A REVIEW OF THE CURRENT STATUS OF THE LONDON WETLAND CENTRE AND RECOMMENDATIONS TO ENHANCE WATER QUALITY

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SUMMARY

The LWC is receiving a heavy loading of phosphorus from the River Thames. Mean inflow concentration is >400 µg l^{-1}. The high nutrient loading is favouring dense growths of cyanobacteria, particularly *Aphanizomenon flos-aquae*. Blooms occurred in July and November 2005. A spring diatom bloom occurred in 2006 also, as a consequence of high densities of algae entering the system from the River Thames. It appears that nutrient recycling from the sediment is not a major part of the dynamics of the system to date; this may change. Macrophytes are not present in Reservoir Lagoon, but remain in Main Lake and Sheltered Lagoon. The more frequent occurrence of dense blooms in recent years is associated with an increasing fish biomass. There is a gradient of fish biomass across the LWC, highest in Reservoir Lagoon and lowest in Sheltered Lagoon. Fish appear to have removed larger benthic invertebrates and predatory zooplankton from the Reservoir Lagoon, and are now reliant upon zooplankton and chironomid prey. Fish predation on zooplankton enables the algal blooms to develop. Fish growth rate appears to have declined over time as densities have increased. Expected further increase in fish biomass will lead to further deterioration of the system. Lack of management action will result in deterioration of Reservoir Lagoon and Main Lake. Sheltered Lagoon appears to be stable and requires little management but, as it is at the hydraulic end of the system, will benefit from improvements upstream. To improve water quality in the LWC it will be necessary to manage both the supply of nutrients to the system and the fish populations.
It is recommended that management take action to,

1. Reduce nutrient concentrations, particularly phosphorus, in the inflowing water by phosphorus stripping. This will reduce the potential for algal blooms and increase water clarity.
2. Reduce fish biomass in the Reservoir Lagoon. This will reduce predation on zooplankton and benthic invertebrates, and will result in improved water clarity and increased macrophyte growth.
3. Introduce piscivorous fish (preferably pike, *Esox lucius*) to Reservoir Lagoon, Main Lake and possibly Sheltered Lagoon. This will help control the fish populations.
4. Continue to monitor the system. It would be preferable to include Total Phosphorus (after digestion), Light Attenuance (measured in situ) and benthic invertebrates in the sampling programme. This will enable any improvements to be assessed and increase the understanding of the system.

Actions 2 and 3 may potentially have a negative impact on piscivorous birds, but the overall improvement in the quality of the site will be beneficial to wildfowl and likely to provide more food for herbivorous and invertivorous birds. However, there is also the possibility that improvements in water clarity and macrophyte abundance will result in better hunting conditions for piscivorous birds.
It is possible that the macrophytes in Reservoir Lagoon will need to be protected from herbivorous birds by mesh enclosures as they re-establish.

INTRODUCTION

The Wildfowl and Wetland Trust's London Wetland Centre is situated within a loop of the River Thames at Barnes (Ordnance Survey TQ 228770). The site comprises a 42 hectare complex of artificial wetlands and water bodies, created by the Wildfowl and Wetland Trust on the site of a former "concrete bowl" reservoir. It is supplied with River Thames water (abstracted at Hampton) via the Thames-Lee Tunnel. Water drawn from the tunnel at the Pump House first enters Reservoir Lagoon, one of three large water bodies on the site. The other two large water bodies, Main Lake and Sheltered Lagoon, are connected to Reservoir Lagoon by a complex of smaller ponds and channels, and an intermittently-flooded Wader Scrape. Water leaves the site via an overflow from Sheltered Lagoon, the hydrological endpoint of the site, to rejoin the adjacent tidal River Thames.

Since its creation the London Wetland Centre has developed into a focal point of conservation, offering hundreds of thousands of visitors the chance to see rare and beautiful wetland wildlife just a stone's throw from central London. In February of 2002 the site was designated a Site of Special Scientific Interest (SSSI), supporting nationally important numbers of Gadwall and Shoveller Duck. The site has also supported a notable flora of aquatic macrophytes.

In recent years, however, dense algal blooms have occurred in the three lakes. As well as being unsightly, the managers of the London Wetland Centre have expressed concern that the algal blooms are indicative of changes within the system that may lead to a decline in the ecological quality of the site. To investigate the factors that lead to the occurrence of the algal blooms at the London Wetland Centre, a series of investigations were commissioned by the Wildfowl and Wetlands Trust. It is the role of this report to collate this information, to provide a more thorough understanding of the causes of the algal blooms, and to recommend remedial action to reduce the impact of the algal blooms on the London Wetland Centre.

DATA COLLECTION

Data have been collected on various biological elements at the London Wetland Centre since its creation, notably on birds, fish, macrophytes, and phytoplankton. These data provide the background against which the current status was assessed. In the year 2005/6 several elements were assessed concurrently, at a number of positions around the London Wetland Centre site. The elements comprise,

Discharge
Discharge of water entering the LWC from the Thames-Lee Tunnel, and leaving the LWC via the outflow from Sheltered Lagoon (WWT and ENSIS).

Water Chemistry
Measured over an annual cycle at eight positions within the LWC, namely the Thames-Lee Tunnel at the Pump House, Reservoir Lagoon, Reed Bed Filters, World's Wetlands, Main Lake, Inflow into Sheltered Lagoon (from World Wetland), Sheltered Lagoon, Outflow from Sheltered Lagoon into River Thames (ENSIS and EA). At each position the following analyates were measured

- Total Phosphorus
- Soluble Reactive Phosphorus
- Total Oxidised Nitrogen
- Ammoniacal Nitrogen
- BOD
- Suspended Solids
- Conductivity
- Chlorophyll

Phytoplankton and zooplankton
Species composition measured over an annual cycle from samples integrated over depth from Reservoir Lagoon, Main Lake, and Sheltered Lagoon (ENSIS).

Macrophytes
Community composition and cover (as PVI, proportion of the water column volume infested) in mid-summer, from Reservoir Lagoon, Main Lake, and Sheltered Lagoon (ENSIS).

Fish
Abundance, biomass, diet and growth in spring and autumn from Reservoir Lagoon, Main Lake, and Sheltered Lagoon (Middlesex University).

This concerted effort was undertaken to ensure a more thorough understanding of the causes of the high densities of algae observed on occasions in the previous year.

RESULTS

Discharge

The LWC is fed by a metered water supply from Thames-Lee Tunnel. Although all water enters via Reservoir Lagoon, and leaves via Sheltered Lagoon, routes of flow through the LWC vary depending on which of the Reservoir Lagoon sluices are open, which in turn is affected by management strategy and season. Whereas residence time could be calculated for Reservoir Lagoon and Sheltered Lagoon, it was not possible to estimate residence time for Main Lake accurately. A minimum value was calculated assuming all the water entering the Reservoir Lagoon passed through Main Lake, as the discharge through World Wetland, Wader Scrap and directly to Sheltered Lagoon were not known.

Annual Water Consumption by the LWC = 467,389 m^3

Residence time for Reservoir Lagoon = 63 days

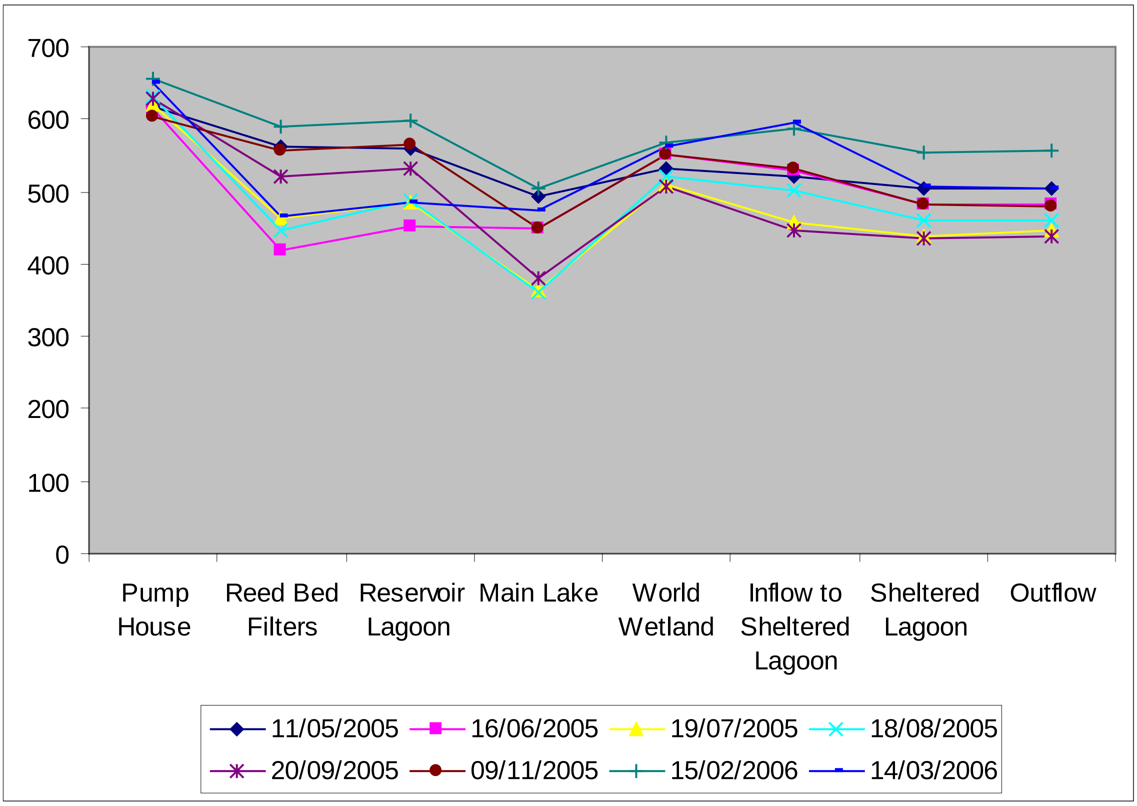
Residence time for Main Lake > 63 days

Residence time for Sheltered Lagoon = 19 days

Conductivity

The conductivity of the water was highest in the inflowing water, sampled at the pump house (Figure 1a). The conductivity was slightly lower within the LWC, particularly the main lake, with this reduction brought about by a loss of ions or by dilution with rainwater. The more marked decline in summer would suggest the loss of ions (through uptake or precipitation) as a more likely cause (Figure 1b).

a)



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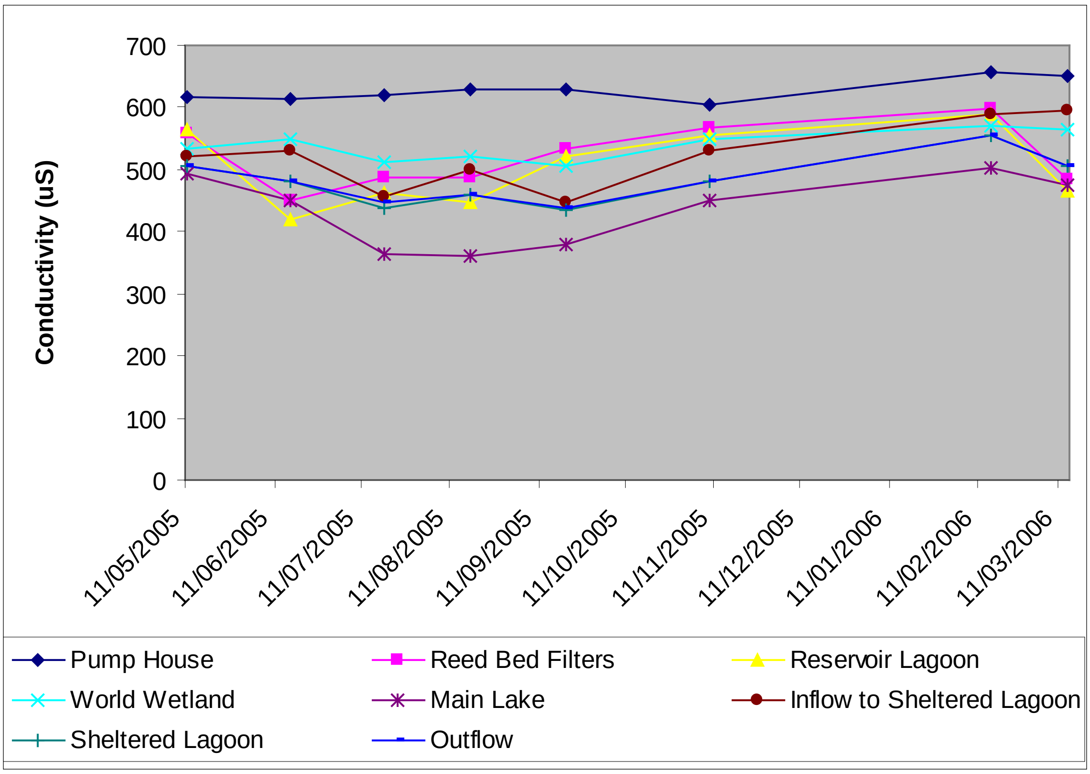


