of Hornsea Mere, although the exact number of tanks and their location is unknown.

The first step in managing this problem is to locate all septic tanks within the area. As most are not registered, this information needs to be derived from other sources. One possible approach is to determine the location of all households that lie outside the areas that are known to be served by mains sewerage systems (May et al., 2010). These households can then be targeted as part of an information campaign aimed at highlighting the need to empty and maintain all septic systems. This could also be supplemented with site visits and inspections and/or a more general public information campaign mediated through local newspapers or council newsletters.

In addition to the above, it is also important to carry out occasional surveys to identify ‘hotspots’ of P contamination in streams and drains across the catchment so any remaining problems can be identified and controlled. It is recommended that such surveys should be undertaken during dry conditions when P concentrations are likely to be at their highest. This is because effluent dilution under high flow conditions, e.g. following heavy rainfall, will tend to make ‘hotspots’ and sources of contamination more difficult to locate. Occasional surveys of pollution ‘hotspots’ will provide information on where efforts to encourage voluntary reductions in discharges have failed and where it might be more appropriate to engage legal enforcement options.

7.1.2.3 Urban runoff

In addition to foul water sewerage systems, some urban areas of the catchment also have grey water drainage systems that collect and transport road and roof runoff and discharge it directly into the mere. These systems include, for example, the pipe that enters the mere near Cheyne Walk, which has been shown to carry nutrient laden runoff (Yates, 2001). As nutrient levels in freshly fallen rain are low, the runoff water from these areas appears to be collecting nutrients *en route* as it travels from the catchment to the mere. The main sources of these nutrients are likely to be detergents entering surface water drains when residents wash their cars or waste from incorrectly plumbed domestic appliances and shower room facilities (Bedworth, 2005; Andrew MacLachlan, East Riding of Yorkshire Council, *pers. comm*.). These problems need to be addressed. The possible diversion of the Cheyne Walk and other outfall pipes away from the mere should also be considered.

A good initial approach for solving this problem would be to highlight to local residents that waste water tipped down the drain goes directly into Hornsea Mere, potentially causing eutrophication problems. In a recent publicity campaign in Scotland, the Scottish Environment Protection Agency (SEPA) addressed similar problems by involving groups of volunteers in stencilling yellow fish beside all surface water drains in residential areas (Figure 7.3) to remind people that waste tipped down a drain could contaminate a watercourse. Guidance on how this campaign was run can be found at http://www.sepa.org.uk/water/water_publications/yellow_fish.aspx. Another possible approach would be to encourage residents from using phosphate free detergents.

Figure 7.3 Yellow fish painted beside road drain to remind residents that pouring waste down a drain can cause contamination of watercourses.

In the longer term, the problem of incorrectly plumbed domestic appliances also needs to be addressed. Tracers (e.g. boron, caffeine, faecal indicators, *etc*.) could be used to identify where these sources of nutrients are important. For example, the presence of high levels of boron in drainage water would confirm contamination with waste containing detergents (Neal et al., 1998), while the presence of caffeine, boron and faecal indicators would suggest sewage contamination.

It should also be noted that soil erosion problems within the catchment are not confined to agricultural areas. Roads also seem to be a source of suspended material entering the mere, with many being very narrow and having soft margins that are disturbed by passing traffic. When it rains, this loosened material may wash off the surface of the road into drainage channels or into the mere, itself. It is also important to note that roads can also be an efficient conduit of eroded soil material from source areas to drainage channels under high rainfall conditions. Consideration needs to be given to how this problem can be resolved, although there is unlikely to be a cheap or immediate solution to this problem. In the short term, the installation of silt traps in areas that have an obvious problem should be considered. In the longer term, improvements to road margins could be addressed when roads are upgraded or re-surfaced.

7.1.3 Implement in-lake measures

7.1.3.1 Reduce P retention

It is possible that P levels in the mere remain high in summer because the outflow is artificially controlled to retain water in the mere to meet stakeholder requirements for amenity purposes over this period. Controlling the outflow in this way means that the flushing is very low during periods when P levels are high, effectively preventing P from leaving the system. If flushing could be increased when P levels are high, more P would be discharged from the system. This would reduce the P retention rate of the mere.

