Modelling phosphorus fluxes in Loweswater

ECRC Research Report Number 159

B. Goldsmith, J. Boyle, M. Kernan, H. Yang, S. Turner, H. Bennion, E. Shilland, J. Shilland,
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Cover photo: Coring at Loweswater © E. Shilland

EXECUTIVE SUMMARY

1. This is the final report to the Loweswater Care Project (in support of the Catchment Restoration Fund for England) ECRC-ENSIS Project 298, 'Loweswater 12-13'. The study was concerned with the spatial and temporal concentrations of sediment phosphorus (P) in the lake and the use of P measurements from the water column and inflow and outflow samples to derive a simple mass balance model for P in the lake.

2. A review of published and unpublished literature on Loweswater highlighted trends in water chemistry since the mid-eighteenth century. Land use and farming practises have changed over the past 200 years which have led to increased nutrient loading to the lake with significant increases occurring in the mid part of the last century. Agricultural intensification is likely to be a significant cause of the problem as well as inadequate septic tank management. Local management efforts, led by the Loweswater Care Project, has sought to reduce the primary sources of nutrients reaching the lake, but total phosphorus (TP) concentrations in the lake remain higher than desired.

3. Temperature and dissolved oxygen (DO) profiling confirmed that the site stratified in summer with major changes in DO occurring below a depth of 8 m. The deeper waters were almost entirely anoxic. During stratification the maximum TP value was recorded at the lake bottom. This is a clear indication that P is being released from the lake bed during summer stratification.

4. Analysis of the stream water from the Dub Beck inflow (data for 2013), shows that P influx remains high enough to explain the elevated lake water P concentrations, despite considerable efforts to reduce catchment P sources.

5. Analysis of the water column P profiles shows that P release from the sediment is only a minor contribution to the P load. While the sediment core data reveals a substantial pool of P in the sediment very little of this should be released each year to the water column. In 2013 it is estimated that more than 90% of the P came from the catchment and only ~10% from the sediment.

6. As with all modelling exercises there are uncertainties inherent in the approach. In this case the model output is based on a single year of input data for the inflow P flux calculations and it would be preferable to have a longer data series to inform the modelling. Inflow fluxes are highly dependent on flow conditions and here, in the absence of flow data from Dub Beck, we used data from a nearby stream. Further, the monthly sampling has resulted in most samples being taken in low flow conditions, thus missing potential storm flow conditions. Finally, stream input information is restricted to Dub Beck, and contributions from the other stream is unknown

7. Nevertheless, the results from the modelling are clear and on that basis we conclude that the priority is for P loading to the lake to be reduced by better catchment

management and that lake manipulation is not warranted. Integrated catchment management supported by modelling together with local stakeholder engagement should provide the most effective means of improving the condition of the lake.

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1. INTRODUCTION AND PROJECT OBJECTIVES

1.1 Study Rationale

Despite lying within a catchment of low intensity farming and low population density, Loweswater has shown the classic signs of eutrophication in recent years. Agricultural intensification is likely to be a significant cause of the problem as well as changes in domestic detergent usage (Bennion *et al*. 2000, Bennion and Winchester 2010). Recent community engagement, led by the Loweswater Care Project Tsouvalis & Waterton, 2102), has aimed to reduce the primary sources of nutrients reaching the lake, but total phosphorus (TP) concentrations in the lake remain higher than desired. The recycling of phosphorus (P) bound within the sediments is a likely cause of the continued enrichment of the water and thus a better understanding of the concentrations and internal cycling of P is required in order to address the longer term management of the lake.

1.2 Objectives

The main objectives of the project were as follows:

i) to determine the spatial distribution of P concentrations in surface sediments from sites above and below the thermocline as a means of assessing the importance of anoxia in P recycling.

ii) to establish changes in the sediment concentration of P (as well as sediment flux) through time using evidence from dated sediment cores.

iii) to determine P fluxes using seasonal water chemistry data from the outflow and from the water column during periods of overturn in the spring and autumn.

iii) to use these data to model P flux within the lake and provide forecasts of future sediment P release.

2. LITERATURE REVIEW

2.1 Loweswater

Loweswater (NGR NY 126 217) is a small lake located in north-west part of the English Lake District, in a catchment which contains both lowland (< 150 m, particularly at the north and southern ends of the lake) and upland areas (maximum altitude is 540 m). The physical characteristics of the lake and its catchment are summarised in Table 1. Compared to other major lakes in the English Lake District, Loweswater is 13th smallest out of 19 in terms of area and volume and 8th in terms of retention time (Maberly *et al*., 2006)

Land use in the Loweswater catchment is summarised in Table 2 which includes percentage cover of the different land use types for both 1972 and 1988 (Lake District National Park data) along with an indication of change over this period. The only notable differences between the two years were that improved pasture increased by 5% whilst rough pasture decreased by around 4%. A map of the 1988 land use data (Figure 1) shows that the catchment is predominantly upland grass moorland and improved pasture with sizeable areas of woodland and bracken. These land use data relate only to the part of the catchment that lies within the Lake District National Park. Approximately 12.5% (c.1 km^2) of the catchment falls outside the National Park boundary and no data were available for this area.

Table 1 The major physical characteristics of Loweswater lake and catchment.

Altitude m	Lake area km^2	Lake length km	Lake max depth m	Lake mean depth m	Volume m^{3}x10^6	Catchment area km^2	Cultivated area %	Approx. retention days	Littoral zone %	Pop per 10^6 m^3 lake vol.
121	0.64	1.8	16	8.4	5.4	8.9	39	150	59	13

Data from Ramsbottom (1976) and Kadiri & Reynolds (1993); human pop per 10^6 m^3 lake volume from 1971 census (Jones *et al.*, 1979); potential littoral zone (0-10 m depth) from Henson (1993).

Table 2 Land use data for the Loweswater catchment within the Lake District National Park

Land cover type	*% in 1972*	*% in 1988*	*Change*
Broad leaved woodland	1.2	1.1	None
Coniferous woodland	4.4	4.7	None
Mixed woodland	2.6	2.6	None
Scrub	0.3	0.3	None
Clear felled/newly planted	0.02	0.8	Small increase
Upland grass moor	40.1	40.0	None
Blanket peat grass moor	3.4	3.4	None
Bracken	10.7	8.9	Small decrease
Improved pasture	22.8	27.8	Increase
Rough pasture	5.6	1.3	Decrease
Open water (lake)	8.2	8.2	None
Bare rock	0.5	0.5	None
Isolated farmstead	0.3	0.3	None

A geochemical study of a number of Cumbrian lakes showed that differences in the chemical concentrations of some 35 elements were primarily due to the diverse regional geology and Loweswater was grouped with other lakes on the north-eastern part of the lake District all underlain by Skiddaw slates (Jones *et al* 1988). A more detailed description of Loweswater, its catchment and its position in the English Lake District Series is provided by Bennion *et al* (2000).

2.2. Water Quality in Loweswater

An early survey of water chemistry in Loweswater (Pearsall, 1930) showed that Loweswater had relatively high nitrate, pH and hardness, and low phosphate and silica concentrations at this time. Subsequent surveys revealed that Loweswater was ranked as 12 out of 16 lakes in terms of increasing degree of enrichment and was clearly one of the more productive lakes in the series (Jones, 1972; Jones *et al*., 1979). The study reported hypolimnetic deoxygenation in Loweswater and in other productive lakes (including Rydal Water, Grasmere, Esthwaite Water and Blelham Tarn).

Between 1974 and 1978 Loweswater was ranked 19 out of 24 Lake District sites surveyed in terms of total anions (Sutcliffe *et al.,* 1982). A comparison of the 1970's data with those from 1955-56 (Carrick & Sutcliffe, 1982) showed that the sum total for means of cations had increased by 20-25% in Loweswater (Sutcliffe *et al*., 1972) and sodium and chloride also increased. Notably there was a significant increase in potassium in Loweswater (from 15 to 20 µeq l^{-1}), which was not seen in other lakes. A threefold increase in nitrate from 9 to 30 µeq l^{-1} was also recorded over this period. The sum of calcium and magnesium increased by 28% in Loweswater and Sutcliffe *et al*. (1982) observed that, generally, the biggest changes in mean calcium plus magnesium occurred in the more productive lakes and suggested that the principal sources were probably the rocks and soils in the catchments, sewage and *in situ* biological production. Agricultural use of lime in Westmorland reached its peak in the 1950s and may have leached into the lakes. However, the sources of alkalinity were not investigated in the study and, therefore, the origin of these ions for Loweswater was not established.

A more recent examination of the ionic composition of surface waters in the region (Sutcliffe, 1988) showed that the major ion concentrations and pH values were very similar to those recorded by Sutcliffe *et al*. (1982). pH appears to have remained unchanged since 1928 (Pearsall, 1930). Loweswater is somewhat different from other northern lakes located on the Skiddaw Slates (Sutcliffe, 1998). Chloride concentration is as high as that of Esthwaite Water which lies on Silurian Slates in the southern Lake District and the Na/Cl ratio is low, similar to that of the southern lakes. The ionic composition suggests some underground connection with groundwater in the Carboniferous rocks to the west, which could be a source of nutrients to Loweswater. Unusually for lakes in this part of the Lake District, Loweswater is relatively productive, ranked 17 amongst 20 major lakes (Kadiri & Reynolds, 1993). Enrichment may be due to local agricultural activity (Sutcliffe, 1988) but there is a history of summer anoxia and high algal productivity extending back to medieval times (Pennington, 1981).

Recent water chemistry data (sampled between October 1998 and January 2000) collected by the Environment Agency (see Bennion *et al*., 2000) showed that the TP values were below the detection limit for most months, but higher concentrations were recorded at various times through the year but generally below 70 µg TP l^{-1}. The soluble reactive P (SRP) concentrations during this period were generally below detection limit of 1 µg l^{-1}. These data suggest that P is the limiting nutrient in Loweswater. Nitrate values were relatively high, ranging from 200-1630 µg l^{-1} (with a mean of 488 µg l^{-1}). Chlorophyll *a* concentrations were also quite high and ranged from 4-14 µg l^{-1} with a mean of c. 8 µg l^{-1}.

A number of lakes in the English Lake District (including Loweswater) had continuous water quality monitoring equipment installed in the mid-1990s, measuring dissolved oxygen, pH, conductivity, temperature and chlorophyll *a*. The instruments were installed in Loweswater in June 1996. Between 1997 and 1999 the temperature profiles show strong thermal stratification in the lake from late April to early September, leading to very low hypolimnetic dissolved oxygen levels (<20%) during July and August (Bennion *et al*., 2000). The surface dissolved oxygen remained high throughout the year, with around 100% saturation during the spring. The pH values were in accordance with earlier surveys with surface pH usually in the range 6.5-7.5, and surface conductivity ranged from 65-85 µS cm^{-1}. In 1997 and 1998, the chlorophyll *a* data showed peak levels in spring of 30-90 µg l^{-1} and summer levels in the range 10-20 µg l^{-1}, falling to steady concentrations less than 10 µg l^{-1} after the turnover in September. In 1999, chlorophyll *a* concentrations were lower and showed peak levels in summer of 25-34 µg l^{-1}. Annual mean chlorophyll *a* concentrations for 1997 and 1998 were 11 µg l^{-1} and 12 µg l^{-1} respectively, placing the lake just into the eutrophic category according to the OECD (1982) classification scheme. The 1997 chlorophyll *a* conditions were reported to be indicative of high productivity and were considered to be unexpected given that the lake lies in an upland catchment (Environment Agency, 1997). Secchi disk results for 1997 gave a minimum value of 1.2 m and an average value of 2.9 m.

There is evidence of a long term increase in nitrate concentrations in Loweswater from the late 1920s to the present day (Sutcliffe *et al*., 1982; Lambert, 1991). There are, however, insufficient data to examine long term trends in P in the lake but comparison of the patchy available data with the recent data indicate that TP concentrations may also have increased slightly in recent years (Jones *et al*., 1979; Sutcliffe *et al*., 1982). Chlorophyll *a* values in 2000 (Bennion *et al*., 2000) are higher than those recorded previously (Lambert, 1991; Jones *et al.,* 1979). There is also a suggestion of a deterioration in light penetration as measured by Secchi disc (Jones *et al*, 1979; Lambert, 1991).

An assessment of water samples taken between 1984 and 2005 shows a distinct pattern of increasing lake productivity due to the increases in phosphorus supply during spring and as an average over the whole year (Maberly *et al*., 2006). The increased productivity over this period has reduced oxygen concentrations in the deeper water and, towards the bottom, Loweswater is anoxic during the summer. This may lead to the release of more phosphate into the water column (Maberly *et al*., 2006)

It is important to note that a direct comparison of the current data with previous surveys is problematic owing to the different sampling and analytical methods, and the variable timing and frequencies of measurements in the studies. Therefore, all of the trends described above must be interpreted with caution.

Using the Secchi disk and chlorophyll *a* measurements (reported in Bennion *et al*., 2000) independently, Loweswater would be classified as eutrophic under the OECD system (1982) and according to the criteria of the Urban Waste Water Treatment Directive (UWWTD).

However, the nutrient concentrations were relatively low with TP concentrations generally below 20 µg TP l^{-1} which places Loweswater into the mesotrophic category. On the basis of water chemistry, therefore, it is very difficult to classify Loweswater using existing schemes. In a regional context, it is one of the more productive lakes in the English Lake District, largely because it has a higher percentage of cultivated catchment than many of the other lakes (cf. Pearsall, 1921). In a national context, however, Loweswater is less productive than many UK lakes, especially those in predominantly lowland catchments, such as the Cheshire and Shropshire Meres and the Norfolk Broads (e.g. Carvalho & Moss, 1995).