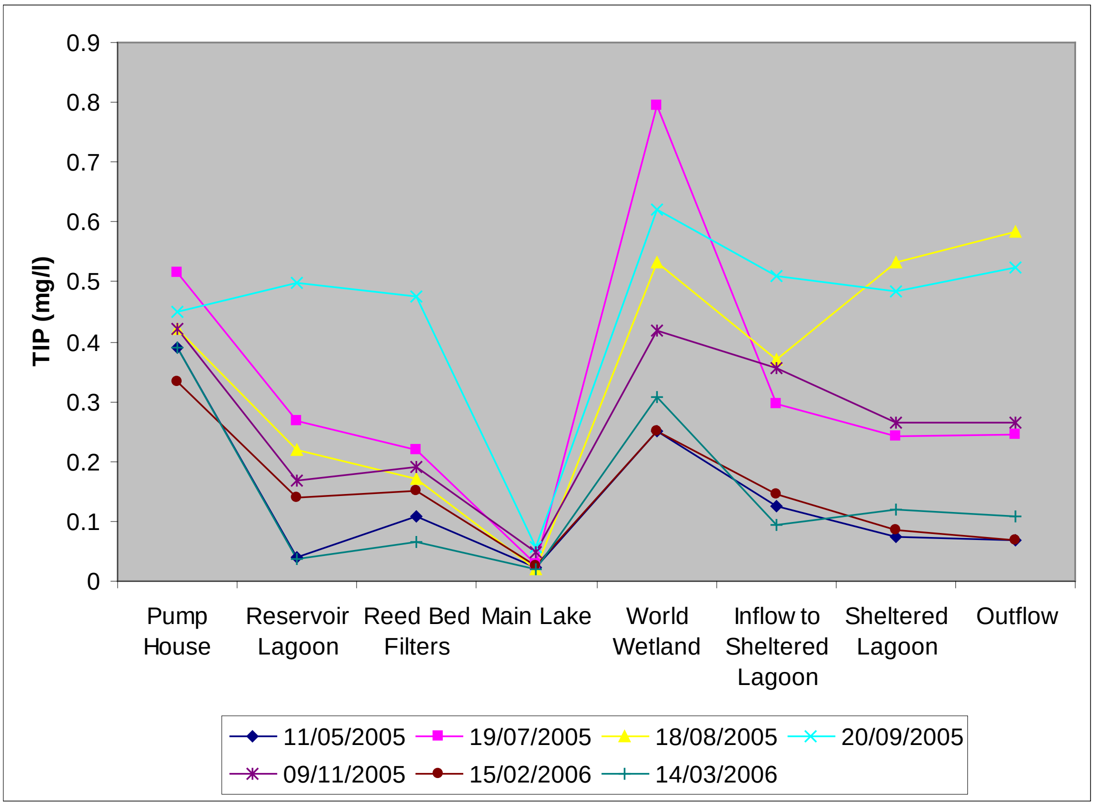
Figure 1. Variation in conductivity with a) position and b) date.

Phosphorus

The water entering the LWC from the River Thames had a high concentration of total inorganic phosphorus, mean concentration = 417 µg l^{-1} (Figure 2a). The concentration declined through the LWC system, reaching the lowest average concentration in Main Lake, through biological uptake. A high concentration of total inorganic phosphorus occurred in World Wetland, where an additional input occurred as a result of faecal matter inputs from wildfowl. Although there was some decline in total inorganic phosphorus concentration by the time the water left World Wetland and entered Sheltered Lagoon, the concentration in Sheltered Lagoon was higher than main lake (Figure 2a).
Over the annual cycle, total inorganic phosphorus tended to increase towards autumn and winter when biological activity in the LWC and in the source of the water, the River Thames, was at its lowest (Figure 2b).

A substantial proportion of the inorganic phosphorus entering the LWC from the Thames-Lee Tunnel was in a readily available form; mean soluble reactive phosphorus concentration = 363 µg l^{-1} (Figure 3a). Once within the LWC the available phosphorus was readily taken up, with concentrations particularly low in the Main Lake. The concentration of soluble reactive phosphorus peaked in World Wetland, due to inputs of bird faecal matter, which appeared to have some influence on the concentration in Sheltered Lagoon downstream.
Soluble reactive phosphorus followed a similar annual cycle to total inorganic phosphorus, peaking in late autumn/winter.

a)



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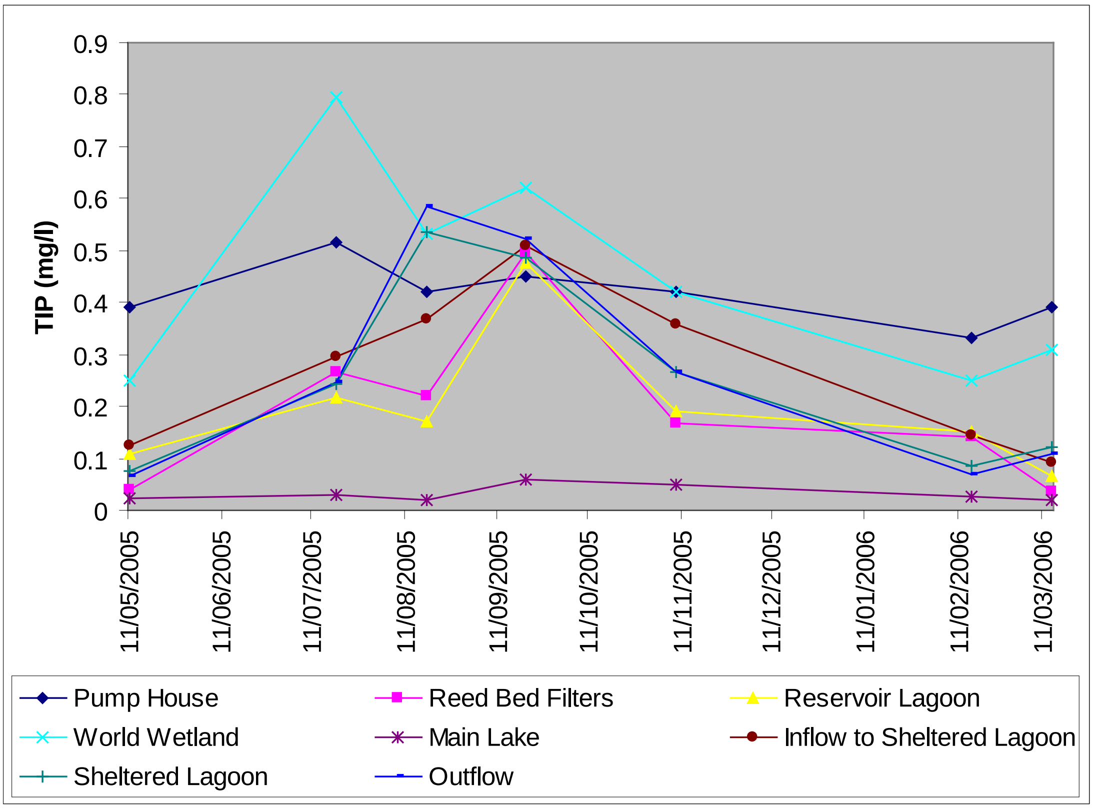
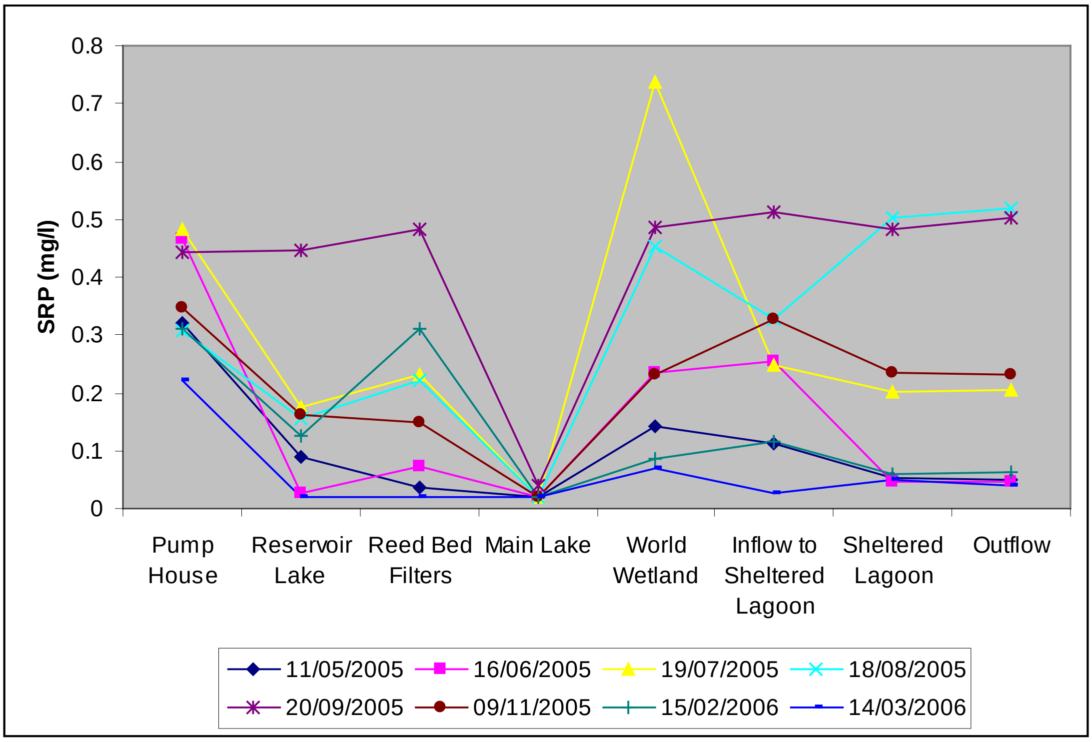


Figure 2. Variation in total inorganic phosphorus concentration on and b) date.

a)



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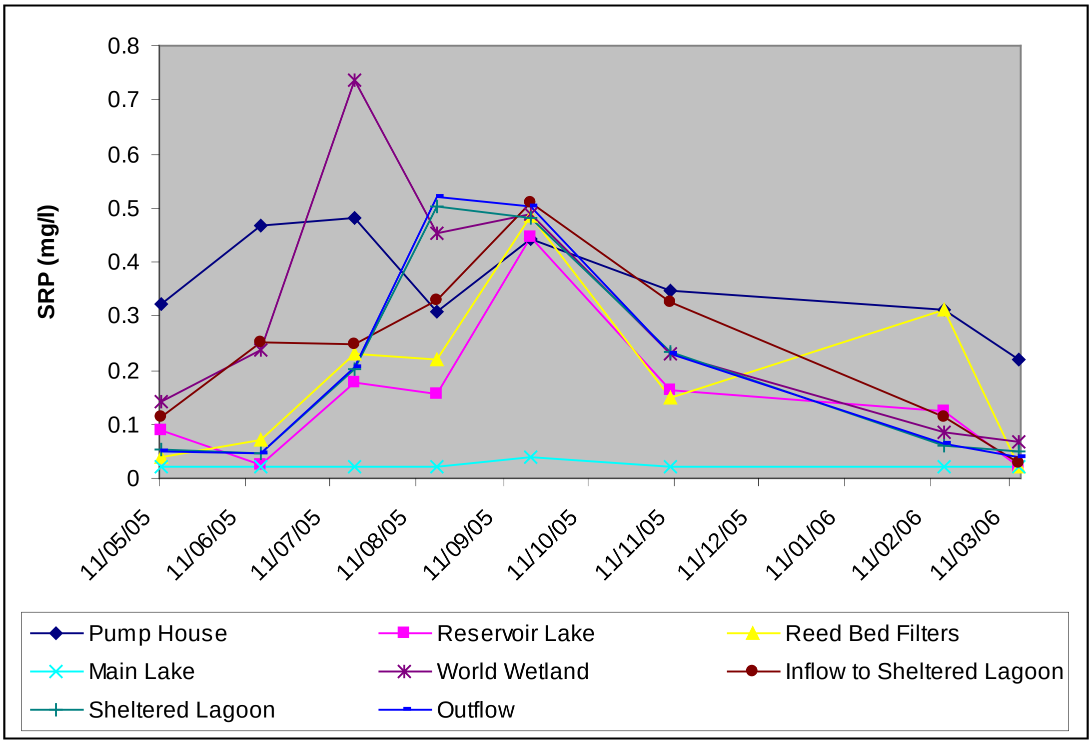


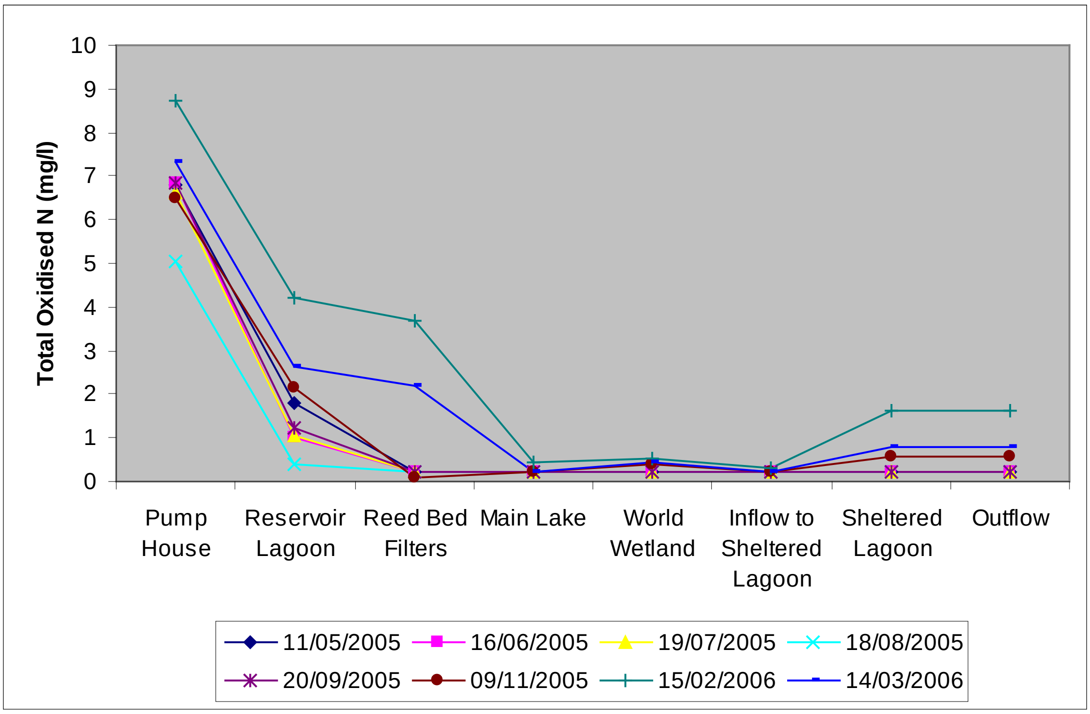
Figure 3. Variation in soluble reactive phosphorus concentration (measured as orthophosphate) with a) position and b) date.