It would be difficult to manage this effectively, while meeting the requirements of all stakeholders, without fairly detailed information on seasonal changes in water level in the mere and rates of flow in the main inflows and outflow. The best way of collecting this information would be to install flow meters or calibrated depth measuring devices that would automatically collect this information on a daily or sub-daily basis. It is therefore recommended that such systems are installed on at least the mere, the three main inflows and the outflow. It should be noted, however, that calibrated depth measurement systems may not be suitable for use on the outflow because, here, an increase in water level might reflect a reduction in flow caused by the effects of a high tide on downstream flows rather than an increase in flow, as would be expected in a freely flowing river. These data and any proposal for changing the water level management regime to increase flushing rates in summer would form part of any future water level management plan for the mere.

In addition to surface water flow, it is possible that interactions with groundwater also affect the hydrological balance of the mere. A project currently being undertaken by the British Geological Survey may provide further information on this.

7.1.3.2 Reduce internal P load

In the longer term, it is possible that reducing inputs to the mere and increasing outputs from it will still not reduce annual average P concentrations sufficiently to meet water quality targets. If so, it may be necessary to consider further measures to reduce P release from the sediments. These options include in-lake measures such as sediment dredging or sediment P stripping/capping. These methods are both relatively expensive and should only be considered if P release from the sediments continues to be a problem once external inputs have been reduced, and only after a careful consideration of the likely ecological impacts and potential cost.

7.1.3.3 Encourage zooplankton grazers

Very few data are available on the various components of the ecosystem in Hornsea Mere, such as predatory birds, fish, zooplankton and algae. Nevertheless, as zooplankton are the most important grazers of algae in lakes, it seems sensible not to implement any management activities that are likely to reduce their numbers. This includes increasing existing populations of zooplanktivorous fish or introducing new species that feed on zooplankton.

The current status of the fish population is unclear, but it has been suggested that fish in the mere are heavily predated upon by cormorants. As a result, they shelter under man-made structures and are rarely found in the open water. It has been suggested that artificially increasing the number of fish refugia across the mere would increase the number of fish and increase their habitat. Care should be taken to ensure that this does not result in increased predation of zooplankton populations by fish, as this would reduce zooplankton grazing and potentially increase the likelihood of algal blooms occurring.

7.1.4 Monitor and assess change

7.1.4.1 Monitor external P inputs and exports

Managing nutrient budgets and hydrological balances in such a way as to promote the recovery of the mere requires basic information on both nutrient concentrations and corresponding rates of flow to be collected at regular intervals for the inflows and outflow. This is because the amount, or load, of nutrients entering the mere from the catchment, or leaving the mere, can only be calculated if both the concentration and flow are known. In the past, several surveys have collected concentration data but only one has collected corresponding flow data. Even this study, which collected data at roughly monthly intervals, did not collect sufficient data on flows for a nutrient budget to be constructed.

The best approach to developing a nutrient budget for the mere would be for samples to be collected at a fortnightly frequency or higher from all inflows and the outflow over a 12 month period. The samples should be analysed for TP, PO_4-P, TN, NO_3-N, NH_3-N, SiO_2, chlorophyll *a*, suspended sediments and dissolved oxygen. Corresponding measurements of stream discharges at the time of sampling should also be taken. These might simply be spot readings of water levels taken from a staff gauge that has been calibrated against flow over a range of high, intermediate and low water levels on each inflow and outflow. Samples should be taken and flows measured as close to the mere as possible. Assessment of nutrient inputs and exports should be made at least every 5 years to track the progress of improvements brought about by management activities.

7.1.4.2 Create a nutrient budget

Once these data have been collected, a nutrient budget can be created from which it will be possible to determine the load of nutrients entering the mere in the inflows and the amount that is leaving *via* the inflow. If more is leaving than is entering, it can be assumed that the mere is beginning to recover. However, if the external load has been reduced and inputs are still greater than exports, additional manipulation of the system may be required to facilitate recovery. This procedure should be repeated at 5-year intervals to monitor the recovery process.