2.3 Algal blooms in Loweswater

As has been observed in a number of lakes in the Lake District Loweswater has experienced algal blooms (Norton, 2006). However, unlike other lakes in the region these blooms contain toxic cyanobacteria and can occur at various times of the year, sometimes lasting for several months (Maberly *et al*., 2006). The earliest phytoplankton surveys reported in the literature indicated evidence of blue-green algae in Loweswater, although apparently not in bloom densities (Pearsall & Pearsall 1929). Loweswater exhibited considerable blue-green algae in its plankton, becoming abundant very early on due to high organic matter in the lake at that time (Pearsall,1932).

Subsequent surveys during 1949-1951, 1955-1956, and 1961-1963 (Gorham *et al*., 1974) showed that Loweswater was one of six lakes with the largest numbers of algae and high algal biomass (Group 3, productive lakes). Loweswater had one of the highest proportions of blue-green algae, only exceeded by Esthwaite Water. A strong correlation between algal standing crop and degree of agricultural activity in the lake catchments was noted suggesting that the environmental factors favouring agricultural productivity also lead to high aquatic productivity. Further, the data from these surveys also indicated that autochthonous sources of sedimentary organic matter are important in these more productive sites (i.e. burial of aquatic plant detritus rich in pigments in the anaerobic sediments). In Loweswater, numbers of blue-green algae increased in 1961-1963 relative to 1949-1951. Meteorological data showed that, in the region, the summer of 1962 was warmer than that of 1951 and the autumn rainfall was lower in the former (Lambert, 1991). Therefore, these patterns could be related to different weather conditions in those years rather than any change in lake productivity**.**

Phytoplankton data collected in 1978 and 1984 were compared with those collected by Gorham *et al*. (1974) to explore changes in lake water quality over a period of two to three decades for a group of twenty lakes (Kadiri & Reynolds, 1993). These data placed Loweswater into the same group as the Gorham *et al*. (1974) study with the lake falling into Group 3, i.e. mildly to strongly eutrophic lakes with abundant algal biomass and relatively abundant blue-green algal populations. The main difference between these data and the earlier study is that there was a two-fold increase in the large algal biomass which may be an indication of enrichment, a suggestion corroborated by the increasing frequency of reported blue-green algal blooms in recent years. There have been a number of reports of blue-green algae blooms and scums dating from 1989 up to 2000 with the years 1989, 1993, 1994 and 1996 the most significant. However, trends in blue-green algae abundance are difficult to discern because of different methodologies employed in the previous studies.

Many of the early studies tended to be based on net collections where large algae, such as blue-greens, would often be exaggerated at the expense of small algae (Bennion *et al*., 2000).

More recently, from the early 2000s, Loweswater has experienced more frequent algal bloom occurrences. A project funded by the Rural Enterprise Scheme (RES) in 2004 was tasked with monitoring Loweswater for a year to assess the potential impacts of farming practices using catchment modelling. This suggested that, as Loweswater was characterised by a long retention time, it was more vulnerable to blooms of toxic blue-green algae compared to other less harmful species. Generally, the level of phytoplankton biomass a lake is able to support increases with retention time as algal loss through flushing is less. Further, the development of slower growing filamentous cyanobacteria is favoured in this environment which would not be the case were flushing more rapid. High productivity results in significant oxygen depletion in the deeper parts of the lake which may allow sediment phosphorus to be released into the water column and thus become available to the phytoplankton (Maberly *et al*., 2006) The modelling exercise highlighted catchment land use as the main source of phosphorus loading to the lake but that the toxic blooms stemmed from slurry and manure holdings and inadequate septic tanks (Norton, 2006; Webb, 2010).

Another factor which may influence the development of blue-green algae is changing weather patterns. In recent years the UK has tended to experience milder winters and warmer summers with higher rainfall. In particular there was an exceptionally warm summer in 1989, following on from a mild winter. Blue-green algal blooms were severe across the UK and three separate blooms were recorded in Loweswater that summer (Bennion *et al*., 2000). The summer of 1991 was cold and damp and blooms were less well developed (Lambert, 1991). It has been observed that high rainfall episodes can cause elevated nutrient run off from agricultural land (Bailey-Watts *et al*., 1990) and this may be the reason for the observed peaks in nutrient concentrations in both Loweswater and its inflows (Bennion *et al*., 2000). Monitoring data shows that Dub Beck, the main inflow to the lake provides the most significant contribution of nutrient loading to the lake (Bennion *et al*., 2000)

2.4 Land- use change in the Loweswater catchment

Archive material from parish summaries of the annual Agricultural Returns from 1866 to 1988 were used to examine land-use change in the Loweswater catchment from the mid-nineteenth to the late twentieth century (Bennion and Winchester, 2010). Overall during this period there was a declining trend in the acreage under tillage, with the oat crop, previously dominant, suffering the greatest decline. Livestock husbandry intensified over the same period with a major increase in the mid-twentieth century. Sheep numbers increased substantially during the 1980s. Coinciding with these changes there were significant alterations in farming in Cumbria which would have been likely to have an impact on Loweswater. The spread of field drainage occurred from the 1820s and 1830s, the same period that applications of lime for fertilization began. This was recorded locally from around the mid-eighteenth century (Bennion and Winchester, 2010). These developments would have enabled more intensive land use, utilising formerly poorly drained land, increasing grass yield and therefore the potential acreage that could be cropped. Given this, it is likely that agricultural productivity increased in Loweswater from the mid-eighteenth century. This factor, together with the increased catchment run off from field drains, may have caused nutrient enrichment in Loweswater around this time.

However, in general the greatest change in land use occurred between 1945 and 1965 when cultivation declined significantly and there was a large increase in cattle numbers. Closer examination of information for this period of change (from 1945 to 1965) highlights the importance of developments in grassland management (Bennion and Winchester, 2010). During these two decades the acreage of improved grassland increased significantly, probably as a result of improving rough grazing land. The shift away from cultivation towards more intensive use of grassland led to a rise in the number of cattle and sheep. Although local data are sparse, this was almost certainly accompanied by an increase in the use of artificial fertilisers. The application of phosphorus- and nitrogen-rich fertilisers together with a greater input of animal waste would have led to higher nutrient loads to Loweswater.

2.5 Previous palaeoecological studies of Loweswater

Loweswater is characterised by a relatively low lying catchment (for the Lake District) and well developed soils (Pearsall, 1921) and is therefore naturally more fertile than many of the other lakes in the English Lake District. A sediment core study of 17 lakes in the region (Pennington, 1981) identified a sediment accumulation rate for Loweswater (for a core taken in 1972) of 0.5 cm yr^{-1}, which was faster than some of the large northern lakes (e.g. Wastwater and Buttermere) but slower than more productive lakes such as Windermere (North Basin), and Esthwaite Water). The study produced evidence of extensive forest clearance around 1000 years ago which resulted in major ecosystem change with increased input of humic substances and a shift towards a diatom flora indicative of more productive waters (Pennington, 1981). Additionally, Pennington (1981) noted a thick layer of mineral sediment associated with mediaeval agriculture which reduced the volume of the hypolimnion of Loweswater so that anaerobic conditions occurred more readily in the summer, despite low primary productivity. The study concluded that, since 1000 BP Loweswater and other shallow lakes have been characterised by seasonal anoxia with a different flora and fauna compared to the deeper lakes.

A detailed geochemical analysis of the sediment core from Loweswater reported in Bennion *et al*. (2000) revealed a decrease in lithogenic elements and an increase in organic matter which would normally be indicative of a reduction of eroded material coming into the lake from the catchment. However, this may also be indicative of an increase in biogenic supply or eutrophication and sharp increases in Si/Ti and P towards from 20 cm upwards in the core support this. There is also evidence for heavy metal pollution of Loweswater with increases in Cd, Zn and Pb above 45 cm. The Pb is certainly of anthropogenic origin and may reflect indirect supply from the catchment prior to 1750. Post-1750 there were steep rises in concentrations of Cd, Pb and Zn which coincide with increases in S concentration. Similar patterns were observed in a core from Bassenthwaite with Pb and Zn concentration peaking ca. 1880 (Morrison, 1997) with a suggestion that they were driven by mining in the catchment. In Loweswater the mining hypothesis is supported by records of metalliferous mines in the Loweswater and Buttermere valleys around this time (Moon & Wildridge, 1970)

Clear evidence of enrichment is provided by changes in the diatom assemblages indicating the onset of enrichment at around 1850 AD with a further increase in productivity since the 1950s (Bennion *et al*., 2000). Prior to 1850, the low intensity farming activities (small stock rearing farms with small scale agriculture) would have meant nutrient loading to the lake was low. The increase from 1850 was in good agreement with the geochemical record which also provided evidence of enrichment over this time period. Subsequent analysis of the sediment record using a diatom inferred TP reconstruction reinforces the evidence of enrichment suggested by the ecological interpretation of the change in species assemblages in the core (Bennion and Winchester 2010). Radiometric dating of the core indicates that the change in diatom assemblages coincides with an increase in sediment accumulation rates. This may be a result of a combination of external inputs to the lake from the surrounding catchment (e.g. from soil erosion and agricultural runoff) and internal sources of organic matter from algal production (Bennion and Winchester 2010).

Despite attempts reduce the primary sources of nutrients reaching the lake from the catchment, led by the Loweswater Care Project, total phosphorus (TP) concentrations in the lake remain higher than desired. Internal nutrient loading from the sediments is the most likely explanation for the continued enrichment of the water column. This has not yet been fully examined, therefore a better understanding of the concentrations and internal cycling of P in the lake is required in order to address the longer term management of the lake. This report presents the results of a project designed to assess the importance of P recycling in the lake.

3. METHODS

With the exchange of phosphorus from the sediments to the water column primarily occurring during anoxia, the focus of the study was the sediments below the summer thermocline (hypolimnion) which has been measured between 8-10 m (maximum depth of lake ca. 16.5 m). An important aspect of the study was to determine the spatial distribution of P concentration both above and below the thermocline and, additionally to establish changes in sediment concentrations (as well as sediment flux) through time from sediment cores. This required cores to be dated using radiometric techniques (specifically ^{210}Pb dating). The seasonal water chemistry data from the outflow and from the water column during periods of overturn in the spring and autumn is critical to understanding the flux of P. The resultant data have been used to model P flux within the lake and provide forecasts of future sediment P release.

The ENSIS team visited Loweswater on three occasions:

i) 16th and 17th October, 2012. Four short sediment cores and 20 surface sediment samples were taken, a dissolved oxygen and temperature profile was generated and water samples were collected down a vertical depth profile for chemical analysis. Additionally a bathymetric survey was undertaken. Appendix 1 comprises a field report from this visit.

ii) 29th April, 2013. Two short sediment cores were taken using a Renberg gravity corer. These cores were processed at no additional cost to WCRT. A dissolved oxygen and temperature profile was generated and water samples were collected down a vertical depth profile for chemical analysis. Appendix 2 comprises a field report from this visit.

iii) 19th July, 2013. A dissolved oxygen and temperature profile were generated and water samples were collected down a vertical depth profile for chemical analysis. Appendix 3 comprises a field report from this visit.

3.1 Sediment sampling

Four short sediment cores (LOWS 3, 4 5 and 6) were taken (2 x deep water >10 m and 2 x shallow < 8m) using a Renberg gravity corer. LOWS4, one of the deep water cores, was sliced at 2.5 mm intervals for the top 5 cm, at 5 mm intervals between 5 and 15 cm and at 1 cm intervals thereafter. The three remaining cores were transported to UCL for extrusion. Details of core depths and location are given in Appendix 1.

A total of 20 surface sediment samples (top 5 mm) were collected (10 from >10m and 10 from <10m) on 17th October, using a Renberg gravity corer, across a depth range of 4.1 to 16 m. Details of sampling depth, code and location are provided in Appendix 1.

3.2 Sediment analysis

3.2.1 Sediment geochemistry

Four cores and 20 surface sediments were analysed using X-Ray Fluorescence (XRF) at high resolution in the upper 5 cm of the cores to determine total phosphorus concentrations. Cores were also analysed for percentage organic content and wet density.

3.2.2. Radiometric dating

Lead-210 (half-life = 22.3 year) is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). Caesium-137 (half-life = 30 years) and ^{241}Am are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. They have been extensively used in the dating of recent sediments. Dried sediment samples from four Loweswater cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Caesium-137 and ^{241}Am were measured by their emissions at 662keV and 59.5keV (Appleby *et al*, 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby *et al*, 1992).

3.3. Water sampling and analysis

Dissolved oxygen and temperature profiles were taken at the deepest point of the lake together with pH and conductivity.

Water samples were collected down a vertical depth profile for chemical analysis using a Van Dorn sampler during spring and autumn to coincide with lake stratification and turnover. 1 x 250 ml Environment Agency National Laboratory Service (NLS) sample was taken for nutrients at each depth (1, 3, 5, 7, 9, 11, 13 and 15 m) along with 1 x 1000 ml NLS sample for general chemistry. These were delivered to Star Cross for analysis on 18th October 2012.

Monthly water samples were collected (by local Care Project workers) from the Loweswater outflow and analysed for total P and orthophosphate (SRP).

3.4. Data modelling

Bathymetric survey data were collected using the boat-mounted Lowrence GPS / Echo sounder. The bathymetric data fed into the P flux modelling reported below.

3.4.1. Lake outflow flux

The lake outflow flux by is determined by multiplying the outflow water flux by the lake/outflows stream water concentration.

Runoff rate has not been measured. Therefore the National River Flow Archive (NRFA) dataset for nearby rivers (1.0 (+/- 0.3) m/yr) was used.