Nitrogen

The concentration of oxidised nitrogen entering the system from the Thames-Lee Tunnel was high, mean 6.8 mg l^{-1}, but this was rapidly taken up or transformed by biological activity within the LWC (Figure 4a). As Reservoir Lagoon receives the water first, oxidised nitrogen was highest at this position, but concentrations were reduced further on passing through the Reed Bed Filters, and into the Main Lake. There was a slight increase again in the Sheltered Lagoon. Over the annual cycle there was a slight increase in winter, when biological activity is lowest (Figure 4b).

Ammonium showed a peak in concentration in World Wetland, due to inputs of bird fecal matter, but concentrations had declined by the time the water had reached the inflow to the Sheltered Lagoon (Figure 5a). Over the annual cycle there was an increase in ammonium concentration in winter, due to reduced biological activity (Figure 5b).

a)



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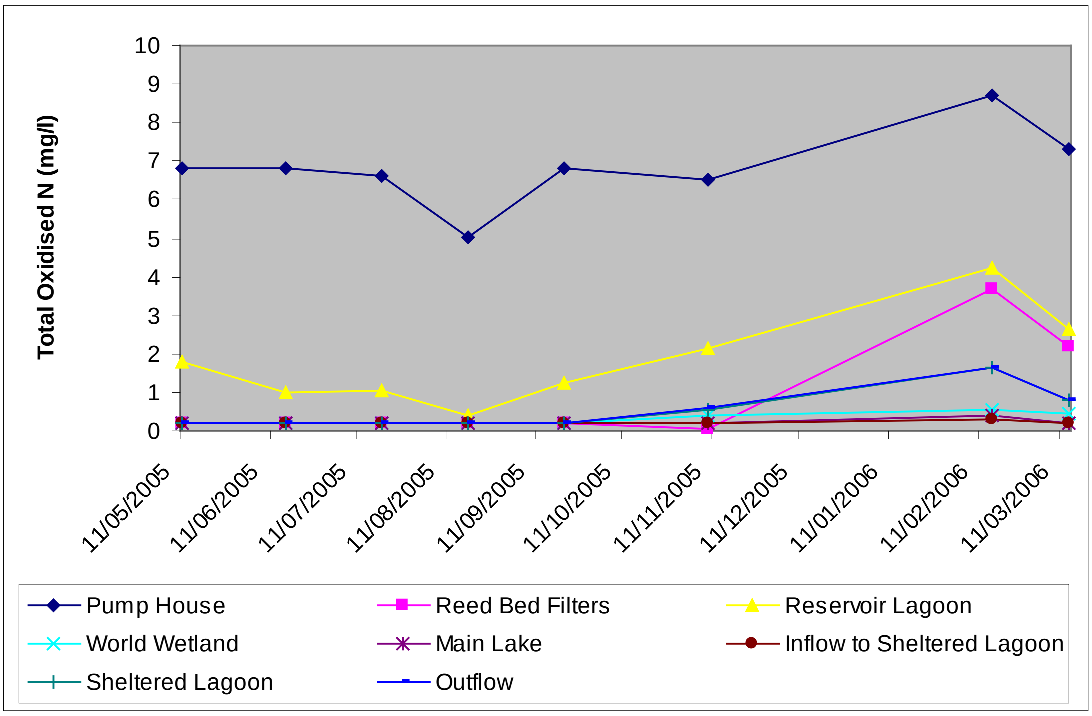
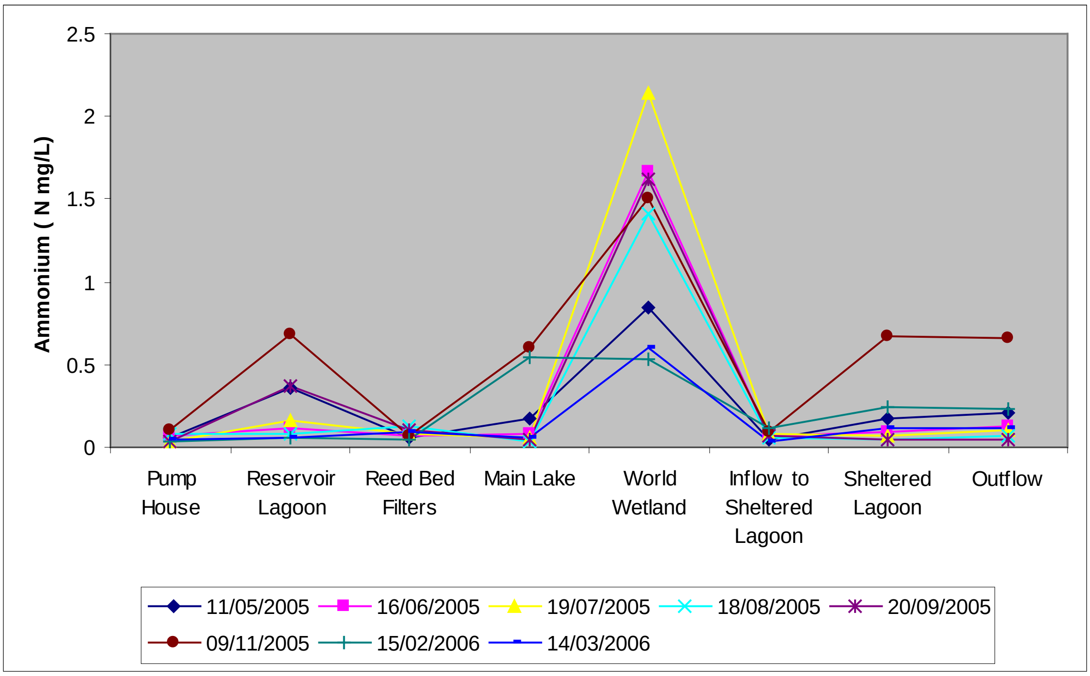


Figure 4. Variation in oxidised nitrogen concentration with a) position and b) date.

a)



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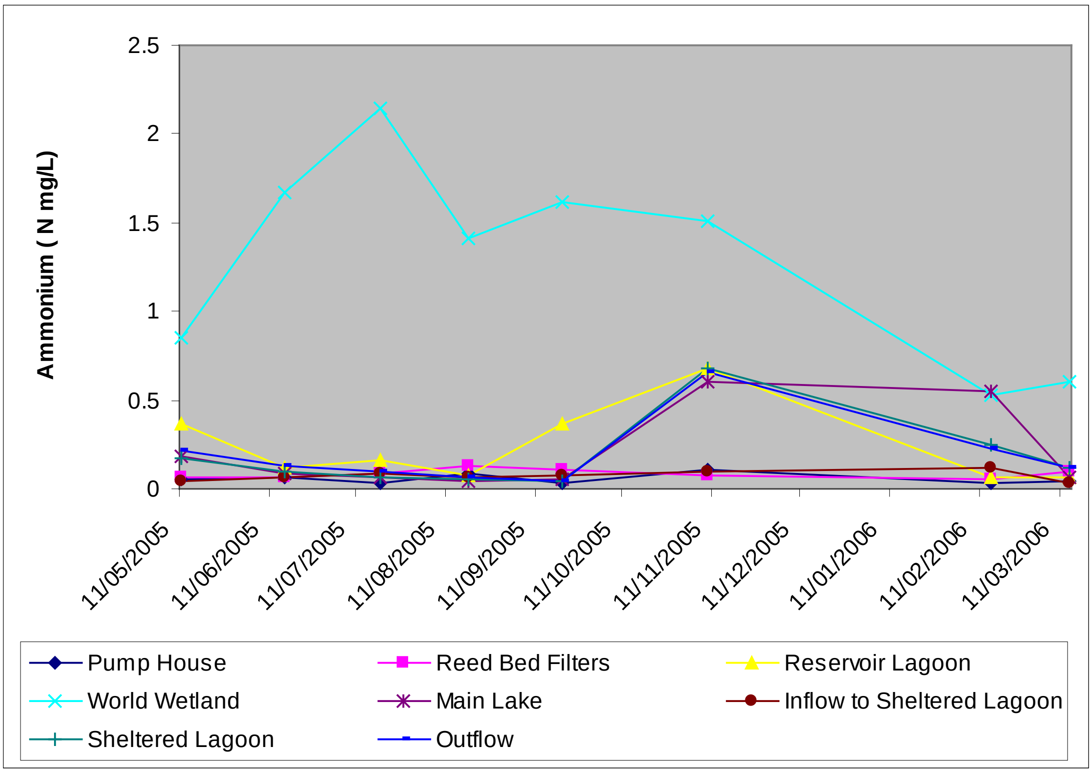
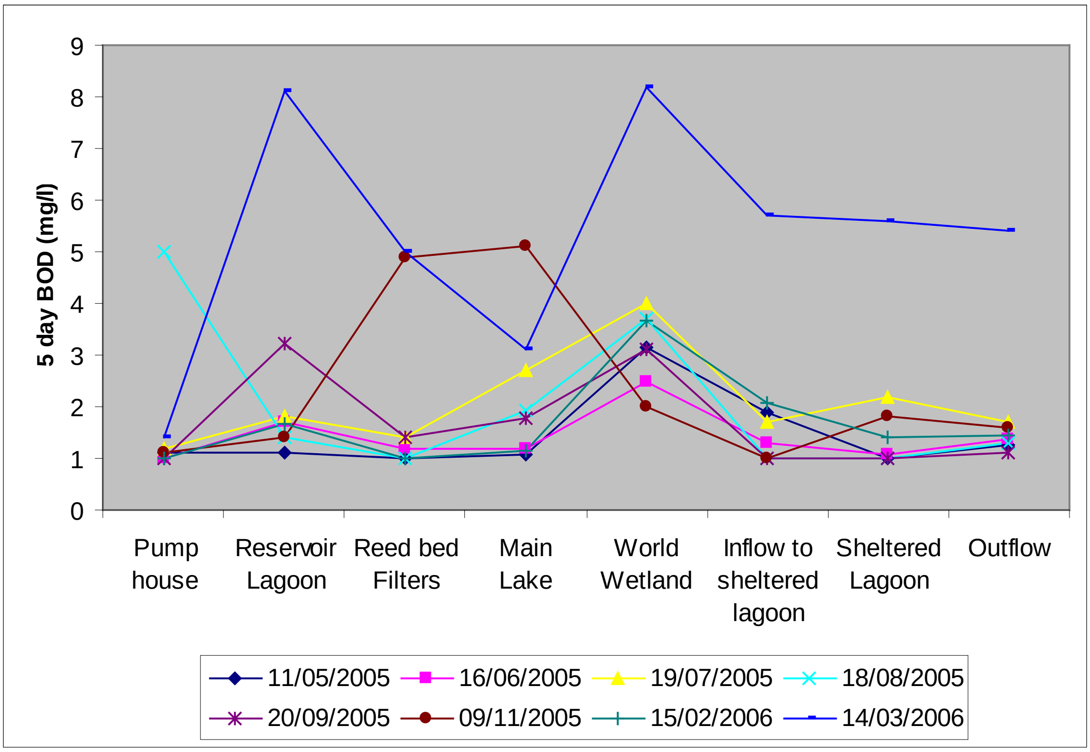


Figure 5 Variation in ammonium concentration with a) position and b) date.