7.1.4.3 Monitor in-lake water quality

The response of the mere to changes in nutrient inputs and outputs needs to be monitored to determine the effectiveness of measures as they are implemented. As a minimum, nutrient and chlorophyll *a* concentrations need to be measured at monthly intervals. This would be mainly a continuation of the monitoring that is already carried out on the mere by the EA, although the location of the sampling site and the degree to which it represents water quality across the mere needs to be reviewed.

As one of the concerns about water quality problems in the mere relates to the incidence and intensity of algal bloom development in the summer months, data on algal species composition and abundance should also be collected. At present, there is only anecdotal evidence that such blooms occur as the chlorophyll *a* levels recorded here are generally low. In addition, it would be useful to measure changes in water transparency at frequent intervals, e.g. weekly, to determine when low water clarity occurs and, by inference, what its likely cause might be. Measurements of water clarity should be made from a boat in open water using a Secchi disk.

Table 7.1 Specific actions required to manage the mere and improve its water quality.

Set management targets			
Criterion	***Target***	***Status***	***Priority***
Phosphorus	Annual mean TP concentration ≤ 50 µg/L (Coverdale, 2009)	Set; may require revision	n/a
Nitrogen	N concentration target required	To be set when methods become available	High
Aquatic birds	Maintain average annual peak counts for Gadwall (≥ 105), Shoveler (≥ 90), Tifted Duck (≥ 500) Pochard (≥ 361) Goldeneye (≥ 210) (Coverdale, 2009)	Set	n/a
Aquatic plants	Maintain species composition characteristic of a naturally eutrophic lake with *Magnapotamion* and *Hydrocharion* type vegetation; maintain maximum growing depth at ≥ 1.8 m (Coverdale 2009)	Set	n/a

Identify/reduce nutrient inputs			
Source	***Actions***	***Status***	***Priority***
Agriculture	Develop nutrient budgets for each farm to reduce N and P surplus	Forms part of NVZ requirements	M
	Identify problem areas by monitoring N, P and suspended solids in drainage water	Forms part of on-going CSF initiative	M
	Encourage farmers to follow best management practices aimed at reducing nutrient loss and soil erosion problems	Forms part of on-going CSF initiative	M
Small point sources	Identify ‘hotspots’ of P contamination across the catchment using a ‘streamwalk’ approach; repeat under high and low flow conditions	To be completed	H
	Identify the main sources of these discharges (consented and unconsented)	To be completed	H
	Reduce discharges from these sources through public information campaigns, voluntary action and legal enforcement	To be completed	H
Urban runoff	Identify urban areas responsible for contaminated runoff to the mere (e.g. *via* discharge pipes or road runoff)	To be completed	M
	Educate residents in best practice for disposing of household waste water	To be completed	M
	Ensure household appliances are correctly plumbed	To be completed	M

Implement in-lake measures			
Objective	***Actions***	***Status***	***Priority***
Reduce P retention in the mere	Monitor flows in inflows and water level in mere for at least one year	To be completed	H
	Construct a hydrological balance for the mere	To be completed	M
	Increase summer flushing rates when P concentrations are high, if possible	To be completed	M
Reduce internal P load from sediments	Explore management options such as dredging and sediment capping	To be completed	L
	Review likely impact of management options on conservation interest of the mere	To be completed	L
	Review likely cost effectiveness of implementing costly management options	To be completed	L
Maintain or increase zooplankton grazing rates	Assess the importance of zooplankton grazing on algal abundance (chlorophyll *a*) in the mere	To be completed	M
	Assess the fish population and its likely impact on densities of zooplankton grazers	To be completed	M
	Avoid management options that could reduce zooplankton numbers significantly, e.g. increasing the number of zooplanktivorous fish	To be completed	M