3.4.2 Lake sediment flux

The value for this flux must be estimated for the whole lake. There are two approaches that can be used. The first is to establish a regression model, for different time slices, between the P flux and water depth. These can then be applied to a hypsometric model for the lake, thereby determining the depth-weighted mean P flux.

i) Hypsometric method

Step 1. Find typical observed flux values for some age slices.
Step 2. Find a flux –depth relationship for each age:
Step 3. Develop a hypsometric curve
Step 4. Combine steps 2 and 3 to derive the contributions from each depth interval.
These steps are described in more detail in the results section below.

ii) ^{210}Pb method

An alternative approach is to assume that unsupported ^{210}Pb is focussed in exactly the same way as sediment P (Dillon & Evans, 1993). We can then calculate a focusing factor as the ratio between the lake core ^{210}Pb inventory to the expected atmospheric inventory. Here the soil inventory values have been used based on the unpublished procedure of Peter Appleby (University of Liverpool, personal communication).

3.5. Macrophyte survey

Loweswater was surveyed for macrophytes by ENSIS on 1st August 2012 as part of the EA Water Framework Directive monitoring. JNCC Common Standards Methodology was used to collect data from 4 x 100 m shoreline transects, each with a boat transect from shore to open water. The results therefore provide fixed point monitoring data rather than a full survey of the site – nonetheless, the Loweswater survey is considered to offer a representative picture of the aquatic flora of the site. The results of the macrophyte survey are presented in Appendix 2.

4. RESULTS

4.1. Oxygen, temperature and water chemistry profiles

Dissolved oxygen and temperature profiles are tabulated in Tables 3 (October) 4 (April) and 5 (July). Nitrate, SRP and TP concentrations are also included in these tables. The profiles are shown in Figures 1, 2 and 3. Details of the location of the profile and NLS sample numbers for each sample are given in Appendices 1, 2 and 3.

Table 3 Dissolved oxygen (DO) and temperature profile data from Loweswater, 16/10/2012 from NY1263321705

Depth m	DO mgl^{-1}	Cond μScm^{-1} (ambient) *	Specific conductance μScm^{-1}~	pH	Temp °C	Nitrate-nitrogen mgl^{-1}	SRP (as P) μgl^{-1}	TP (as P) μgl^{-1}
0	9.75	48.0	65.9	6.18	10.5			
1	9.75	48.0	65.9	6.24	10.5	0.204	1.8	12
2	9.72	48.0	65.9	6.26	10.5			
3	9.72	48.0	65.9	6.29	10.5	0.204	1.8	16.3
4	9.67	48.0	65.9	6.30	10.5			
5	9.68	48.0	65.9	6.32	10.5	0.203	1.5	10.5
6	9.63	48.0	65.9	6.32	10.5			
7	9.62	48.0	65.9	6.35	10.5	0.2	1.8	10.2
8	9.56	48.0	65.9	6.36	10.5			
9	9.56	48.0	65.9	6.38	10.5	0.204	2.3	11.5
10	9.59	48.0	65.9	6.37	10.5			
11	9.57	48.0	65.9	6.38	10.5	0.199	2.5	8.6
12	9.46	48.0	65.9	6.39	10.5			
13	9.49	48.0	65.9	6.40	10.5	0.204	1.6	11
14	9.53	48.0	65.9	6.42	10.5			
15	9.52	48.0	65.9	6.43	10.5	0.205	1.4	9.8
16	9.46	48.6	66.7	6.44	10.5			
10	9.53	48.0	65.9	6.43	10.5			
5	9.48	48.0	65.9	6.46	10.5			
0	9.55	48.0	65.9	6.49	10.5			

*Measured uncompensated for temperature
~Specific conductance derived using a temperature coefficient of variation (2%)

In October the lake was isothermal (i.e. a difference of less than 1°C between the top and bottom) and well mixed chemically with minimal variation in dissolved oxygen, pH and SRP (Table 3; Figure 1). Dissolved oxygen was ca. 9.5 mg l^{-1} with slightly higher values towards the surface. pH increased towards the bottom, ranging from 6.18 (at the surface) to 6.49 Conductivity was 48 µS cm^{-1} and the temperature was 10.5°C throughout the profile. Nitrate-nitrogen (recorded at 2 m intervals) remained stable around 0.2 mg l^{-1} with SRP ranging from 1.4 µg l^{-1} towards the bottom to 2.5 µg l^{-1}. There were some slight fluctuations in TP values from 8.6 µg l^{-1} at 11 m to 16.3 µg l^{-1} 3 m from the surface. Secchi depth was 3.1 m.

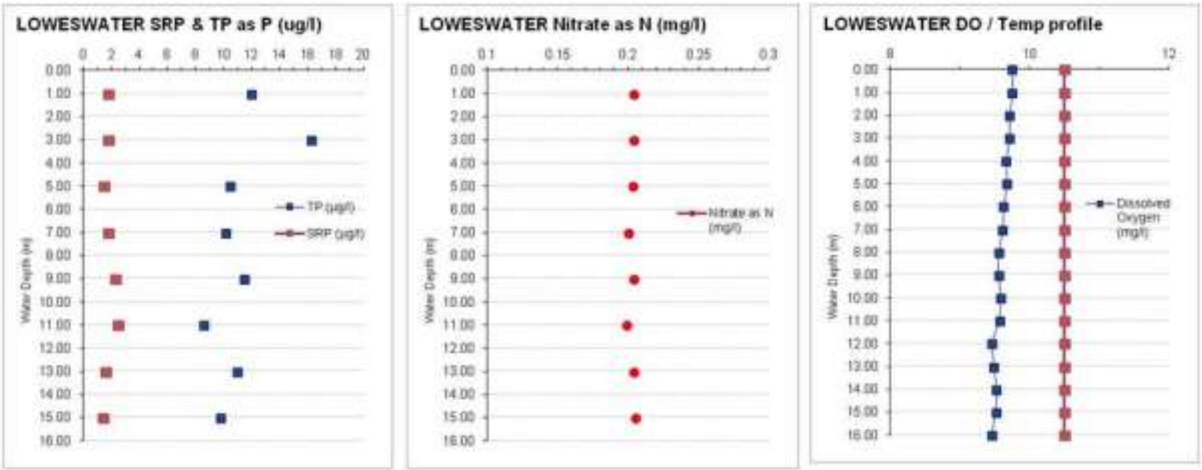

Figure 1 Loweswater profile results, 16th October 2012

As expected, the water column was also well mixed in April (Table 4; Figure 2). The water was relatively clear but had a noticeable green tinge to it. Secchi depth was recorded as 3.8 m. The data for nitrate-nitrogen, orthophosphate (as P) and total phosphorus (as P) are shown in Table 5. The profiles are shown in Figure 2.

Table 4 Dissolved oxygen (DO) and temperature profile data from Loweswater, taken on 29/04/2013 from NY1268321686 - 16.2 m depth

Depth m	DO mgl^{-1}	Cond μScm^{-1} (ambient)*	Specific conductance μScm^{-1}~	pH	Temp °C	Nitrate-nitrogen mgl^{-1}	SRP (as P) μgl^{-1}	TP (as P) μgl^{-1}
0	13.74	44.2	62.8	7.32	8.1			
1	13.50	44.3	62.9	7.27	8.1	0.368	1.09	10.7
2	13.48	44.2	62.8	7.24	8.1			
3	13.42	44.2	62.8	7.24	8.1	0.365	1.4	10.6
4	13.39	44.3	62.9	7.24	8.1			
5	13.40	44.2	62.8	7.24	8.1	0.363	1.2	10.4
6	13.39	44.2	62.8	7.26	8.1			
7	13.35	44.2	62.8	7.24	8.1	0.366	1.1	10.6
8	13.38	44.2	62.8	7.24	8.1			
9	13.40	44.2	62.8	7.24	8.1	0.365	1.1	9.8
10	13.39	44.2	62.8	7.27	8.1			
11	13.42	44.2	62.8	7.26	8.1	0.358	<1.0	10.4
12	13.40	44.2	62.8	7.26	8.1			
13	13.41	44.2	62.8	7.26	8.1	0.354	<1.0	9.4
14	13.44	44.2	62.8	7.26	8.1			
15	13.44	44.2	62.8	7.28	8.1	0.367	1.03	9.6
16	13.21	44.5	63.2	7.24	8.1			
10	13.41	44.2		7.28	8.1			
5	13.40	44.2		7.24	8.1			
0	13.71	44.2		7.29	8.1			

*Measured uncompensated for temperature

~Measured Specific conductance

Dissolved oxygen was higher than recorded in October, around 13.5 mg l^{-1} throughout the column. pH was stable around 7.25. Conductivity was 44.2 µS cm^{-1} and the temperature was 8.1°C throughout the profile, 2.4°C colder than in October. Nitrate-nitrogen (recorded at 2 m intervals) remained stable around 0.35 mg l^{-1} with SRP ranging from <1 µg l^{-1} towards the bottom to 1.4 µg l^{-1} at 3 m. TP values were relatively constant, between 9.4 and 10.7 µg l^{-1}.

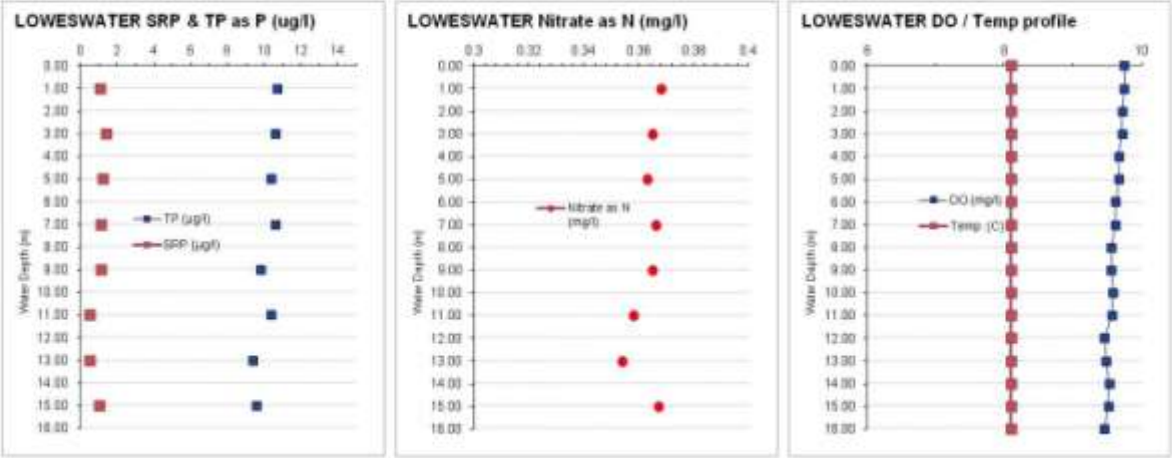

Figure 2 Loweswater profile results, 29th April 2013

In July, following fine summer weather the site was fully stratified with major changes in temperature and dissolved oxygen below a depth of 8 m (Table 5). The deeper waters were almost entirely anoxic, less than 1 mg l^{-1} compared with values around 9-10 mg l^{-1} towards the surface. pH declined by almost one pH unit from the surface to the bottom. Conductivity was stable (around 72 µS cm^{-1} up to a depth of 13 m below which it increased up to 88 µS cm^{-1}. The temperature at the surface was 23.3°C declining to 10.4 °C at the bottom. Nitrate-nitrogen increased steadily from very low values at the surface (0.0072 mg l^{-1}, peaking at 0.285 mg l^{-1} before declining again. TP values declined from 17.7 µg l^{-1} at 2 m to 9.6 µg l^{-1} at 8 m from the surface before increasing slightly and then declining towards the bottom. However, the maximum TP value was recorded at the lake bottom (19.9 µgl^{-1}). Secchi depth was recorded as 4.9 m. The profiles are shown in Figure 3. The data for nitrate-nitrogen, orthophosphate (as P) and total phosphorus (as P) are also shown in Table 6.

Previous results on temperature and stratification showed that the lake stratifies into a warmer upper epilimnion and a cooler hypolimnion from May, persisting until September (Maberly *et al.*, 2006) with a maximum temperature difference between top and bottom recorded in mid July, a pattern similar to those observed in other major lakes in the region. Maberly *et al.* (2006) noted that oxygen depletion at depth began in early May in Loweswater with the bottom water becoming anoxic by mid-June. The higher oxygen concentrations observed towards the surface reflect those recorded previously (Maberly *et al.*, 2006). The oxygen maximum at 4 m depth recorded here is consistent with a sub-surface phytoplankton maximum commonly seen in stratified lakes (Maberly *et al.*, 2006)

Table 5 Dissolved oxygen (DO) and temperature profile data from Loweswater, taken on 19/07/2013 from NY1272021670 – 16.5 m water depth

Depth m	DO mgl^{-1}	Cond µScm^{-1} (ambient)*	Specific conductance µScm^{-1}~	pH	Temp °C	Nitrate nitrogen mgl^{-1}	SRP (as P) µgl^{-1}	TP (as P) µgl^{-1}
0	9.25	66.8	71	7.62	23.3	0.0072	6.20	17.20
1	8.71	66.8	71	7.62	23.3			
2	9.05	67.8	72	7.68	22.8	0.0084	10.30	17.70
3	9.50	66.4	72	7.68	21.5			
4	10.14	61.3	72	7.68	18.0	0.0685	4.70	11.30
5	9.22	59.2	71	7.52	16.8			
6	8.75	57.2	70	7.22	16.1			
7	8.12	58.0	71	7.17	15.6	0.104	2.80	14.90
8	7.26	56.9	71	7.01	15.0	0.117	2.20	9.60
9	5.51	56.5	72	6.91	13.7	0.128	2.90	11.40
10	4.07	55.0	73	6.71	12.1	0.147	1.60	13.40
11	3.65	53.2	72	6.74	11.2	0.216	3.00	11.00
12	2.30	53.2	72	6.62	10.9	0.274	2.50	9.70
13	1.20	53.9	73	6.64	10.7	0.284	3.20	8.80
14	0.54	58.3	79	6.66	10.5	0.285	2.10	10.10
15	0.21	63.7	88	6.84	10.4	0.198	4.03	12.30
16	0.23	63.0	87	6.79	10.4	0.0858	3.20	19.90
10	4.26				12.0			
5	9.31				16.8			
0	9.30				23.3			