BOD

Biological Oxygen Demand appears to be correlated with algal blooms, with the exception of World Wetland, where the high inputs of bird faecal matter result in high BOD (Figure 6).

a)



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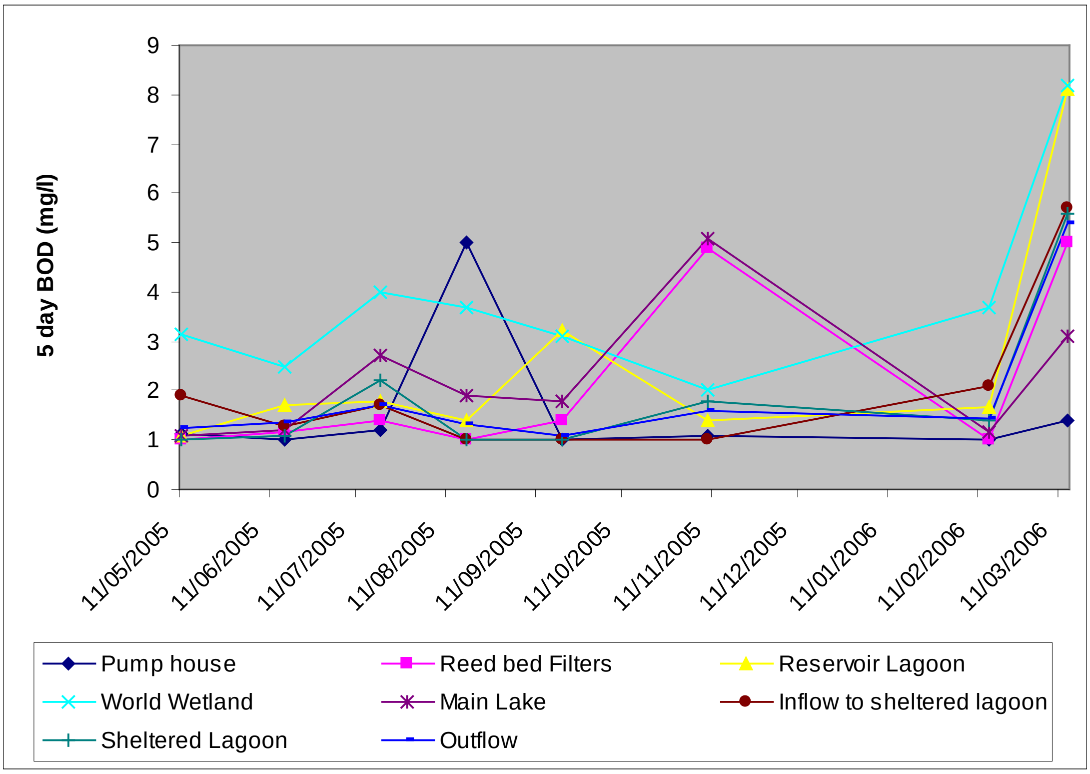


Figure 6. Variation in 5 day biological oxygen demand with a) position and b) date.

Chlorophyll

Chlorophyll peaked in July and in Main Lake in November in 2005, and again in March 2006 (Figure 7). When calculated as the concentration of chlorophyll relative to that in the inflowing water from the Thames-Lee Tunnel the peak in spring 2006, though still evident, was reduced, and the peaks in summer and late summer/autumn 2005 were still evident (Figure 8). The highest chlorophyll concentrations tended to occur in Main Lake (Figure 9).

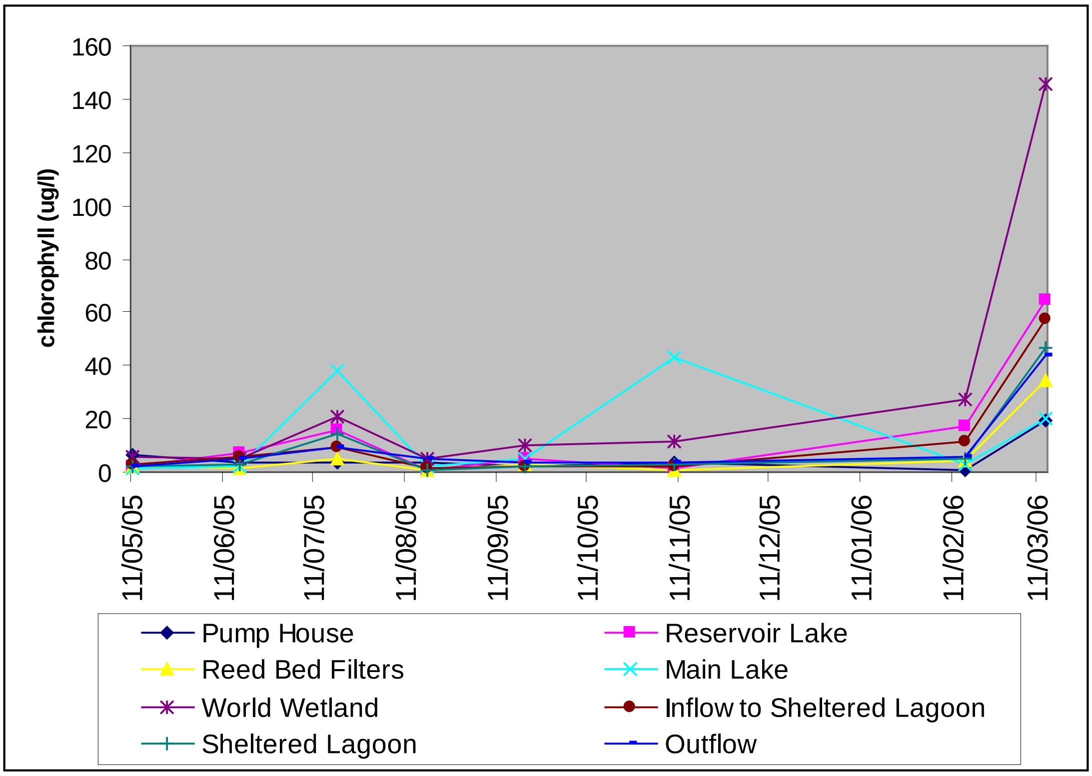


Figure 7. Variation in chlorophyll concentration with date.

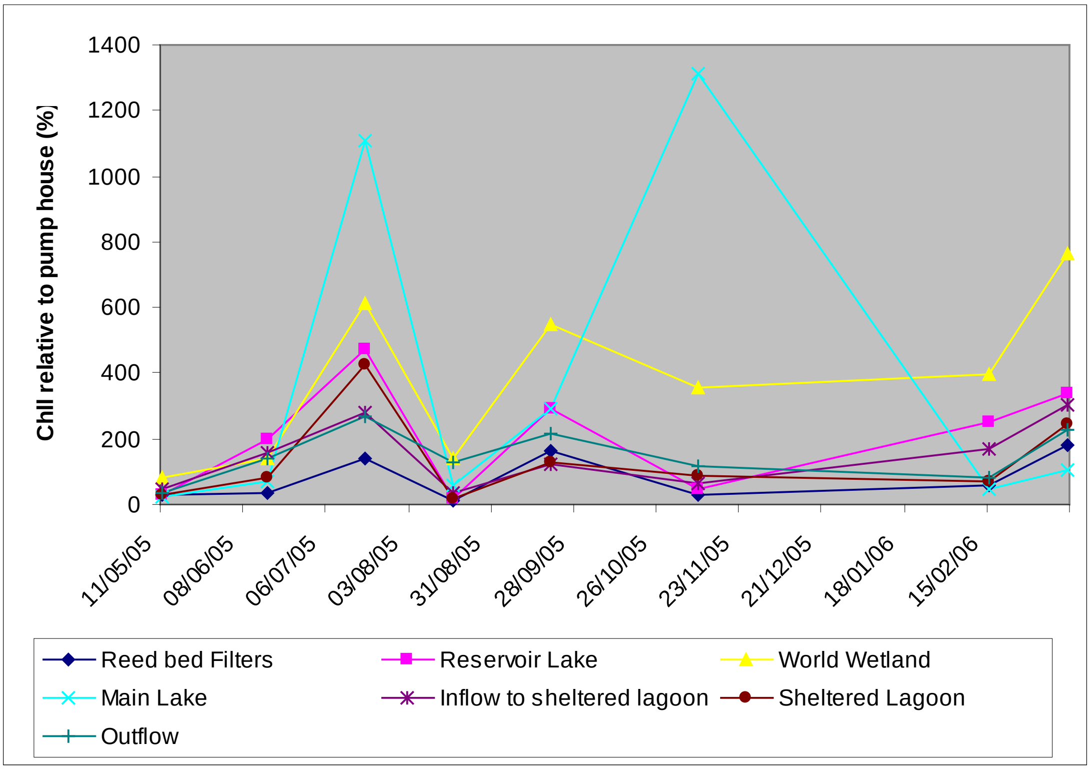


Figure 8. Variation in chlorophyll concentration relative to the concentration in the inflowing water measured at the pump house with date.

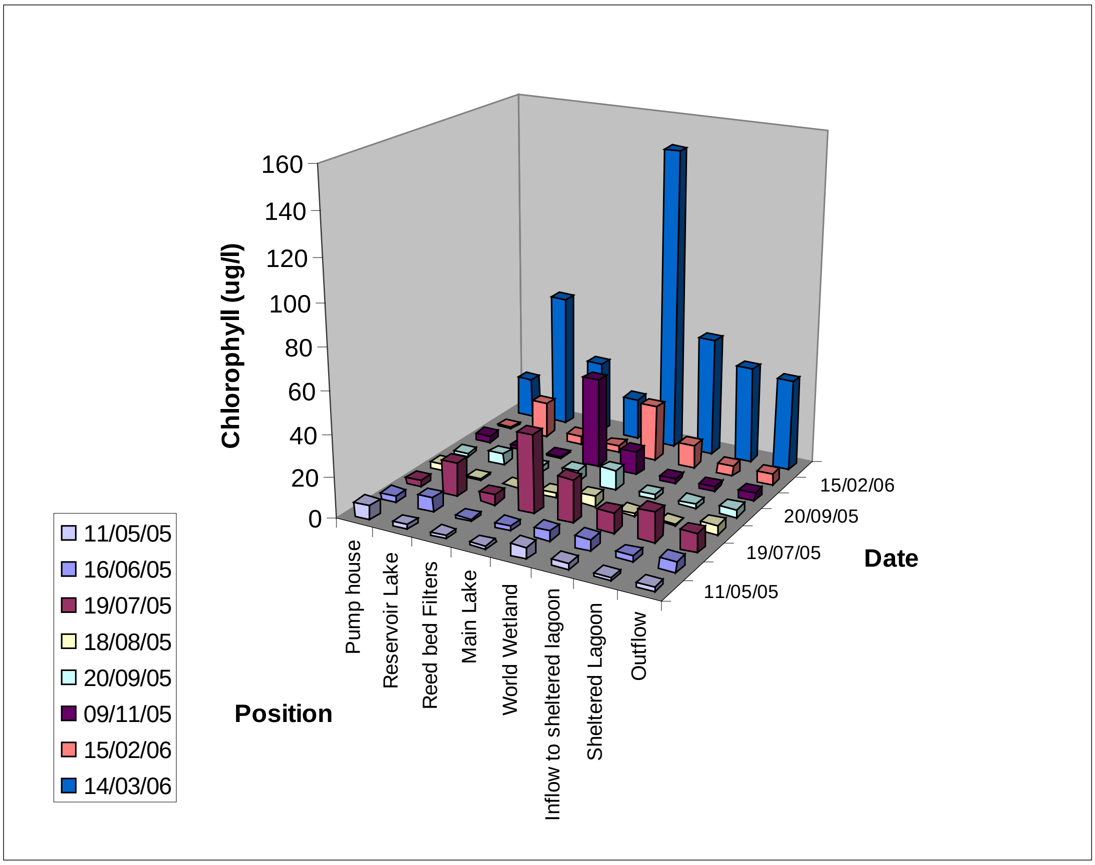


Figure 9. Variation in chlorophyll concentration with position and date.

Phosphorus recycling

One major unknown in the LWC was the influence of phosphorus recycling from the sediment. Once eutrophic lakes develop anoxia at depth, the conditions in the sediment change such that phosphorus is released into the water column. The phosphorus concentrations in the water then become unresponsive to changes in inflow concentrations. To determine if the LWC is recycling phosphorus a budget for the system was calculated from the inflow and outflow concentrations and the discharge. As total phosphorus concentrations were not available, phosphorus flux was estimated from total inorganic phosphorus and chlorophyll concentrations.

Over an annual cycle the LWC retained 56.9 Kg phosphorus, i.e. the LWC is acting as a phosphorus sink rather than a source and recycling is not a major component of the phosphorus dynamics of the system. When the phosphorus budget is partitioned between sampling occasions it is apparent that there is some export of phosphorus in summer and spring corresponding to the times when algal blooms were apparent in the system (Figure 10). This is likely to be a result of reduced light penetration leading to anoxia at depth and some recycling of phosphorus at these times.

Despite concerns about the change in consistency of the sediment in the Reservoir Lagoon, at this time recycling of phosphorus does not appear to be a major component of the phosphorus dynamics of the LWC.

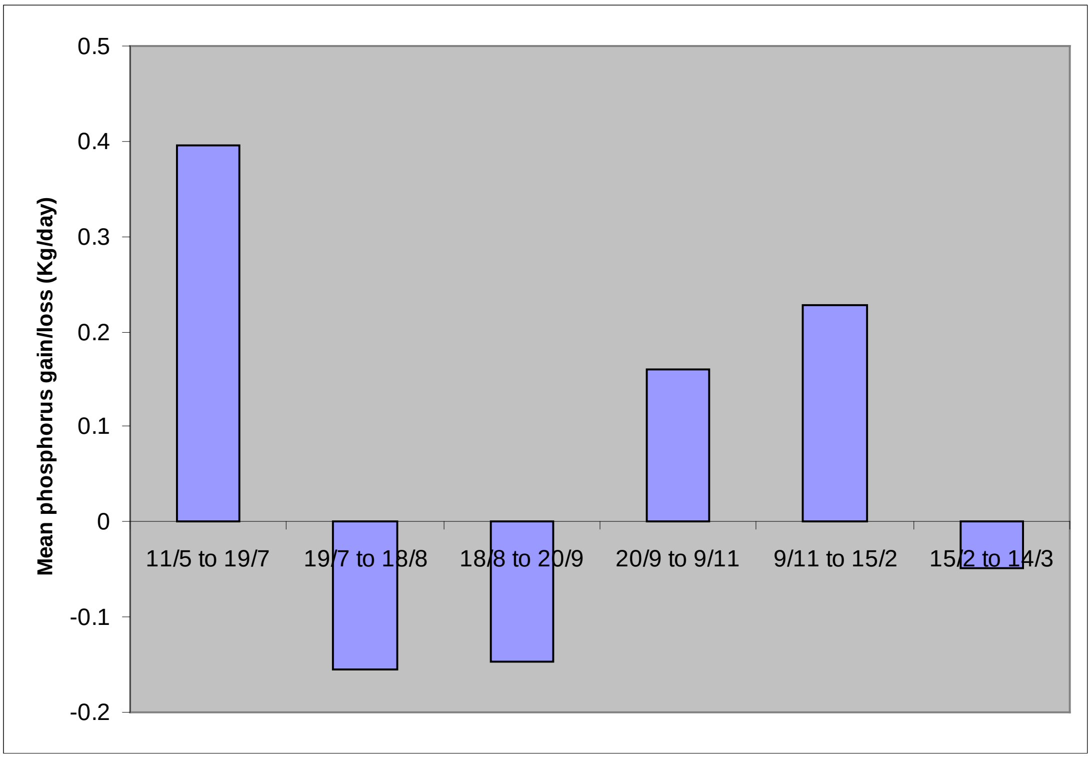


Figure 10. Mean daily phosphorus gain/loss from the LWC system over an annual cycle, with estimates calculated for each interval between sampling occasions. Gain (positive) indicates accumulation of phosphorus with the system, loss (negative) indicates release of phosphorus from the system.