Monitor and assess change			
Variables	***Action***	***Status***	***Priority***
P inputs from catchment and losses to outflow	Monitor water chemistry and flows in inflows and outflow at weekly/fortnightly intervals for at least one year	To be completed	H
	Determine annual and seasonal inputs from each inflow and losses from the outflow	To be completed	H
Nutrient budget	Construct a nutrient budget for the mere to determine P retention rate (a negative value would indicate recovery)	To be completed	M
	Review at 5-yearly intervals to monitor progress of restoration measures	To be completed	M
In-lake water quality	Review location of routine sampling site to address issues relating to its proximity to pipes/drains delivery contaminated water to the mere	To be completed	H
	Record transparency at frequent intervals from a boat using a Secchi disk	To be completed	H
	Monitor water chemistry, chlorophyll a concentrations and water level	To be continued	H

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10 List of abbreviations

AMP	Asset Management Plan
CSF	Catchment Sensitive Farming
CSM	Common Standards Monitoring
CEH	Centre for Ecology and Hydrology
DoE	Department of the Environment
DI-TP	Diatom phosphorus transfer function
DO	Dissolved oxygen
EA	Environment Agency
ELS	Entry Level Stewardship
GIS	Geographical Information System
HIFI	**H**ull University **I**nstitute of **Fi**sheries
HLS	Higher Level Stewardship
JNCC	Joint Nature Conservation Committee
LCM2000	Land Cover Map of Great Britain 2000
N	Nitrogen
NE	Natural England
NGR	National Grid Reference
NRA	National Rivers Authority
NVZ	Nitrate Vulnerable Zone
OP	Orthophosphate
OS	Ordnance Survey
P	Phosphorus
PE	Population equivalent
RoC	Review of Consents
SAC	Special Area of Conservation
SEPA	Scottish Environment Protection Agency
SPA	Special Protection Area

SRP	Soluble reactive phosphorus
SS	Suspended solids
SSSI	Site of Special Scientific Interest
TP	Total phosphorus
WFD	Water Treatment Framework Directive

Appendix 1 Sampling sites for spatial survey of TP concentrations across Hornsea Mere, 1/12/09.

Site	Latitude (Degrees)	Longitude (Decimal degrees)
1	53.90692	-0.17667
2	53.90636	-0.17597
3	53.90569	-0.17586
4	53.90481	-0.17594
5	53.90514	-0.17750
6	53.90608	-0.17961
7	53.90703	-0.18075
8	53.90806	-0.18175
9	53.90900	-0.18311
10	53.90883	-0.18011
11	53.90903	-0.17686
12	53.90811	-0.17833
13	53.90844	-0.18358
14	53.90892	-0.18447
15	53.90936	-0.18528
16	53.90833	-0.18622
17	53.90703	-0.18225
18	53.90556	-0.18103
19	53.90439	-0.18058
20	53.90272	-0.17978
21	53.90317	-0.18192
22	53.90483	-0.18481
23	53.90650	-0.18650
24	53.90942	-0.19003
25	53.90942	-0.19217
26	53.90772	-0.19125
27	53.90567	-0.18989
28	53.90333	-0.18844
29	53.90300	-0.19119
30	53.90458	-0.19281
31	53.90708	-0.19483
32	53.90717	-0.19692
33	53.90586	-0.19633
34	53.90439	-0.19522
35	53.90264	-0.19403
36	53.90342	-0.19706
37	53.90381	-0.19842
38	53.90411	-0.19983
39	53.90344	-0.20119
40	53.90267	-0.20167
41	53.90192	-0.20217
42	53.90164	-0.20392
43	53.90214	-0.20633

Appendix 2 Sampling sites for sediment survey across Hornsea Mere, 1/12/09.

Site	Latitude (Degrees)	Longitude (Decimal degrees)
1	53.90569	-0.17719
2	53.90428	-0.18417
3	53.90361	-0.19139
4	53.90375	-0.19797
5	53.90200	-0.20617
6	53.90572	-0.19644
7	53.90908	-0.19069
8	53.90606	-0.18594
9	53.90858	-0.17967