*Ambient conductivity derived a temperature coefficient of variation (2%) - calculated from specific cond.
~Measured specific conductance

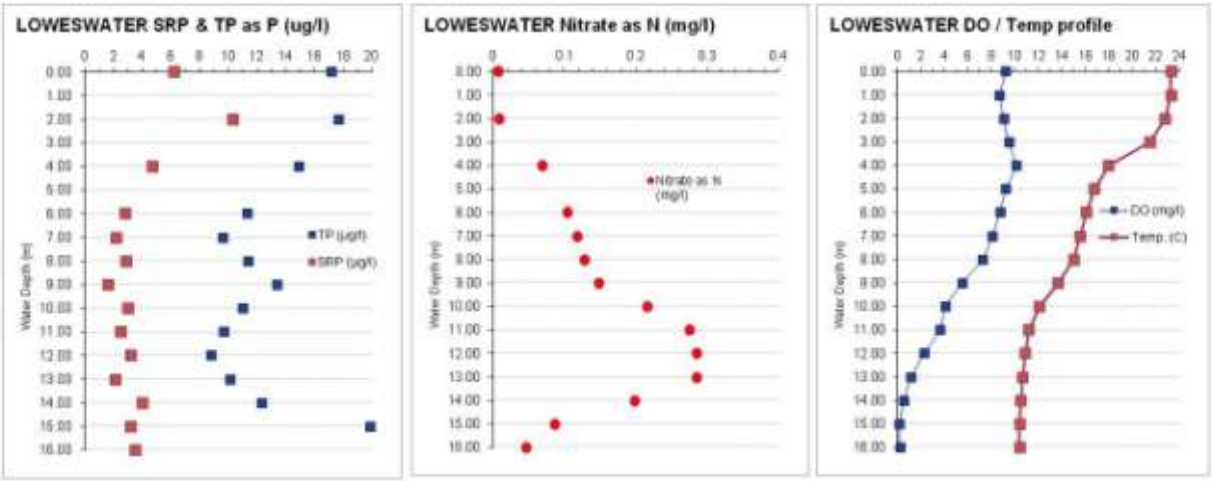

Figure 3 Loweswater profile results, 19th July 2013

4.2 Lake bathymetry

Results from a lake bathymetric survey are shown in Fig. 4, including the location of the short cores and surface sediment samples. The lake is shallow towards its northern end gradually sloping towards the deepest part (16 m), close to the eastern shore. Steeper gradients towards the main basin were recorded from the western and eastern shores. The total volume of the lake is 547111 m^3 and the surface area is 61.6 ha. The bathymetric survey determined the mean and maximum depths to be 8.55 m and 16.24 m respectively. The bathymetric data have been used in the P flux modelling (section 4.6 - see Fig. 19 for the hypsometric curve showing the relationship between depth and surface area).

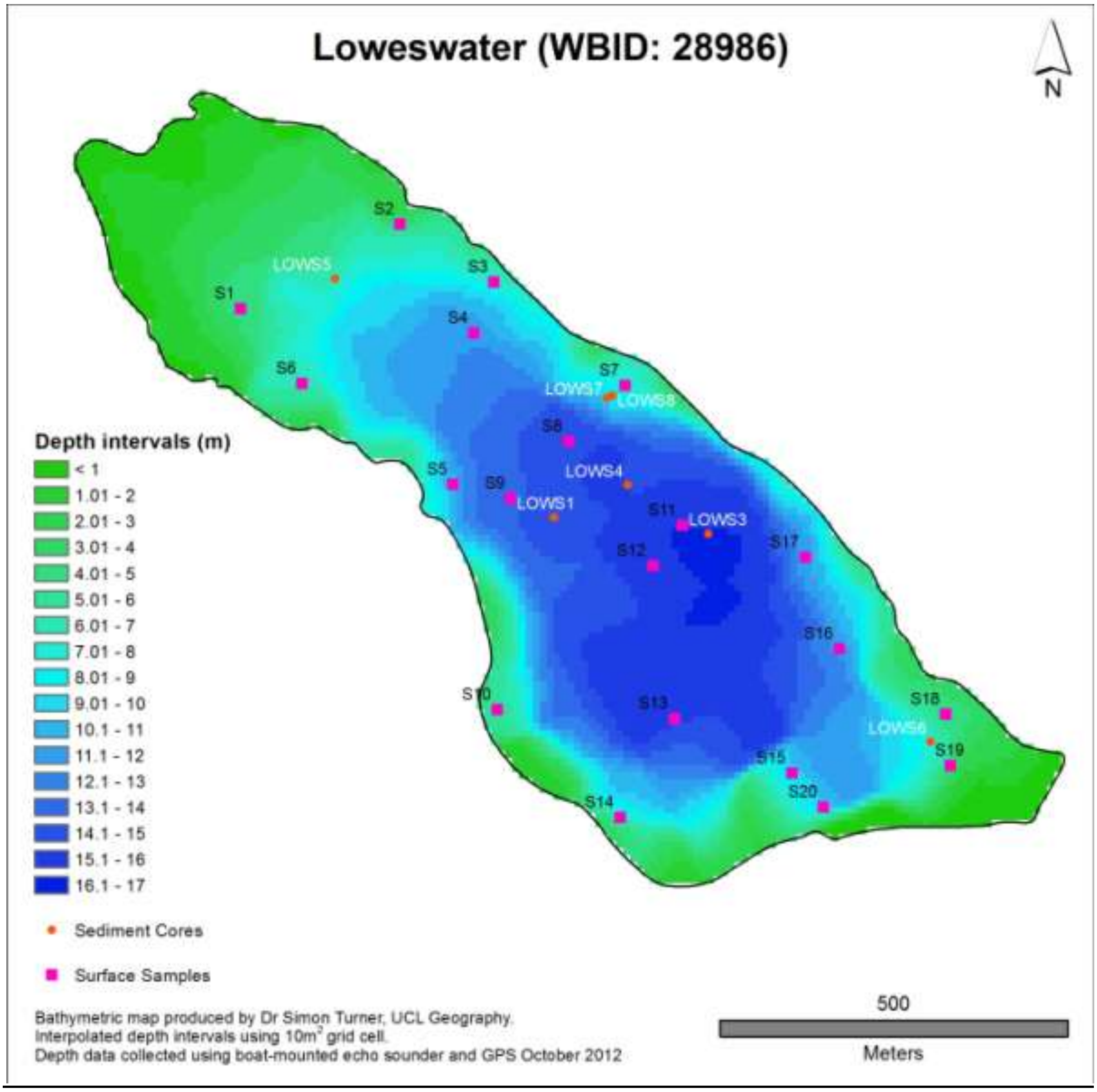

Figure 4 Bathymetry of Loweswater showing location of short cores and surface sediment samples

4.3 Sediment geochemistry

The graphs (Fig 5a-b) below show total sediment phosphorus concentrations down through the sediment cores. Fig. 6 shows sediment P data from all four cores on a single graph.

Although the total sediment P appears to correlate relatively well between the cores, the sediment dating (see below) places these results within a more accurate time context. All four cores show an increase in total elemental P towards the top, with increasing concentrations in the top 4 cm. The core taken from Loweswater in 1999 (Bennion *et al*., 2000) had a sediment accumulation rate of 0.43 cm per year in the uppermost sediments and thus the upper 4 cm of these recent cores may only represent the past 10 years of sediment accumulation. Further interpretation is provided below.

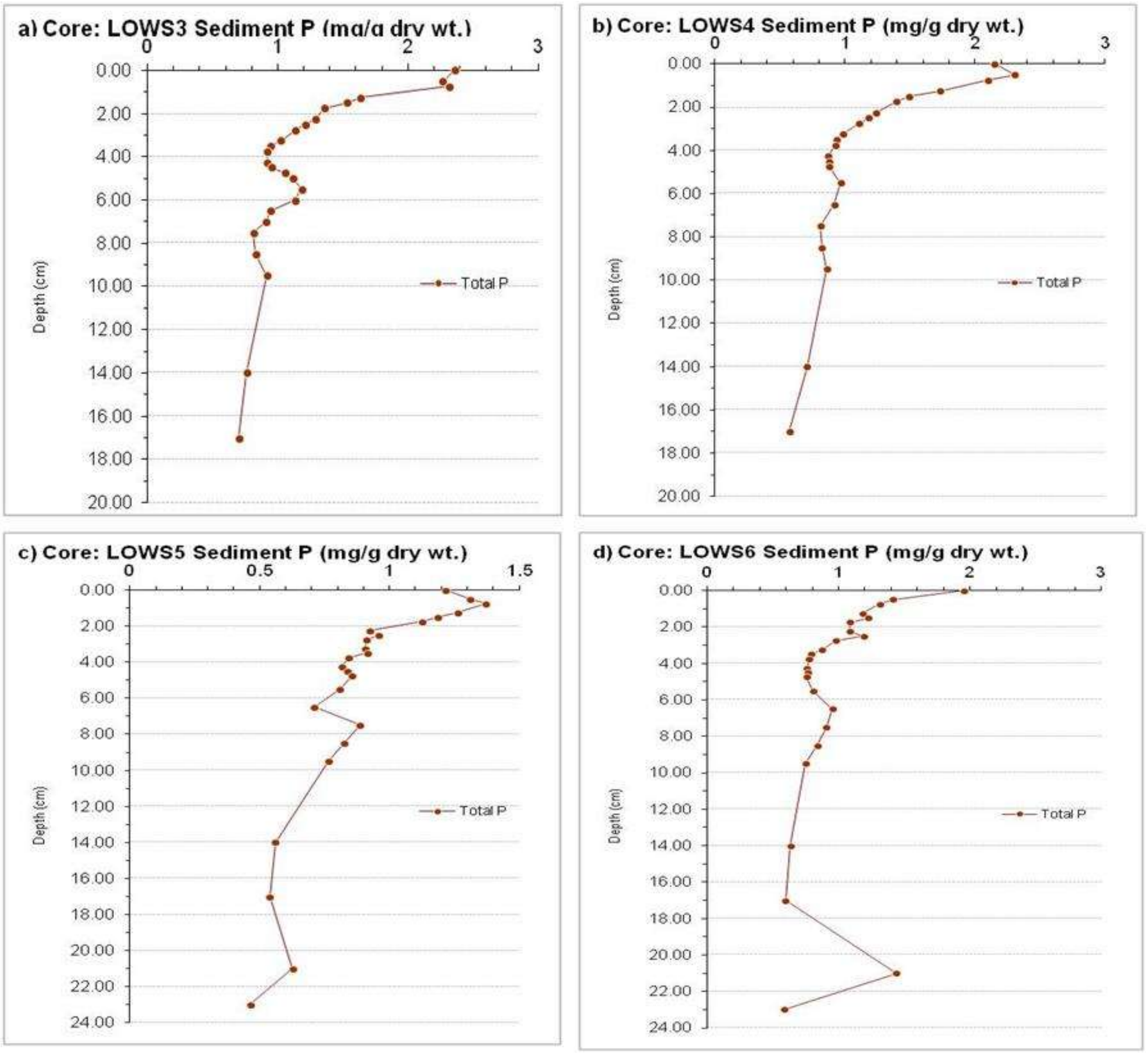

Figure 5 Total Sediment phosphorus concentrations of a) Core LOWS 3 - NY1266621691 (water depth 16.8 m), b) Core LOWS 4 - NY1255021761 (water depth 15.9) c) Core LOWS 5 - NY1213022058 (water depth 7.4 m), and Core LOWS 6- NY1298621392 (water depth 6.3)

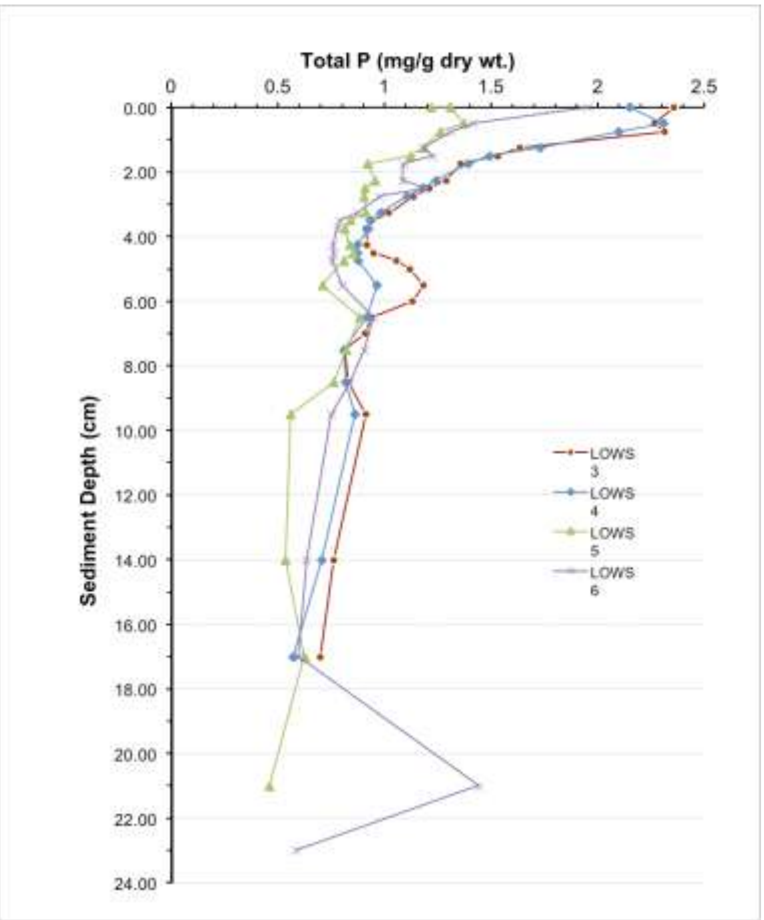

Figure 6 Sediment P from cores LOWS3, 4, 5 and 6)

The surface sediments taken from different water depths throughout the lake basin range in total P levels from c. 0.8 – 2.5 mg / g dry weight. Table 6 provides data on dry weight, loss on ignition, phosphorus (see Fig. 7 for total P) and water depth for each surface sediment sample. There is a trend towards higher P values in deeper water – probably reflecting the more complex chemistry within the periodically anoxic areas of the lake (see Fig. 8).