Algal Community Composition

Algal densities were highest in Main Lake and least in Sheltered Lagoon, where the maximum was approximately one fifth that in Main Lake (Figure 11). The cyanobacterium *Aphanizomenon flos-aquae* was dominant in all three lakes in 2005 and was the main constituent of the blooms in summer and autumn (together with Chlorococcales and *Anabaena* in autumn in Main Lake). In contrast, the bloom in spring 2006 was formed by high densities of diatoms. Summer blooms of *Aphanizomenon* are characteristic of high nutrient lakes (Reynolds, 1984). The spring diatom bloom seems to be a consequence of events in the River Thames. Chlorophyll was higher in the water sampled at the Pump House than at any other time (Figure 7) and the increase in chlorophyll low relative to the inflowing water (Figure 8), suggesting that an inoculum of diatoms originating from the spring bloom in the River Thames entered the LWC via the Thames-Lee Tunnel and flourished once it had reached the lakes.

a)

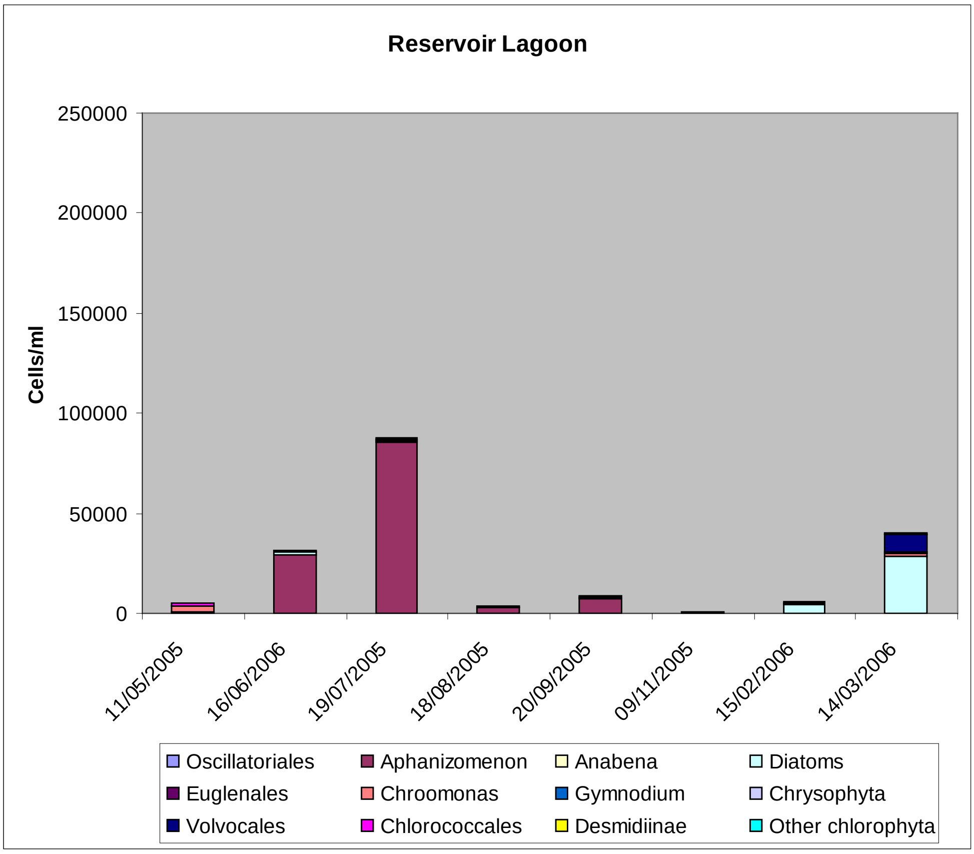
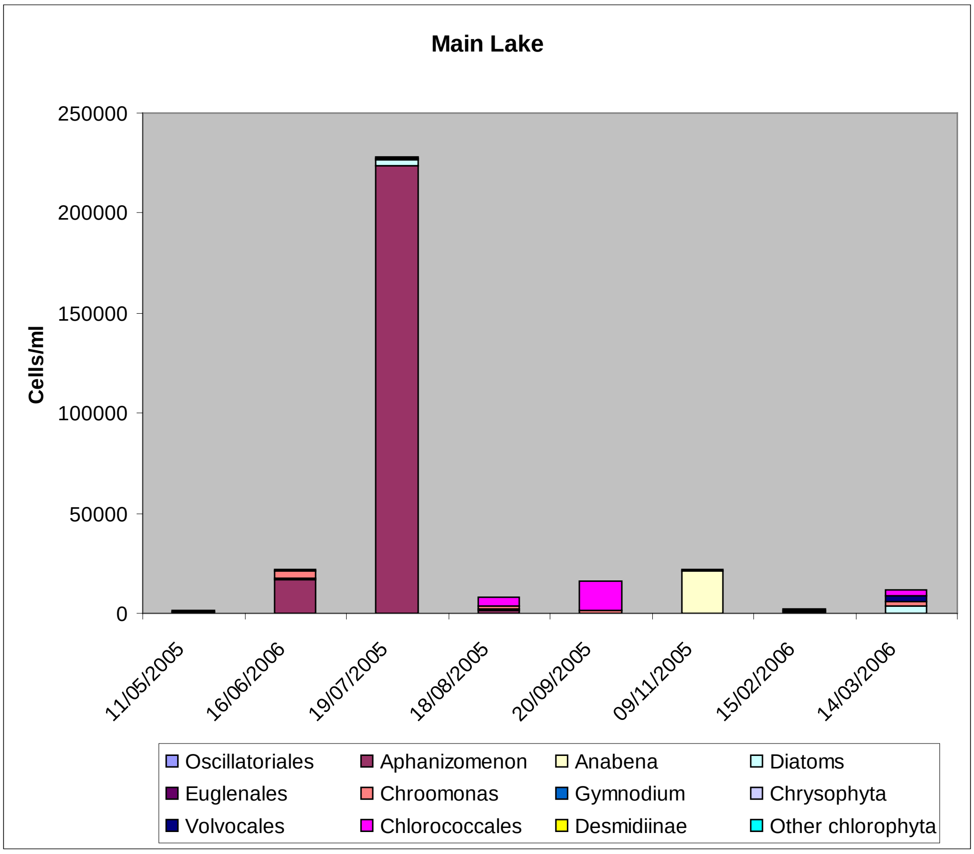
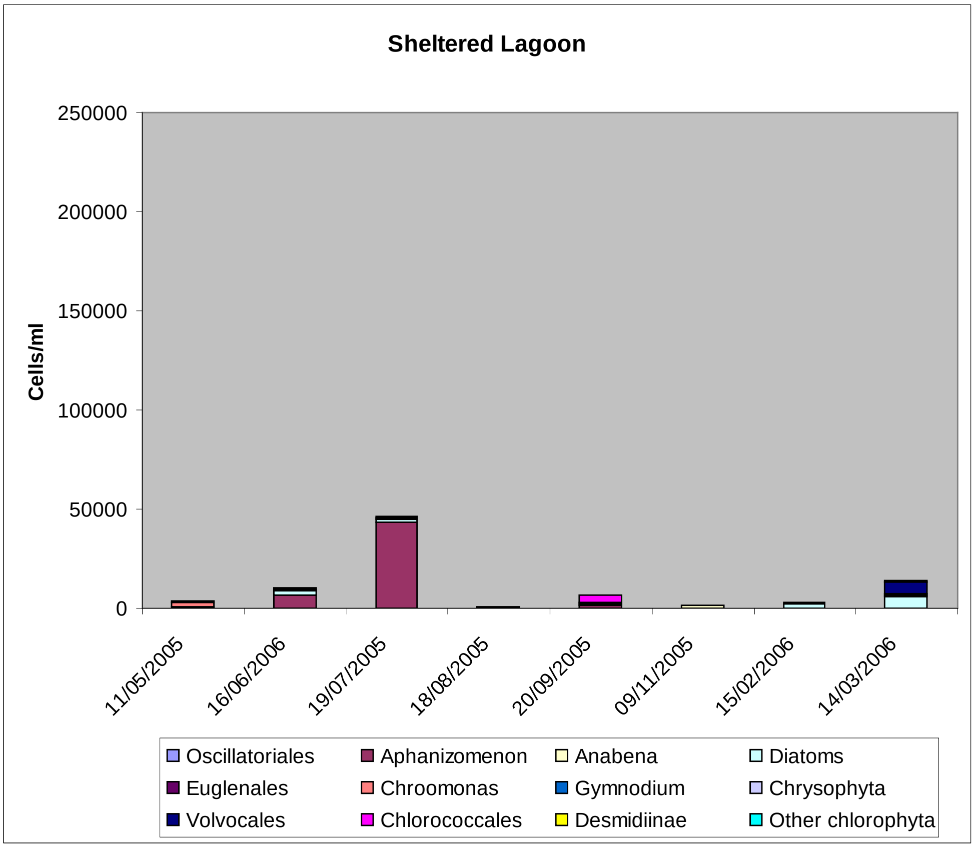


Figure 11. Variation in algal community composition and density, measured as cells ml^{-1}, with date in the three large water bodies, a) Reservoir Lagoon, b) Main Lake and c) Sheltered Lagoon.

b)


Main Lake
250000
200000
150000
100000
50000
0
Cells/ml
11/05/2005
16/06/2006
19/07/2005
18/08/2005
20/09/2005
09/11/2005
15/02/2006
14/03/2006
Oscillatoriales
Aphanizomenon
Anabena
Diatoms
Euglenales
Chroomonas
Gymnodium
Chrysophyta
Volvocales
Chlorococcales
Desmidiinae
Other chlorophyta

c)


Sheltered Lagoon
250000
200000
150000
100000
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0
Cells/ml
11/05/2005
16/06/2006
19/07/2005
18/08/2005
20/09/2005
09/11/2005
15/02/2006
14/03/2006
Oscillatoriales
Aphanizomenon
Anabena
Diatoms
Euglenales
Chroomonas
Gymnodium
Chrysophyta
Volvocales
Chlorococcales
Desmidiinae
Other chlorophyta

Macrophytes

Despite the blooms of *Aphanizomenon*, the Main Lake and Sheltered Lagoon supported a reasonable flora of aquatic macrophytes (Figure 12). Macrophytes were very sparse in the Reservoir Lagoon. In the Main Lake *Chara globularis* and *Chara vulgaris* were the dominant taxa. In the Sheltered Lagoon *Ceratophyllum demersum*, *Potamogeton pectinatus* and *Potamogeton berchtoldii* were the dominant taxa. *P. berchtoldii* was present in all three lakes. The occurrence of *Ceratophyllum* in the Sheltered Lagoon is probably associated with reduced water movement and higher nitrogen concentrations at this position. The lack of macrophytes in the Reservoir Lagoon is probably a consequence of the high densities of fish at that position (see below) and the fact that this lake is the first to receive the nutrient laden water from the Thames-Lee Tunnel.

The continued presence of macrophytes, and particularly eutrophication sensitive taxa such as *Chara*, despite dense blooms of *Aphazinomenon* is encouraging. However, the lack of macrophytes in the Reservoir Lagoon presents a possible future scenario if the conditions in the Main Lake follow a similar trajectory.

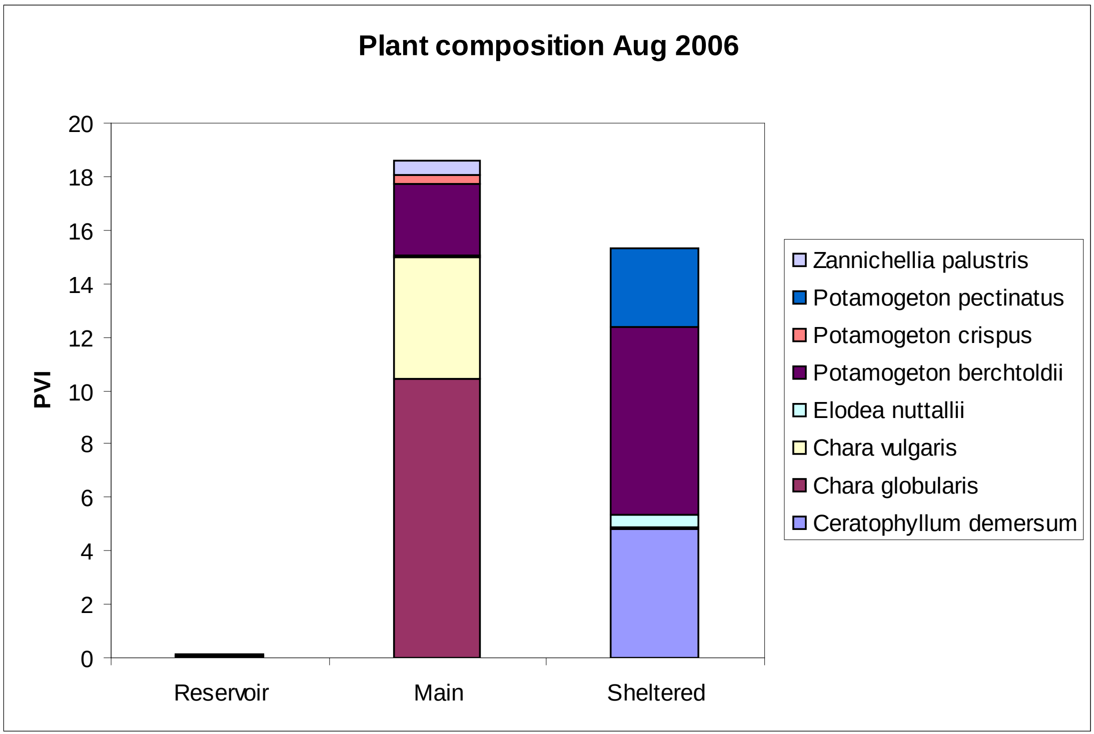


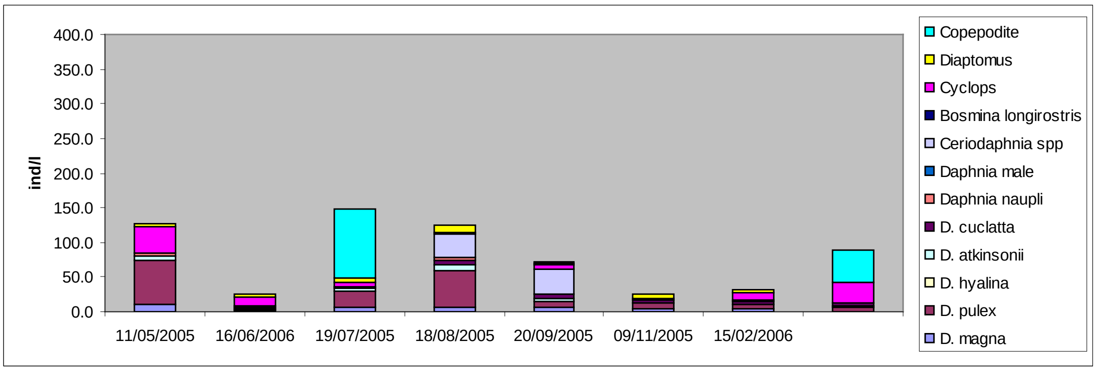
Figure 12. Plant community composition (as proportion of water column volume infested)

Zooplankton

A variety of different zooplankton species were found in the LWC. However, the three lakes have marked differences in their zooplankton community. Main Lake had the lowest mean density of *Daphnia* spp. and the highest density of *Ceriodaphnia*, and showed most temporal variation (Figure 15). Although *Daphnia* spp. followed a similar pattern of temporal variation to those in the Main Lake, the Sheltered Lagoon showed the most temporally stable zooplankton densities (Figures 13 & 16). The Sheltered Lagoon had the highest densities of benthic and epiphytic taxa, particularly large taxa such as *Eurycercus lamellatus*. Reservoir Lagoon had the highest densities of *Daphnia* spp., but these followed a different pattern of temporal variation to the other two lakes peaking in August when densities in the other two lakes were low (Figure 15). Reservoir Lagoon had the lowest densities of benthic and epiphytic taxa and lacked any of the larger taxa (Figure 14a).

In all three lakes *Ceriodaphnia* spp. tended to occur in late summer (August/September), coinciding with reduced densities of *Daphnia* spp. (Figure 15). *Daphnia magna* were present in all three lakes, but declined in summer particularly in the Main Lake. *Bosmina* also occurred in late summer in all three lakes but at very low densities. These changes represent a decline in size, and are associated with predation by fish particularly young of the year. Nevertheless, fish predation was not sufficiently high to push the community further towards *Bosmina* dominance.

a)



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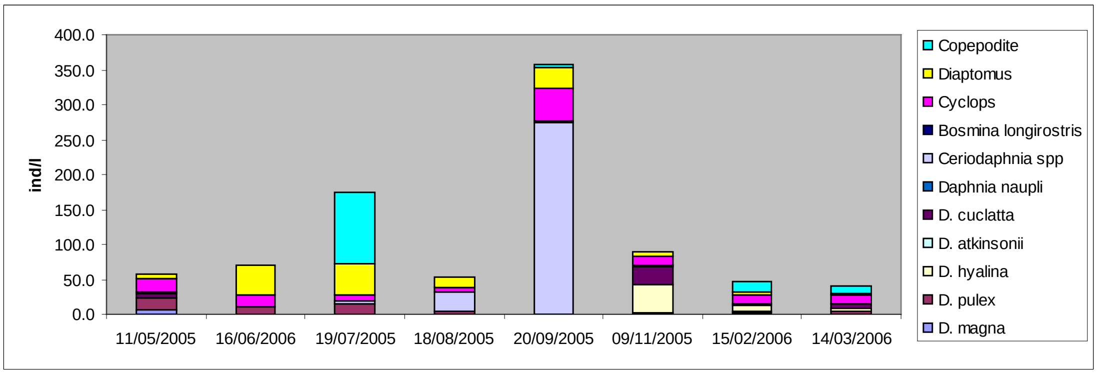

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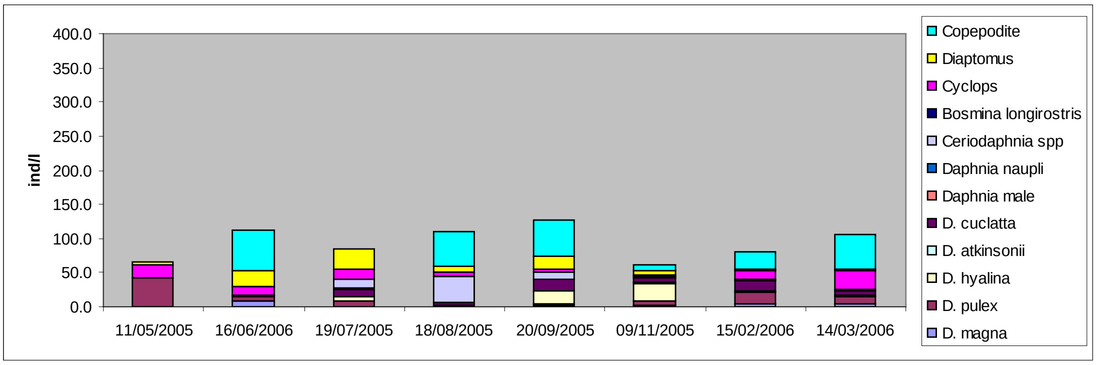


Figure 13. Variation in planktonic zooplankton community composition and density, measured as individuals l^{-1}, with date in the three large water bodies, a) Reservoir Lagoon, b) Main Lake and c) Sheltered Lagoon.

a)

b)

c)

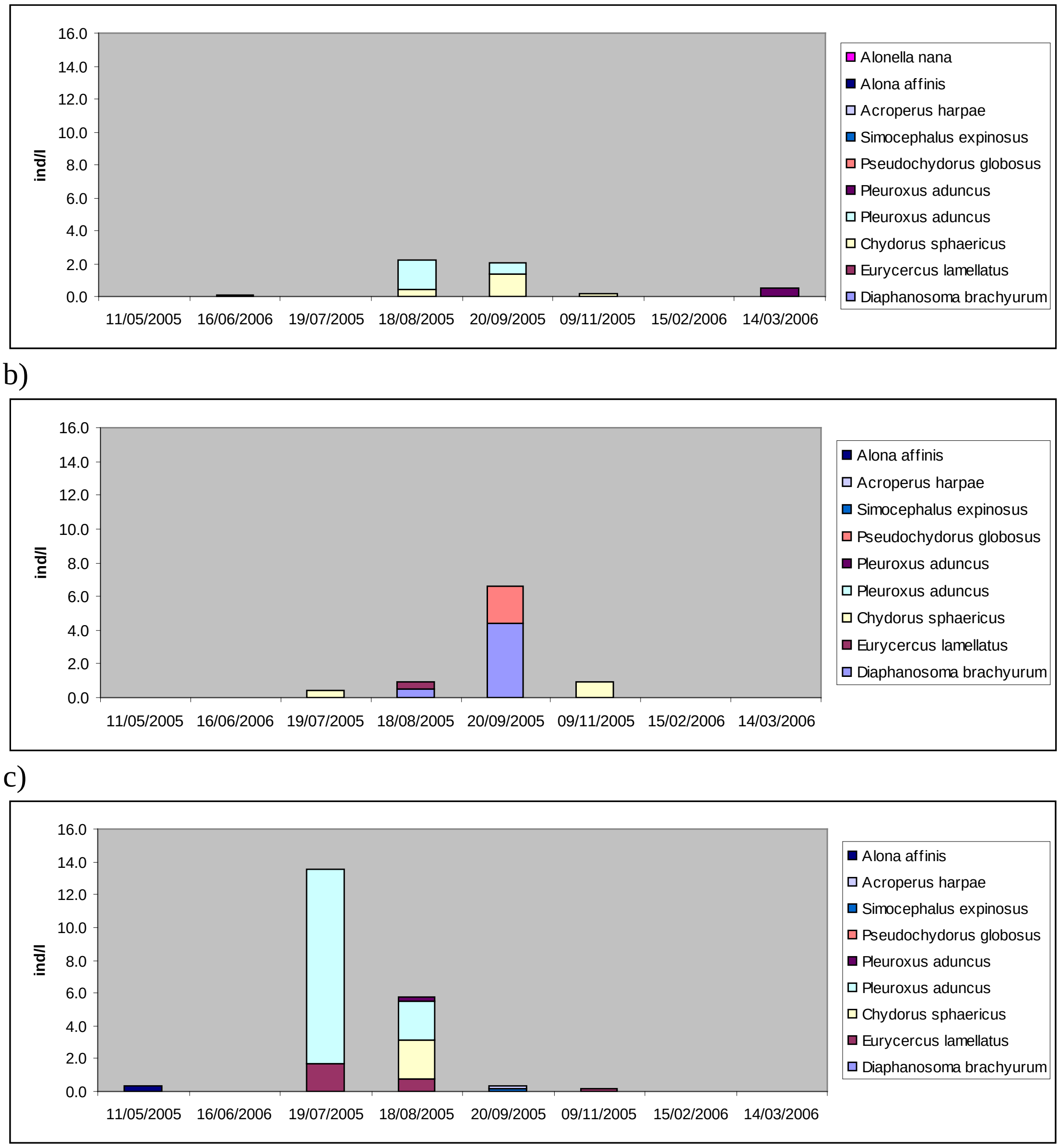
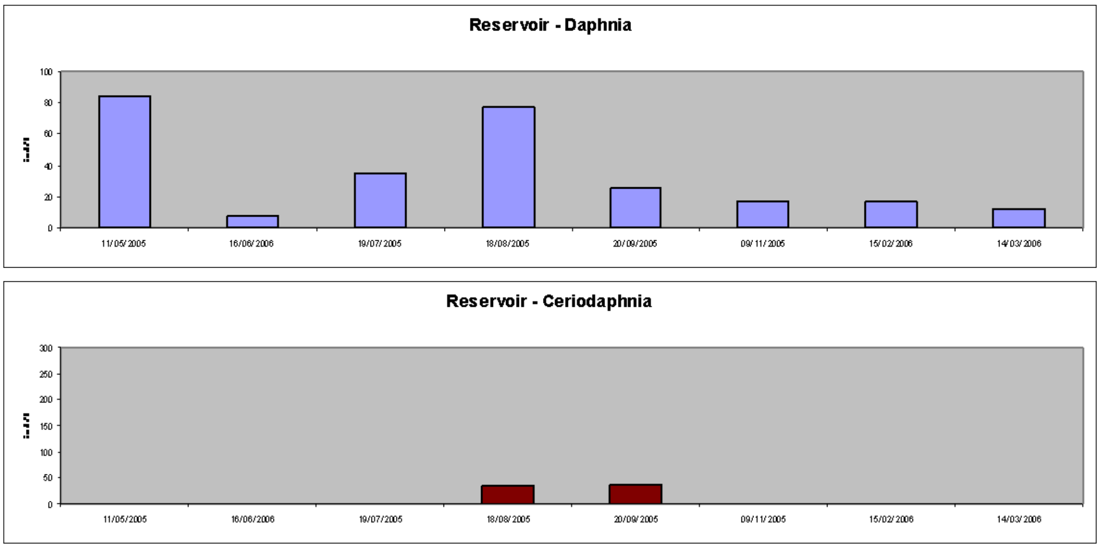


Figure 14. Variation in benthic/epiphytic zooplankton community composition and density, measured as individuals l^{-1}, with date in the three large water bodies, a) Reservoir Lagoon, b) Main Lake and c) Sheltered Lagoon.