Table 6 Surface sediment - values for dry weight (%), LOI, P2O5(%),P2O5(mg/l), TP (mg/l) and water depth (m)

	%	%	%	mg/g	mg/g	m
	Dry Wt.	LOI	P2O5	P2O5	Total as P	Water depth
SS1	21.1373	21.0915	0.2951	2.951	1.288	4.3
SS2	17.8695	19.3651	0.2653	2.653	1.158	4.1
SS3	7.8395	19.1077	0.3359	3.359	1.467	6
SS4	17.7428	18.9220	0.3117	3.117	1.361	11.3
SS5	38.5210	11.8153	0.1885	1.885	0.823	13
SS6	17.9792	21.4022	0.2881	2.881	1.258	6.8
SS7	5.7816	19.1257	0.3173	3.173	1.385	7
SS8	15.0873	20.0957	0.4282	4.282	1.870	14.8
SS9	21.7031	16.5176	0.3004	3.004	1.312	14
SS10	19.0526	27.8806	0.2783	2.783	1.215	6.4
SS11	11.1306	21.0240	0.5458	5.458	2.383	16
SS12	7.4077	21.0816	0.5678	5.678	2.479	15.3
SS13	5.6203	22.6607	0.3692	3.692	1.612	15.3
SS14	18.8032	19.0727	0.266	2.66	1.161	8.4
SS15	15.1957	18.2216	0.2467	2.467	1.077	12.6
SS16	16.6791	19.7614	0.3336	3.336	1.457	12
SS17	6.5948	18.5149	0.2499	2.499	1.091	12.4
SS18	12.0862	19.7222	0.2848	2.848	1.243	5.4
SS19	16.5463	18.5651	0.186	1.86	0.812	4.8
SS20	17.7452	18.6927	0.3314	3.314	1.447	7.2
L3	3.3412	26.0870	0.5403	5.403	2.359	16.8
L4	2.9531	27.2727	0.493	4.93	2.153	15.9
L5	11.8963	18.9735	0.279	2.79	1.218	7.4
L6	8.8314	19.1253	0.4471	4.471	1.952	6.3

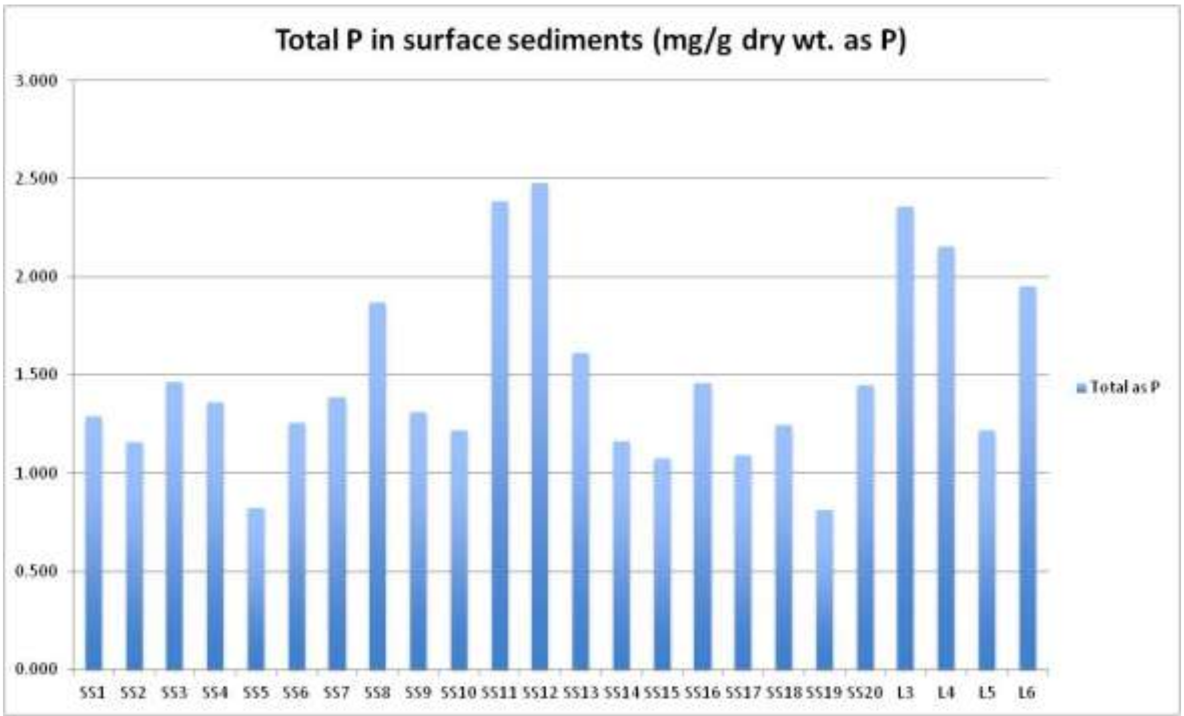

Figure 7 Total P in surface sediments (mg/g dry wt. as P)

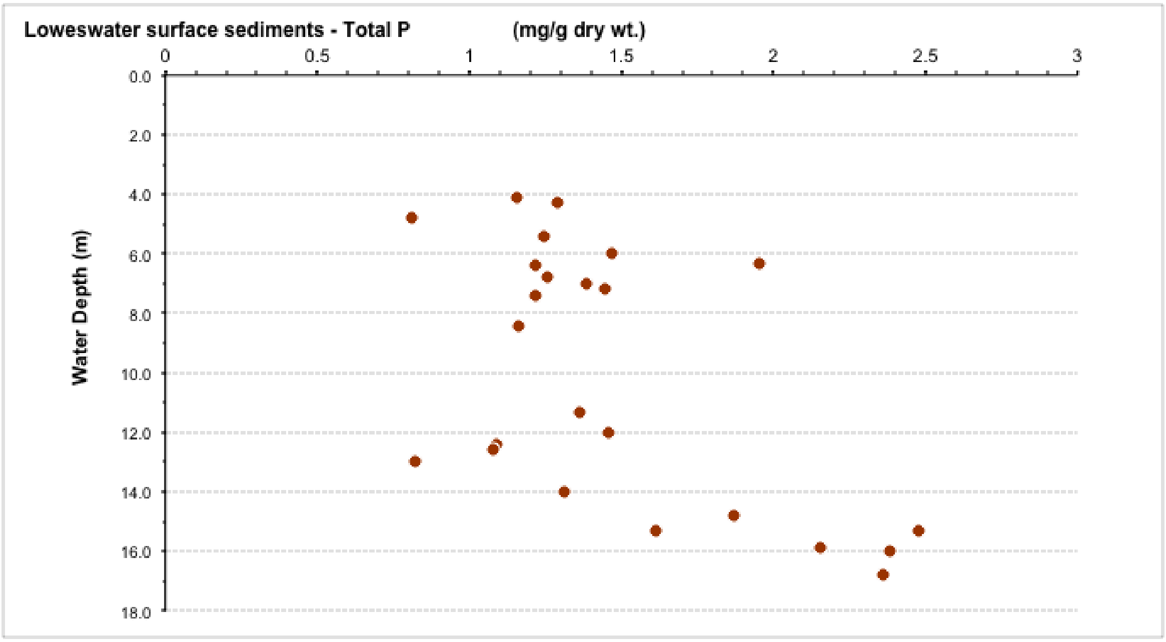

Figure 8 Graph plotting Total P in Loweswater surface sediment against water depth

4.4 Report on the radiometric dating of LOWS 3, 4, 5 and 6.

The radiometric dating results from the four cores are presented here, including a summary of Lead-210 activity, artificial fallout radionuclides, (^{137}Cs activity) and the core chronology (accompanied by stratigraphic plots). The raw data are shown in Appendix 4.

4.4.1 LOWS3

Lead-210 Activity

It seems that total ^{210}Pb activity reaches equilibrium with the supported ^{210}Pb at around 19 cm of the core. Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity (as supported ^{210}Pb) from total ^{210}Pb activity, decline irregularly with depth (Figure 9b), but the decline is close to an exponential trend, suggesting small changes in sediment accumulation rates.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth shows a well resolved peak at 6.25 cm (Figure 9c). There are ^{241}Am in samples between 8 and 10.5 cm of the core. The ^{137}Cs and ^{241}Am profiles indicate that the ^{137}Cs peak at 6.25 cm is derived from the 1986 fallout of the Chernobyl accident, and because of the high fallout in 1986, it has obscured the ^{137}Cs peak caused by the 1963 fallout maximum from the atmospheric testing of nuclear weapons.

Core Chronology

Use of the CIC (constant initial concentration) model was precluded by the non-monotonic variation in unsupported ^{210}Pb activities. ^{210}Pb chronologies were calculated using the CRS (constant rate of ^{210}Pb supply) dating model (Appleby and Oldfield, 1978). The CRS dating model places the 1986 and 1963 depths just above 6.25 cm and just below 8.25 cm, respectively, which are in agreement with the depths suggested by the ^{137}Cs and ^{241}Am records. Radiometric chronologies and sediment accumulation rates of the core are given in Appendix 4 and shown in Figure 10. The data show that accumulation rates have gradually increased from the 1870s to the 1930s, followed by a relatively uniform value in the last 80 years or so with a mean of 0.039 g cm^{-2} yr^{-1}.

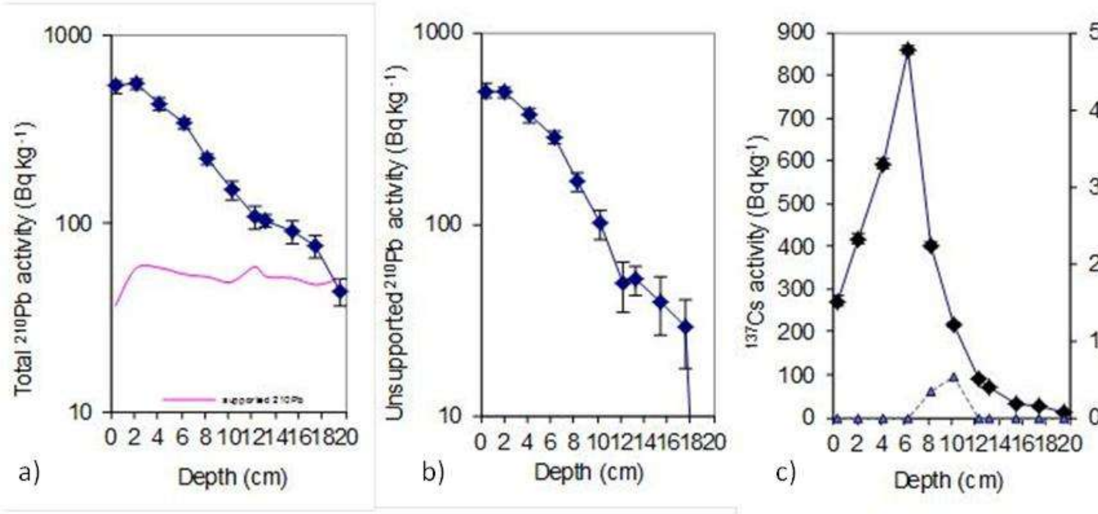

Figure 9 Fallout radionuclide concentrations in core LOWS3 taken from Loweswater, England, showing (a) total 210Pb, (b) unsupported 210Pb, (c) 137Cs and 241Am concentrations versus depth.

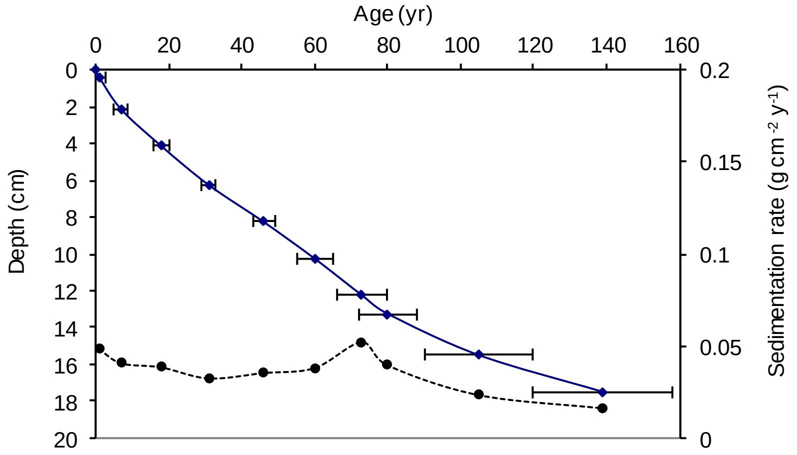

Figure 10 Radiometric chronology of core LOWS3 taken from Loweswater, England, showing the CRS model 210Pb dates and sediment accumulation rates. The solid line shows age and the dashed line indicates accumulation rate.

4.4.2.LOWS4

Lead-210 Activity

The equilibrium of total ^{210}Pb activity with the supported ^{210}Pb occurs at around 17 cm of the core. Unsupported ^{210}Pb activities overall also decline irregularly with depth. However, in 2.13 to 10.25 cm section, unsupported ^{210}Pb activities decline more or less exponentially with depth (Figure 11b), suggesting relatively uniform accumulation rates.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth shows a well resolved peak at 6.25 cm, and there are detectable ^{241}Am from 2.13 to 12.25 cm with a small peak at 10.25 cm. With reference to LOWS3, it is almost certain that the ^{127}Cs peak at 6.25 cm was derived from the Chernobyl accident fallout in 1986, and the 1963 fallout maximum of ^{137}Cs from the atmospheric testing of nuclear weapons has been obscured by the 1986 fallout.