a)



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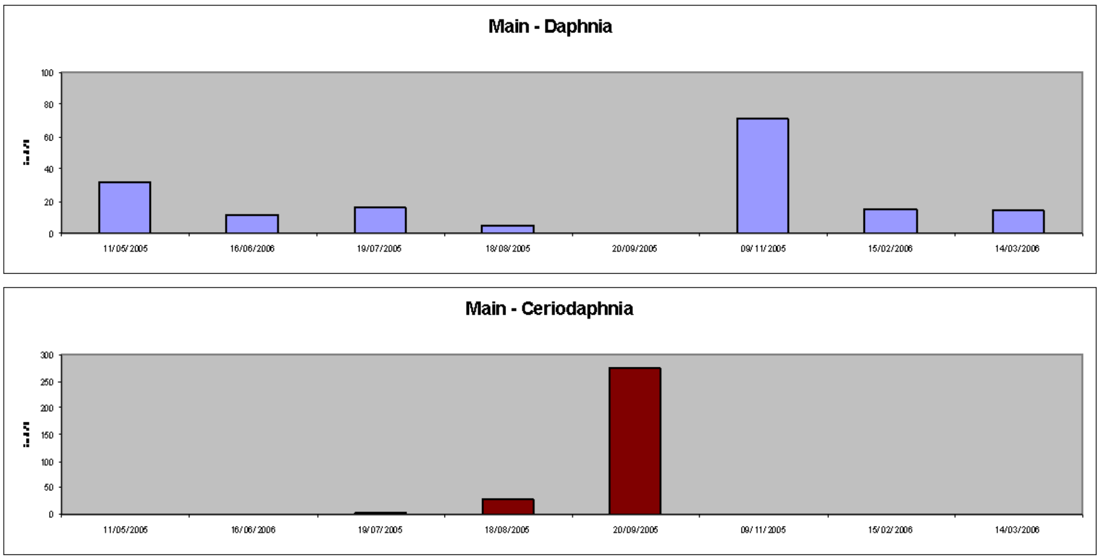

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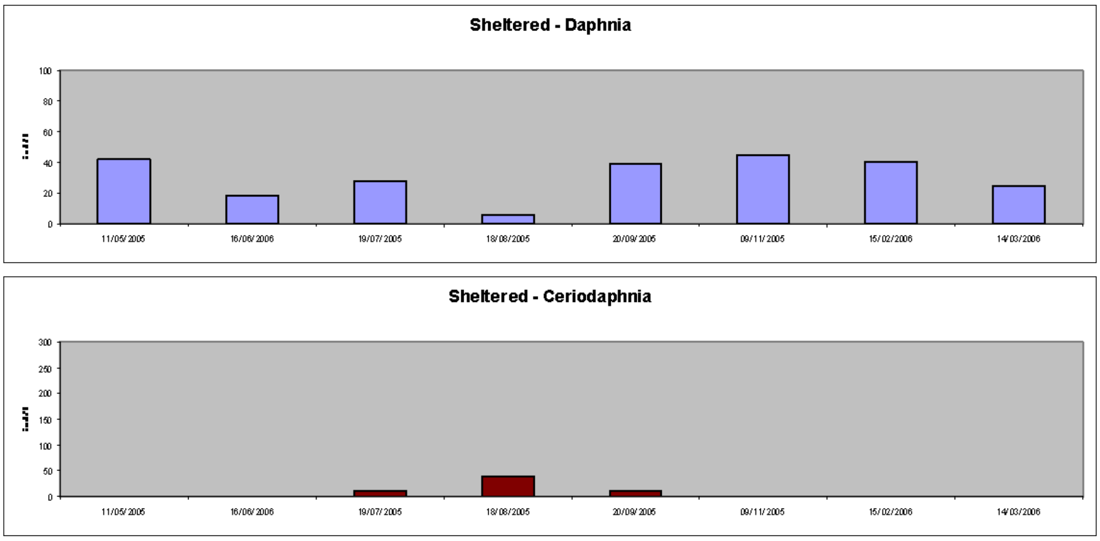


Figure 15. Variation in total *Daphnia* and *Ceriodaphnia* (ind l^{-1}) with date in the three large water bodies, a) Reservoir Lagoon, b) Main Lake and c) Sheltered Lagoon.

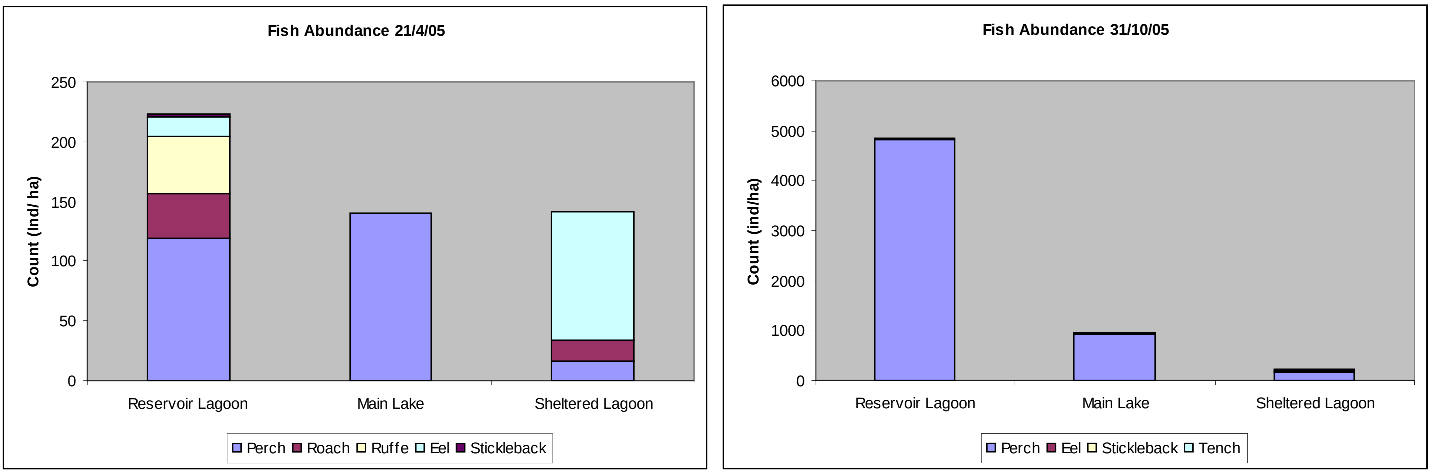
Fish

The fish populations have been steadily increasing in the LWC since its creation, and communities dominated by perch now occur in all three lakes. However, there are differences among the three lakes in densities and biomass, which declined from the Reservoir Lagoon to the Sheltered Lagoon with the Main Lake intermediate (Figure 16). Diversity appeared to be lowest in the Main Lake, but it is not clear if this is due poor efficiency of capture. Recruitment of perch was apparent in all three lakes.

There appeared to be a difference in biomass and abundance between the spring and autumn fishings, but this was probably due to changes in efficiency associated with changes in fish behaviour. Autumn biomass was in excess of 85 kg ha^{-1} in the Reservoir Lagoon, and 35 kg ha^{-1} in the Main Lake (Figure 16 b). Plant loss is often associated with fish biomass in excess of 50 kg ha^{-1}.

Fish growth, estimated using scale annuli, appears to have declined in subsequent cohorts since 2001 in Main Lake and Reservoir Lagoon, as densities have increased (Kett, Lynch & Campbell, 2006). There also appeared to have been a change in fish diet in the Reservoir Lagoon since 1999 (Figure 17). Large benthic invertebrate and predatory zooplankton prey have been lost from the diet and been replaced by a diet of chironomids and zooplankton (Figure 18). Perch diet in the Main Lake comprised almost entirely chironomids and zooplankton in 2005. The decline in growth of subsequent cohorts of perch appears to reflect this decline in large prey in the diet. The paucity of benthic zooplankton found in the Reservoir Lagoon would support this suggestion.

a)



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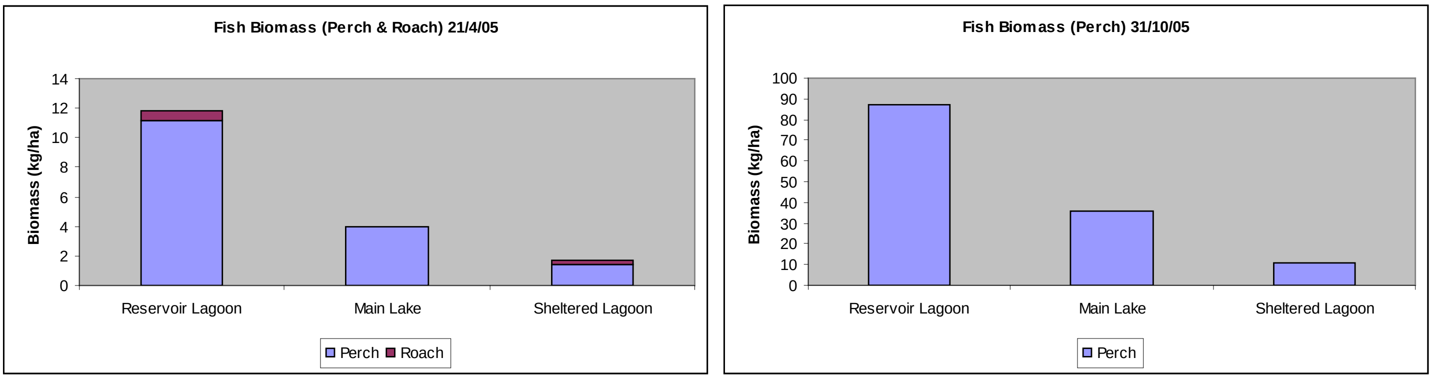

Figure 16. Variation in a) fish abundance and composition and b) biomass (of roach and perch only) measured in spring and autumn 2005.

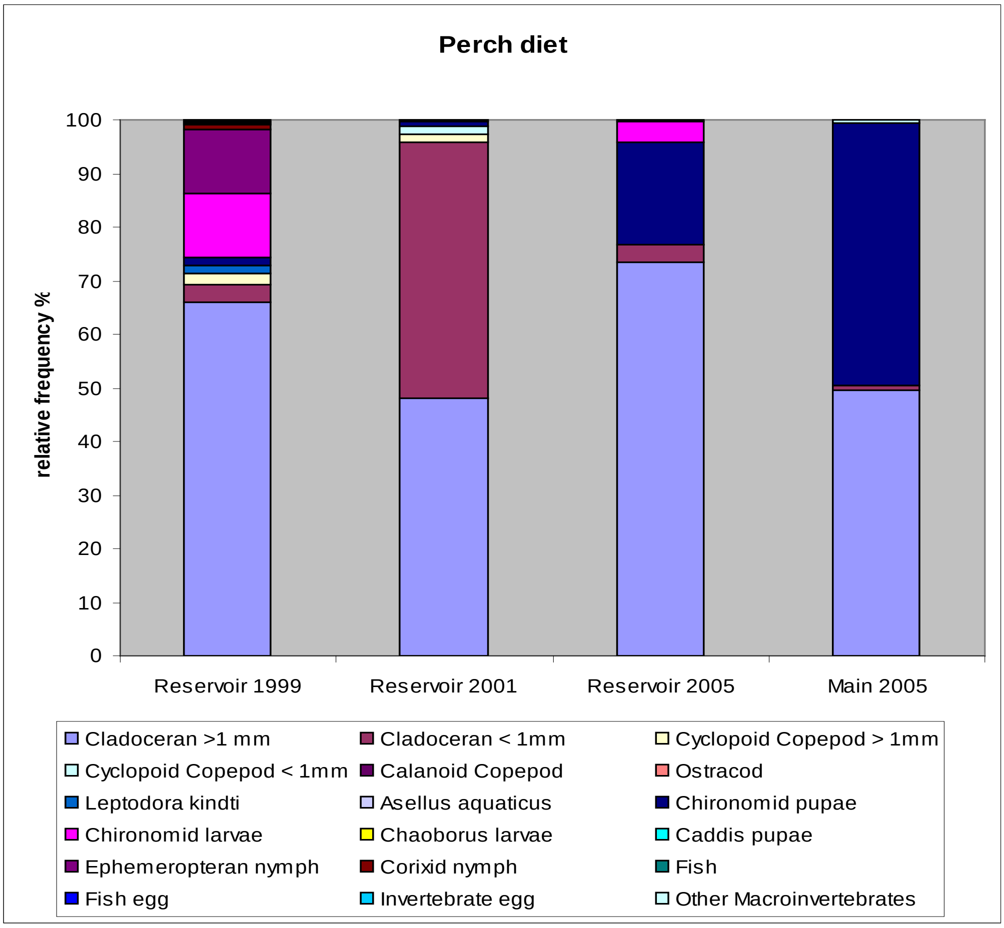

Figure 17. Relative frequency of prey found in perch guts in the Reservoir Lagoon in 1999, 2001 and 2005, and in the Main Lake in 2005.

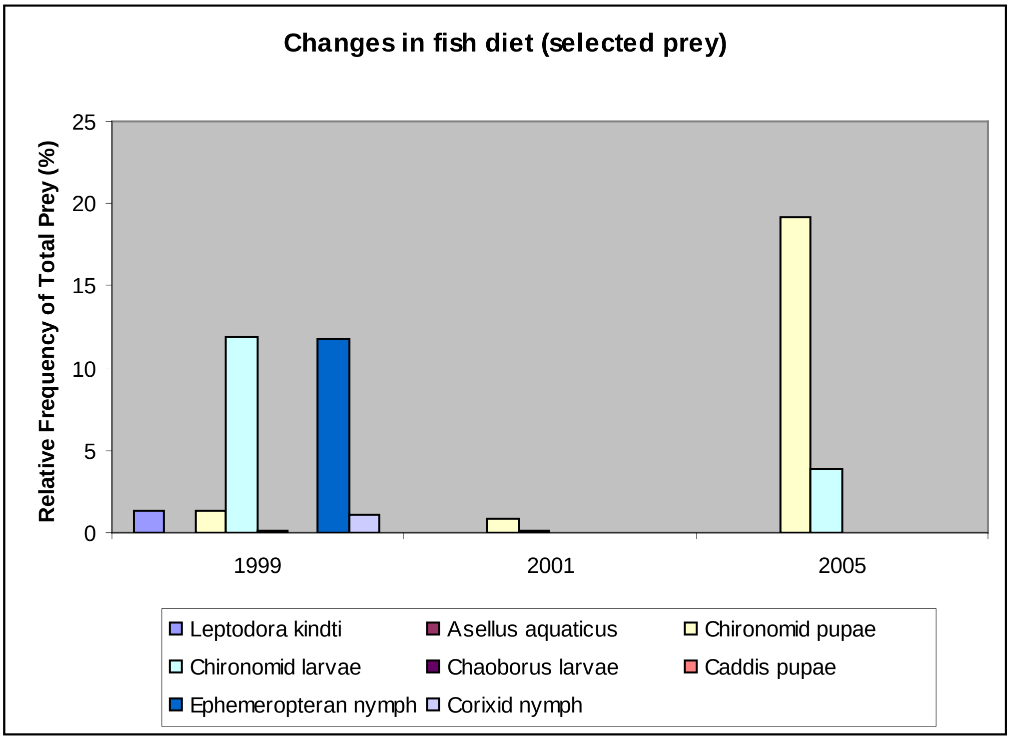

Figure 18. Change in the relative frequency of selected large prey found in the guts of perch from the Reservoir Lagoon over time, 1999-2005.

DISCUSSION

As in recent years, the London Wetland Centre experienced dense algal blooms during 2005 and early 2006. In July and November (in Main Lake) 2005 these comprised mainly of the cyanobacteria *Aphanizomenon flos-aquae* and *Anabaena* respectively, and in spring 2006 predominantly of diatoms. The spring diatom bloom appeared to be of different origin to the cyanobacteria blooms, more a reflection of events in the River Thames than of conditions in the LWC, with the bloom being a further development of what was occurring in the river. The bloom in July 2005 was particularly dense, with very high concentrations of *Aphanizomenon* especially in Main Lake. The occurrence of such blooms is a concern, and if allowed to continue to occur will result in a large scale loss of macrophytes from the Main Lake and possibly Sheltered Lagoon. This would be detrimental to the LWC, and likely to have consequences both aesthetic and in terms of wildfowl numbers. For effective management decisions to be made, it is necessary to understand the factors that result in bloom formation. The two most important constraints on algal growth are the availability of nutrients and, through the effect of predation on zooplankton, the biomass of fish (Scheffer 1998).

The concentrations of nutrients flowing into the LWC were high, particularly phosphorus (mean >400 $\mu g\ l^{-1}$), and are typical of hypertrophic conditions. Whilst these do not present a problem for the River Thames, the constraints on phytoplankton growth change markedly once the water enters the LWC (Hilton *et al.* 2006). The high concentrations of phosphorus are likely to result in algal blooms, despite the relatively short residence time (Le Cren & Lowe-McConnell, 1980). Summer blooms of *Aphanizomenon flos-aquae*, as were observed in 2005, are typical of such high nutrient conditions (Reynolds, 1984). The Main Lake has the longest residence time (in excess of 63 days), and it was here that the blooms were most intense. Rapid flushing of the Sheltered Lagoon (Residence time 19 days) helps prevent blooms forming, but chlorophyll concentrations in this water body were influenced strongly by conditions in the other water bodies.

Oxidised nitrogen (usually mainly nitrate) concentration was high in the inflowing water also, but was rapidly reduced as the water passed through the Reservoir Lagoon and Reed Bed Filters, and was depleted by the time the water reached the Main Lake.

A further source of nutrients to the system was World Wetland, where a notable increase in phosphorus, ammonium and BOD occurred, probably as a consequence of the high densities of wildfowl in this part of the LWC. Currently, these inputs have little impact on the system and are removed by biological activity by the time the water enters the Sheltered Lagoon.

The sediment presents a further potential source of nutrients which may be released from the sediment during algal blooms. Whilst the system appeared to be retaining phosphorus overall, there were occasions when the system appeared to be exporting phosphorus released from the sediment. These coincided with the occurrence of algal blooms and increased ammonium concentrations. This source of nutrients is of concern, as high algal densities become self perpetuating once the release of phosphorus from the sediment becomes a regular feature of a lake. High densities of algae reduce light penetration into the lower water column, and anoxia develops such that phosphorus is released from the sediment and ammonia concentration increase.

Currently, release from the sediment does not appear to be a substantial component of the dynamics of nutrients in the LWC, but this situation may change if the concentration in the inflowing water is reduced.

Despite the high nutrient concentrations in the system, lakes with a total phosphorus concentration in excess of that found at the LWC can, and do, develop macrophytes and remain relatively clear (Carvalho 1994; Mjelde & Faafeng 1997), typically under conditions where fish biomass is low (Jones & Sayer 2003). Lakes maintain clear water conditions where macrophytes fill a substantial proportion of the water column, and a suite of positive feedback mechanisms reduce algal densities. Prime amongst these positive feedback mechanisms that stabilise plant dominance and clear water conditions is the grazing of phytoplankton by large zooplankton.

Whilst larger *Daphnia* are present within the LWC the formation of “grass-clipping” colonies of *Aphanizomenon* enable this cyanobacterium to avoid grazing by zooplankton, such that the presence of large zooplankton will not prevent bloom formation. Even though larger zooplankton were present at a moderate density, the nutrient conditions will encourage dense growths of *Aphanizomenon*.

As well as nutrient concentrations, fish populations have a marked influence on shallow lake ecosystems. The fish populations in the LWC, principally perch, have been increasing since 1999. Fish predation has an impact upon zooplankton populations such that larger Cladocerans tended to decline in abundance towards late summer, to be replaced by smaller taxa, as the young fish of the year fed upon them. There was a clear gradient in fish biomass across the site, highest in Reservoir Lagoon and lowest in Sheltered Lagoon. From the changes in perch diet, it is apparent that the fish in the Reservoir Lagoon have largely removed the larger benthic invertebrates and predatory zooplankton from the community. Hence, the perch appeared to be feeding pelagically upon zooplankton and chironomids. Piscivory was not prevalent in the perch diet. Perch do not become piscivorous when feeding in the pelagic, or do so at a larger size than when they are feeding on macroinvertebrates in the littoral (Svanbäck & Eklöv 2002). As prey size, and hence perch growth rate, have declined over time in the Reservoir Lagoon, it is less likely that the perch will become piscivorous. With declining food quality and a lack of piscivory, the population will become more stunted over time, and conditions will shift to favour cyprinids. The population of piscivorous birds present at the LWC, whilst actively feeding upon the fish, are not acting as a constraint on the fish populations which have increased in terms of biomass and numbers over time. Any shift in community composition towards a cyprinid community would be detrimental, as it would tend to reinforce, and exaggerate, the current situation, where macrophytes are lacking and cyanobacteria frequently form blooms.

The autumn fish biomass is now such that macrophytes would not be expected to persist in Reservoir Lagoon (Moss, Madgwick & Phillips 1996). However, there was a considerable difference in the data collected in spring and autumn, which may in part be due to behaviour of the fish (schooling in autumn) aiding capture. The difficult conditions for fishing contributes to the uncertainty in the data also. Nevertheless, the high fish biomass appears to have had a considerable impact upon Reservoir Lagoon. Fish biomass in the other two lakes appeared to be lower and the impacts less. It should be noted that even though estimated fish biomass was moderate in Main Lake, densities of *Daphnia* were lowest and most temporally variable, and densities of algae were highest. The fish biomass in Main Lake is approaching a level where loss of plants would be expected (circa 50 kg ha^{-1}). Significant increase above the current biomass is likely to result in plant loss.

Despite the blooms of *Aphanizomenon*, the Main Lake and Sheltered Lagoon supported a reasonable flora of aquatic macrophytes. Macrophytes are virtually absent from the Reservoir Lagoon, as would be expected from the high densities of fish in this lake. Whilst it is possible that herbivorous birds are helping to maintain the current low densities of macrophytes in the Reservoir Lagoon, they are unlikely to be the initial cause. Herbivorous birds only have a significant impact upon submerged macrophytes when the ratio of birds to plants is high, i.e. at high waterfowl densities, at very low vegetation densities, or in the colonisation phase of the vegetation (Marklund *et al.* 2002). Without a reduction in the fish biomass in Reservoir Lagoon it is unlikely that macrophytes will return to this lake. It is important to address Reservoir Lagoon as this lake lies at the hydraulic head of the LWC system, and will influence the rest of the system.

Main Lake still supports a good flora of macrophytes, including *Chara globularis* and *Chara vulgaris*, even though the highest densities of algae were found in this water body. It was not possible to calculate residence time of this water body accurately, as the inflow/outflow discharge was not monitored, but it is estimated to be in excess of 63 days and is without doubt the longest of the three large water bodies. The long residence time may have an effect on algal populations, allowing them develop further than in the other water bodies. It is evident that the replenishment of inorganic phosphorus in Main Lake is not as rapid as in the other water bodies, and concentrations become deplete as they are utilised by biological activity. *Daphnia* densities were lower in Main Lake than the other water bodies and *Daphnia* were absent in late summer, replaced by the smaller *Ceriodaphnia* and *Bosmina*. The loss of *Daphnia* is likely to be a consequence of predation by fish, but *Ceriodaphnia* are strongly associated with vegetation. A second, autumn bloom of *Anabaena* developed in the month after *Ceriodaphnia* populations peaked, possibly associated with dieback of the macrophytes; *Daphnia* returned in numbers at this time. Perch diet was very similar to that in Reservoir Lagoon and indicates a heavy reliance upon zooplankton and chironomids; larger invertebrates are lacking from the diet. It is likely that both the presence of vegetation and fish predation affect the zooplankton in this water body. However, the similarity to Reservoir Lagoon, in terms of fish diet and increasing fish biomass, are a concern, and action will need to be taken to ensure that this water body does not follow a similar trajectory. If management action results in a reduction in algal density, it is likely that the macrophytes in Main Lake will respond to the increased water clarity. However, if the fish populations continue to increase the plants will be lost from this lake.

Sheltered Lagoon also had a good flora of macrophytes, dominated by *Ceratophyllum* possibly as a consequence of the higher nitrogen concentrations in this water body. The concentrations of algae and densities of fish were the lowest, and zooplankton density was the highest in Sheltered Lagoon. The residence time is also shortest. This water body is at the least risk of losing its macrophytes, but as it is the last water body in the hydrological sequence and receives water from all the other water bodies, it is influenced by conditions elsewhere in the LWC.

SUMMARY

It is clear that the LWC is receiving a heavy loading of phosphorus from the River Thames. This nutrient loading is making conditions possible for dense growths of algae, particularly cyanobacteria. It appears that nutrient recycling from the sediment is not a major part of the dynamics of the system to date, but this may change. Macrophytes are not present in Reservoir Lagoon, but remain in Main Lake and Sheltered Lagoon. The more frequent occurrence of dense blooms is associated with increasing fish biomass. Fish appear to have removed larger benthic invertebrates and predatory zooplankton from the Reservoir Lagoon, and are now reliant upon zooplankton and chironomid prey. Fish growth rate appears to have declined over time as densities increased. Expected further increase in fish biomass will lead to further deterioration of the system. To improve water quality in the LWC it will be necessary to manage both the supply of nutrients to the system and the fish populations.

RECOMMENDATIONS

Action needs to be taken to reduce the intensity of algal blooms. It is recommended that management take action to,

1. Reduce nutrient concentrations, particularly phosphorus, in the inflowing water by phosphorus stripping. This will reduce the potential for algal blooms to develop and increase water clarity.
2. Reduce fish biomass in the Reservoir Lagoon. It is recommended that the resultant biomass should be less than 35 kg ha^{-1}. This will reduce predation on zooplankton and benthic invertebrates, and will result in improved water clarity and increased macrophyte growth.
3. Introduce piscivorous fish (preferably pike, *Esox lucius*) to stabilize fish populations in Reservoir Lagoon, Main Lake and possibly Sheltered Lagoon. This will help control the fish populations.
4. Continue to monitor the system. It would be preferable to include total phosphorus (after digestion), light attenuance, oxygen profiles (measured in situ) and benthic invertebrates in the sampling programme. This will enable any improvements to be assessed and increase the understanding of the system.

Actions 2 and 3 may potentially have a negative impact on piscivorous birds, but the overall improvement in the quality of the site will be beneficial to wildfowl and likely to provide more food for herbivorous and invertivorous birds. However, there is also the possibility that improvements in water clarity and macrophyte abundance will result in better hunting conditions for piscivorous birds.
It is possible that the macrophytes in Reservoir Lagoon will need to be protected from herbivorous by mesh enclosures as they re-establish, but this action should be delayed until the other recommendations have been implemented.

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