Core Chronology

Again, use of the CIC model was precluded by the non-monotonic variation in unsupported ^{210}Pb activities. The CRS dating model places the 1963 and 1986 depths in between 8.25 and 10.25 cm, and close to 6.25 cm, respectively, which are also in agreement with the depths suggested by the ^{137}Cs and ^{241}Am records. Sediment accumulation rates calculated using the CRS model show a slow increase from 1850s of c. 0.005 g cm^{-2} yr^{-1} to the present day values of c. 0.05 g cm^{-2} yr^{-1}.

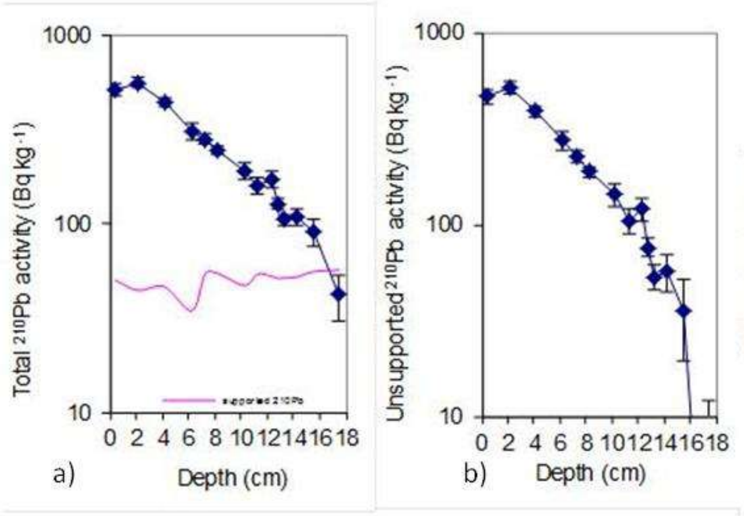

Figure 11 Fallout radionuclide concentrations in core LOWS4 taken from Loweswater, England, showing (a) total 210Pb, (b) unsupported 210Pb, (c) 137Cs and 241Am concentrations versus depth.

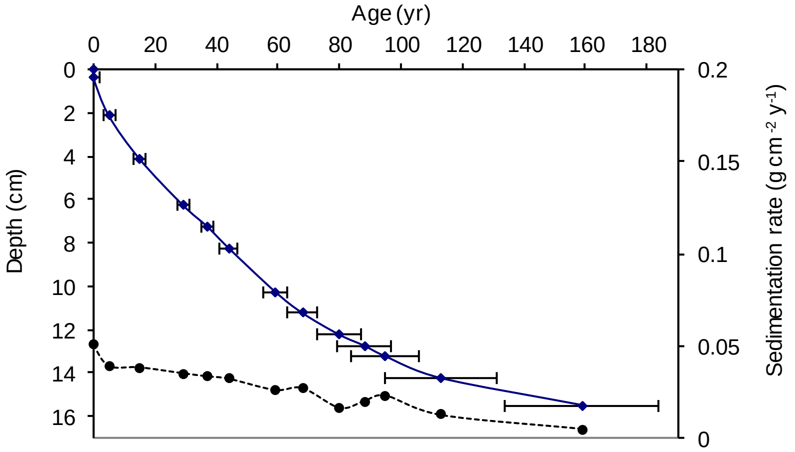

Figure 12 Radiometric chronology of core LOWS4 taken from Loweswater, England, showing the CRS model 210Pb dates and sediment accumulation rates. The solid line shows age and the dashed line indicates accumulation rate.

4.4.3 LOWS5

Lead-210 Activity

Equilibrium of total ^{210}Pb activity with the supported ^{210}Pb occurs at a depth around 13 cm of the core. Unsupported ^{210}Pb activities decline with small departures from a more or less exponential trend with depth (Figure 13b), suggesting smooth changes in sediment accumulation rates.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth shows a peak between 3.13 and 4.25 cm. There are detectable ^{241}Am activities in the section between 3.13 and 9.25 cm, with a relatively high value at 6.25 cm, suggesting 1963 maximum fallout from the atmospheric testing of nuclear weapons. Hence, the ^{137}Cs peak is likely to be derived from the fallout of the 1986 Chernobyl accident, and the high fallout in 1986 has obscured the 1963 ^{137}Cs peak derived from the atmospheric testing of nuclear weapons.

Core Chronology

Because of the non-monotonic variation in unsupported ^{210}Pb activity, the CIC model cannot be used for the core. The CRS dating model places the 1963 and 1986 depths in 6.25 – 7.25 cm and 3.13 – 4.25 cm sections, respectively, which are in agreement with the depths suggested by the ^{137}Cs and ^{241}Am records. Sediment accumulation rates are relatively uniform in the last 120 years or so in the core, with a mean value of 0.02 g cm^{-2} yr^{-1}.

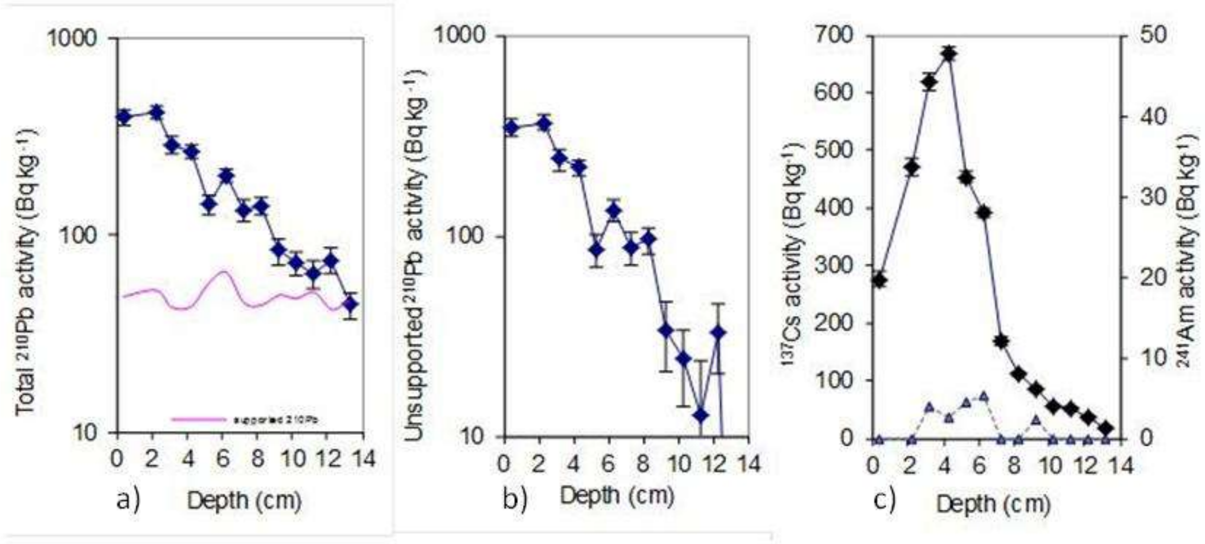

Figure 13 Fallout radionuclide concentrations in core LOWS5 taken from Loweswater, England, showing (a) total 210Pb, (b) unsupported 210Pb, (c) 137Cs and 241Am concentrations versus depth

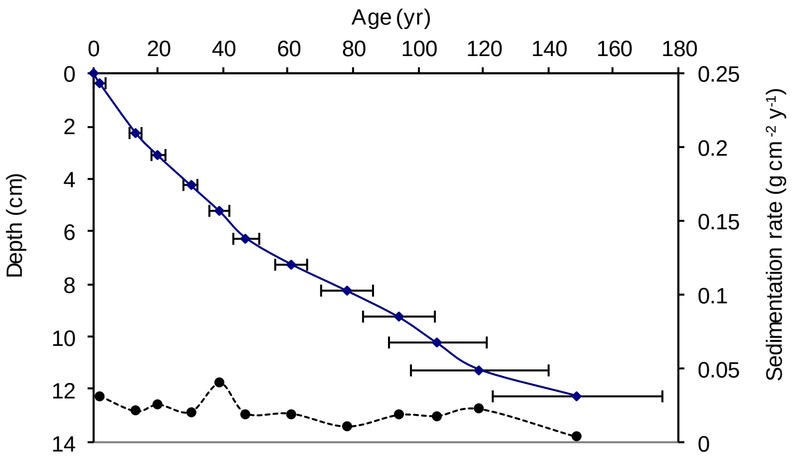

Figure 14 Radiometric chronology of core LOWS5 taken from Loweswater, England, showing the CRS model 210Pb dates and sediment accumulation rates. The solid line shows age and the dashed line indicates accumulation rate.

4.4.4 LOWS6

Lead-210 Activity

Total ^{210}Pb activity reaches equilibrium with the supported ^{210}Pb activity at a depth of c.11 cm of the core. Decline of unsupported ^{210}Pb activities with depth shows different features in the core (Figure 15b). The maximum unsupported ^{210}Pb activity is below the surface sediments, suggesting increase in sediment accumulation rates in recent years. Unsupported ^{210}Pb activities decline more or less exponentially with depth in 1 – 4.5 cm and 5 – 8.5 cm sections, respectively, suggesting different but uniform accumulation rates within these sections.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth shows a well resolved peak at 3.13 cm. There are also detectable ^{241}Am activities below the ^{137}Cs peak, which confirms the ^{137}Cs peak was derived from the fallout of the 1986 Chernobyl accident, and the 1963 depth is likely in between 4.25 and 6.25 cm.

Core Chronology

Because of the non-monotonic variation in unsupported ^{210}Pb activity, the chronologies were calculated using the CRS model. The CRS dating model places 1963 and 1986 depths at 5.5 and 3.3 cm, respectively, in agreement with the depths suggested by the ^{137}Cs and ^{241}Am records, and validating the CRS chronologies as shown in Table 12. Sediment accumulation rates show that the rates changed from one relatively uniform value of 0.011 g cm^{-2} yr^{-1} between the 1880s and 1960s to another relatively uniform value of 0.021 g cm^{-2} yr^{-1} in the last 50 years or so.

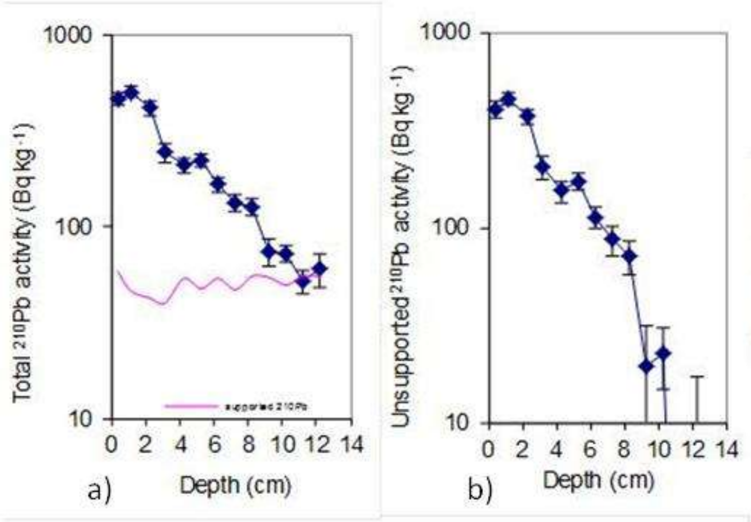

Figure 15 Fallout radionuclide concentrations in core LOWS6 taken from Loweswater, England, showing (a) total 210Pb, (b) unsupported 210Pb, (c) 137Cs and 241Am concentrations versus depth.

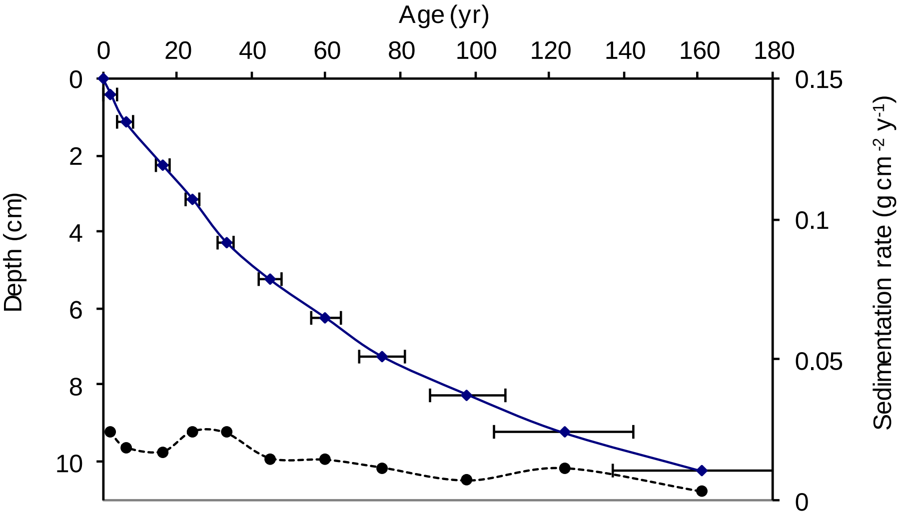

Figure 16 Radiometric chronology of core LOWS6 taken from Loweswater, England, showing the CRS model 210Pb dates and sediment accumulation rates. The solid line shows age and the dashed line indicates accumulation rate.

4.5 Water samples from Loweswater (lake, inflow and outflow)

Monthly samples for water chemistry were taken at three locations from January to December 2013; i) Dub Beck at Waterend (inflow), ii) Within lake sample and iii) outflow (Dub Beck). Fig. 17 shows the TP and SRP record for the three locations over the monitoring period.

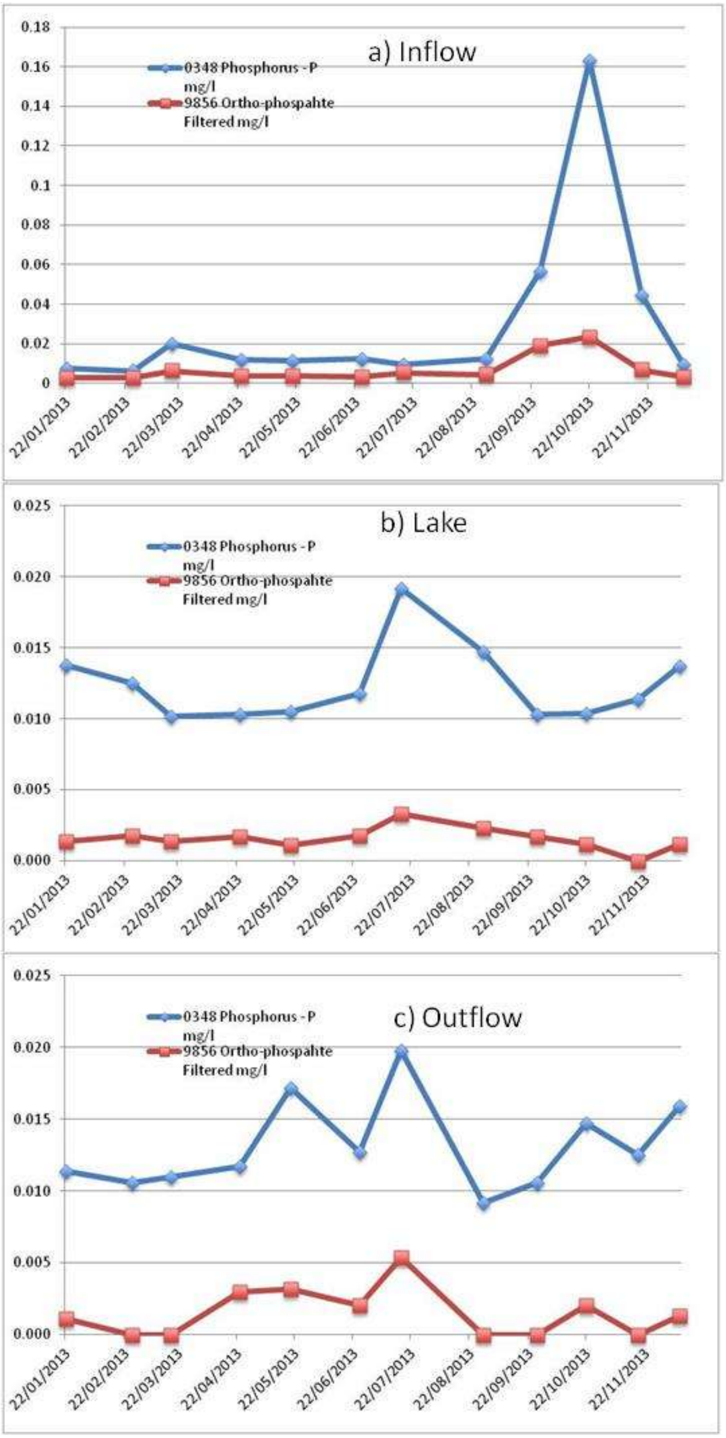

Figure 17 Phosphorus - P mg/l and Ortho-phosphate Filtered mg/l values sampled monthly during 2013 at a) Dub Beck at Waterend (inflow), b) Within lake sample and c) outflow (Dub Beck).

The chemistry data for a range of determinands are shown in Appendix 5. The inflow into Loweswater is characterised by very low levels of TP and SRP. TP rose to a maximum of 0.16 mg l^{-1} in October. Within the lake both TP and SRP remained low throughout the monitoring period with a slightly elevated concentration for the former in August. Low concentrations were also recorded in the outflow with peaks in both in July.

As flow data were not available it is not possible to determine loading. Data from a nearby stream were used in the P flux calculations described below.

4.6 Determination of phosphorus mass balance at Loweswater

4.6.1 Lake outflow flux

The lake outflow flux by is determined by multiplying the outflow water flux by the lake/outflows stream water concentration.

These two water concentrations are indistinguishable:
Outflow stream = 13.1 (+/- 3.2) mg P m^{-3})
Lake = 12.6 (+/- 2.7) (mg P m^{-3})

The mean was used to find the outflow flux.

Runoff rate has not been measured. Therefore the National River Flow Archive (NRFA) dataset for nearby rivers (1.0 (+/- 0.3) m/yr) was used.

Thus the catchment area normalised outflow flux (or loading, hence $L_{outflow}$) is given by:

$L_{outflow}$ (mg P m^{-2} CA yr^{-1}) = P concentration (mg m^{-3}) * Runoff (m yr^{-1}) * (Catchment area +Lake area)/Catchment area
= 12.9*1.0*(7.683+0.614)/7.683

4.6.2 Lake sediment flux

The raw flux data show higher values in the deep water cores (LOWS3 and LOWS 4 - the red and blue lines in Figure 18), and all show strong enrichment after about 2000 AD. The exponential shape for the recent enrichment suggests that it is not permanent. This is confirmed by the results for LOWS1 (Bennion *et al*., 2000), which shows the same peak but ten years earlier in keeping with its 1999 coring date (see Fig. 19)

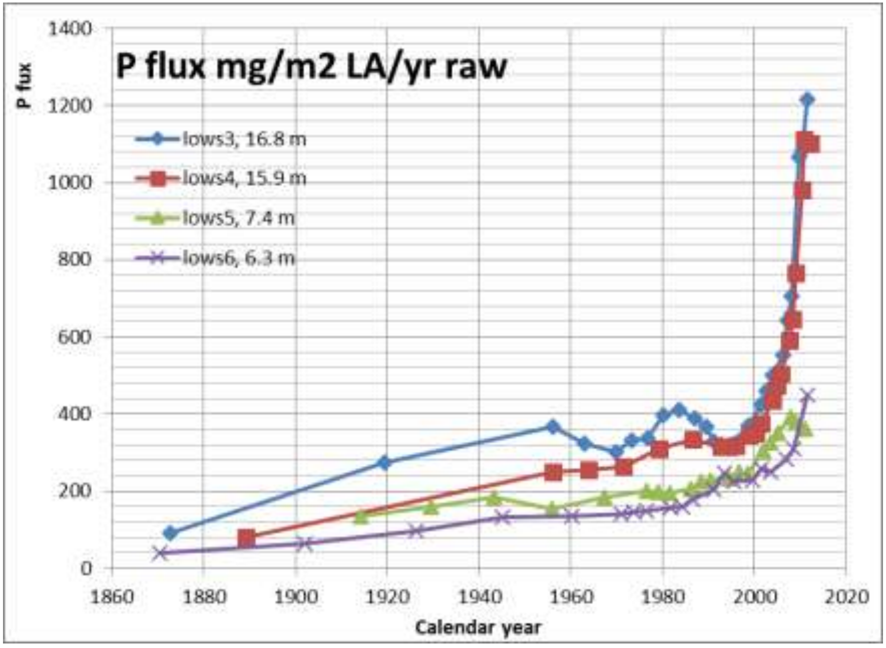

Figure 18 P flux in sediment cores Lows 3, 4, 5 and 6.

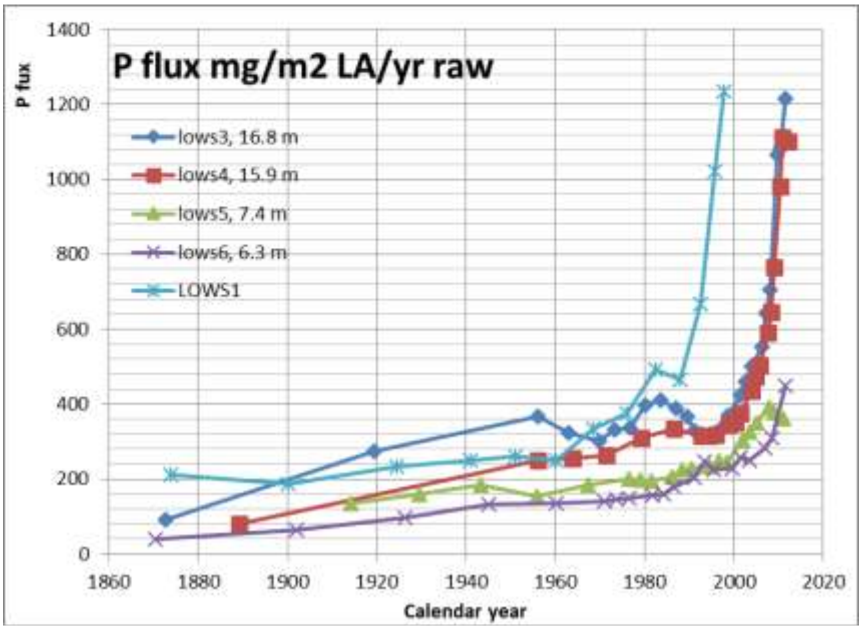

Figure 19 P flux in sediment cores LOWS 1, 3, 4, 5 and 6.

The stationary peak is considered further in the discussion. It is probable, given the contrast between LOWS1 and the later cores, that the trends prior to about 2000 AD represent the underlying permanent burial of P.

The value for this flux must be estimated for the whole lake. As described above (section 3.4.2)there are two approaches that can be used. The first is to establish a regression model, for different time slices, between the P flux and water depth and the second is to use the ^{210}Pb method. These can then be applied to a hypsometric model for the lake, thereby determining the depth-weighted mean P flux.

i) Hypsometric method

Step 1. Find typical observed flux values for some age slices. To smooth any artefacts arising from the CRS model, second order polynomials were fitted to the raw flux data for sediment older than AD2000. These polynomials were used to obtain P flux values for 1900, 1940 and 2012 (extrapolated to 2012 to avoid the stationary peak).

Step 2. Find a flux –depth relationship for each age:
These relationships are shown in Figure 20.

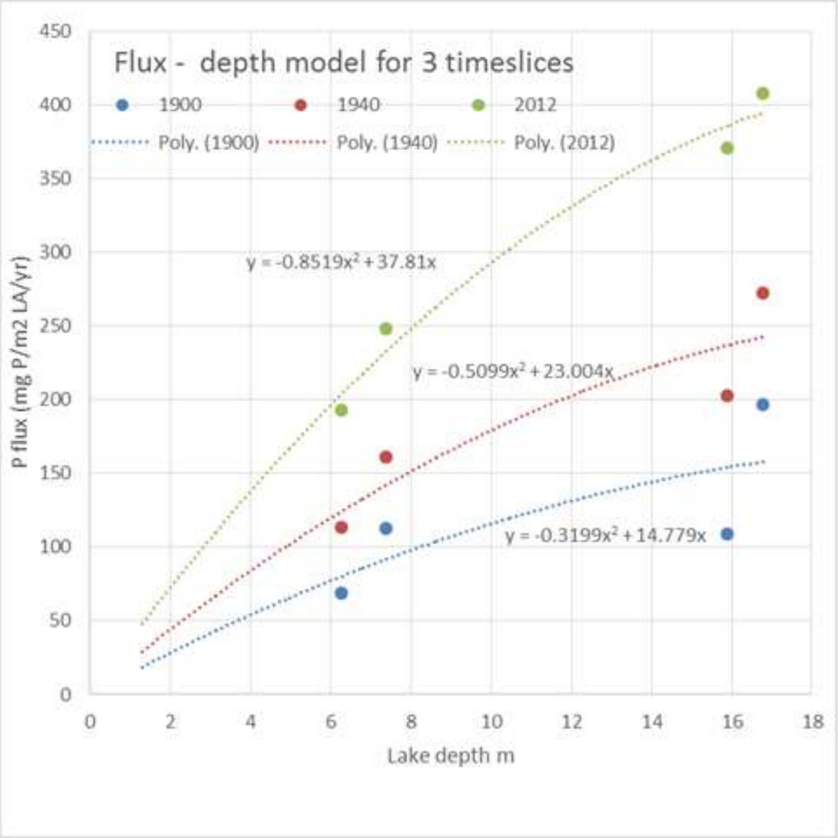

Figure 20 Flux depth relationships for three time slices; 1900, 1940 and 2012.

Step 3. Develop a hypsometric curve
This curve (Fig. 21) is calculated from the digital bathymetry:

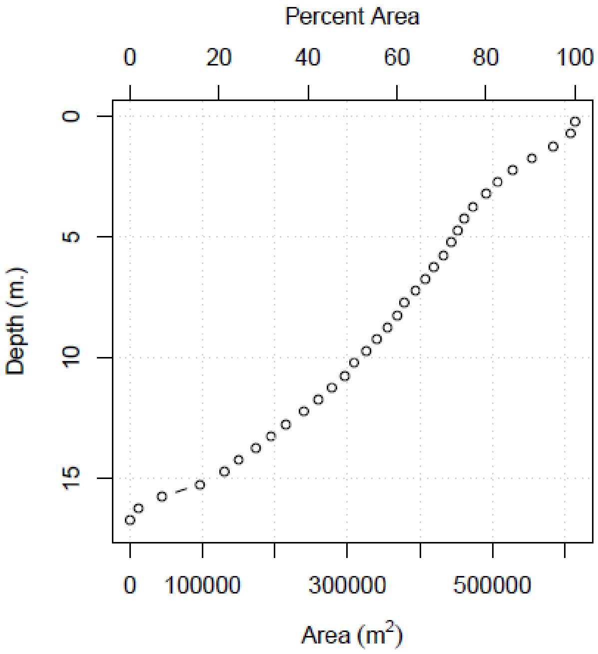

Figure 21 Hypsometric curve for Loweswater

Step 4. Combine steps 2 and 3 to get the contributions from each depth interval. This produces the data shown in Table 7.

Table 7 P flux information at each depth and for three time slices (1900, 1940 and 2012)

Depth m	Hypsometric fraction	P fluxes mg P m^{-2}LA yr^{-1} (mid depth)			P flux * depth interval area		
		1900	1940	2012	1900	1940	2012
0	1.00	-29.5	-46.5	-76.1			
0.5	0.99	-18.9	-29.8	-48.8			
1	0.95	-8.5	-13.6	-22.4			
1.5	0.90	1.6	2.1	3.3	0.1	0.1	0.1
2	0.86	11.3	17.2	28.1	0.4	0.6	1.0
2.5	0.83	20.7	31.9	52.0	0.5	0.8	1.3
3	0.80	29.8	46.1	75.2	0.9	1.4	2.2
3.5	0.77	38.6	59.8	97.5	0.8	1.2	1.9
4	0.75	47.1	73.0	119.0	0.7	1.1	1.7
4.5	0.74	55.3	85.7	139.7	0.8	1.3	2.0
5	0.72	63.1	97.9	159.6	1.1	1.7	2.8
5.5	0.70	70.7	109.5	178.6	1.6	2.4	3.9
6	0.68	77.9	120.7	196.8	1.5	2.3	3.8
6.5	0.66	84.8	131.4	214.2	1.8	2.8	4.6
7	0.64	91.4	141.6	230.8	2.3	3.6	5.9
7.5	0.62	97.7	151.3	246.5	1.5	2.3	3.8
8	0.60	103.6	160.5	261.5	2.3	3.6	5.8
8.5	0.58	109.3	169.2	275.6	2.7	4.2	6.8
9	0.55	114.6	177.4	288.9	2.7	4.1	6.7
9.5	0.53	119.6	185.1	301.3	3.3	5.1	8.2
10	0.50	124.3	192.3	312.9	2.6	4.0	6.5
10.5	0.48	128.7	199.0	323.8	3.6	5.6	9.1
11	0.45	132.8	205.2	333.7	4.1	6.4	10.4
11.5	0.42	136.5	210.9	342.9	4.4	6.8	11.1
12	0.39	139.9	216.1	351.3	5.8	8.9	14.5
12.5	0.35	143.1	220.8	358.8	4.7	7.3	11.8
13	0.32	145.9	225.1	365.5	5.0	7.7	12.4
13.5	0.28	148.4	228.8	371.4	5.8	8.9	14.4
14	0.24	150.5	232.0	376.4	4.7	7.3	11.8
14.5	0.21	152.4	234.7	380.7	8.4	13.0	21.1
15	0.16	154.0	236.9	384.1	13.1	20.1	32.6
15.5	0.07	155.2	238.6	386.7	8.2	12.6	20.4
16	0.02	156.1	239.8	388.4	3.1	4.7	7.6
16.5	0.00	156.7	240.6	389.4	0.1	0.1	0.1

These can then be summed as follows:

Date	1900	1940	2012
Total P flux (mg P m^{-2} LA yr^{-1})	98	152	247

ii) ^{210}Pb method

An alternative approach is to assume that unsupported ^{210}Pb is focussed in exactly the same way as sediment P. We can then calculate a focusing factor as the ratio between the lake core ^{210}Pb inventory to the expected atmospheric inventory. Here the soil inventory values have been used based on the unpublished procedure of Appleby to produce;

	210-Pb inventory	Focusing factor
lows3	7859	2.10
lows4	4552	1.21
lows5	3658	0.98
lows6	3337	0.89

Normalising the raw fluxes using the focussing factor greatly reduces the difference between the curves (Figure 22). Each is now a direct estimate of the lake-wide mean P flux. These are the values that have been used to estimate $L_{sediment}$ (the loading, or flux, of P buried in the sediment, normalised to lake area, mg P m^{-2} LA yr^{-1})

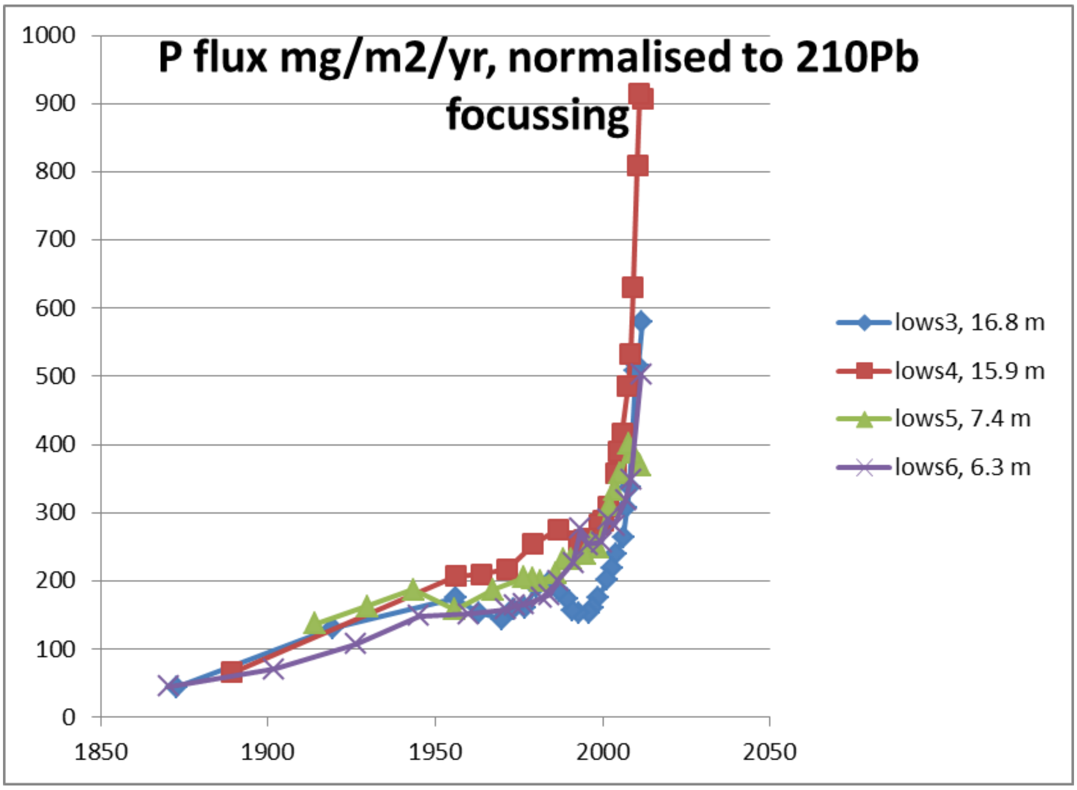

Figure 22 P flux mg/m2/yr normalised to 210Pb focussing

Inflow stream data

In the absence of flow data to accompany the measured TP values for Dub Beck, flows below are estimated from the depth equivalent flow data for the Eden at Sheepmount (Fig. 23). If the flows are multiplied by the TP values, point flux values can be generated for the sampling times (expressed on a per m^2 catchment area basis). The average value of these inflow samples is 27 mg P m^{-2} CA yr^{-1}, slightly lower than the estimated value based on observed sediment burial and outflow loss data (32 mg P m^{-2} yr^{-1}). However, it is clear that samples were by chance taken in low flow conditions, and it seems likely that the average sample greatly underestimates the true mean.

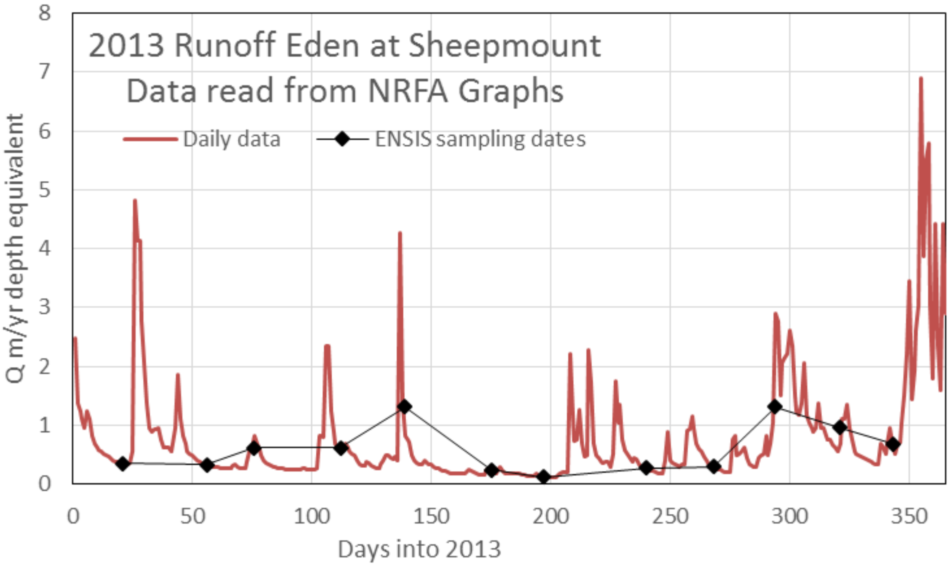

Figure 23 2013 runoff data from the Eden at Sheepmount - read from NRFA graphs

Figure 24 shows the relationship between the point flux values and the stream flow (as estimated from the Eden). It is clear both that P flux increases with flow, and that this relationship is only poorly captured. Applying the linear fit to the Eden river flow data we get an estimated total P supply (for Dub Beck, but averaged for the whole catchment) of 45 mg P m^{-2} CA yr^{-1}, a value rather higher than the mass balance estimate. If the correlation between P concentration and river flow is used instead to generate this estimate, the total P supply increases to 75 mg P/m^{-2} CA yr^{-1}. However, it must be stressed both that Dub Beck is not representative of the whole catchment, and that the data are too sparse to make a reliable estimate.

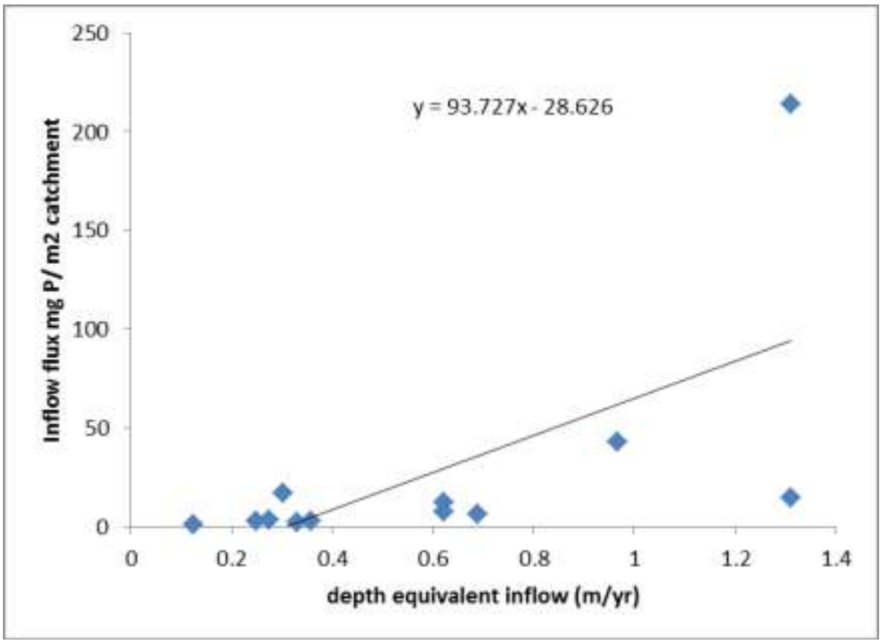

Figure 24 Relationship between the point flux values and the stream flow (as estimated from the Eden

Input-output balance for 2013

The basic mass balance for Loweswater phosphorus in 2013, expressed in terms of catchment area (CA) normalised loadings (L), is as follows:

- $L_{outflow}$ = 14 mg P m^{-2} CA yr^{-1} (uncertainty entirely due to outflowing water flux, is perhaps 25%)
- $L_{sediment}$ = 18 mg P m^{-2} CA yr^{-1}
- L_{in} = sum of $L_{sediment}$ and $L_{outflow}$ therefore = 32 mg P m^{-2} CA yr^{-1})

Where:

- L_{in} (mg P m^{-2} CA yr^{-1}), despite being calculated from the output loadings, comprises the sum of inflowing stream, non-stream runoff and atmospheric supply,
- L_{ouflow} is the outflow stream loading
- $L_{sediment}$ is the permanent burial rate of P in the sediment, and excludes temporally cycling of labile P pool with the water column.

The mass balance is perfectly consistent with the empirical P retention (R_p = $L_{sediment}/(L_{sediment} + L_{outflow})$ coefficient of Kirchner and Dillon (1975), which comes out at 0.53 while the numbers above come to 0.56.

The L_{in} value is in keeping with the rural setting given the number of fields and properties. The influx is also consistent with the limited direct measurement of stream inflows. Specifically, Dub Beck is capable of explaining most of the P influx.

Potential internal loading

Each core shows a near-surface stationary peak (that is, a peak that is stationary with respect to the sediment surface, and thus migrated upwards as sediment accumulation occurs). The pool of labile P contained in this peak, which is relatively similar in all cores, is

220 +/- 70 mg P m^{-2} CA. Given a current L_{in} value of 32 mg P m^{-2} CA yr^{-1}, the pool comprises 7 years of external loading. Thus, while release of P from this pool is an important factor influencing water column P concentrations in the summer, it is unimportant for the long term P budget.

The last 100 years

The 2012 L_{in} is estimated to be 32 mg P m^{-2} CA yr^{-1}. In 1940 it was 19 and in 1900 just 12 mg mg P m^{-2} CA yr^{-1}. The corresponding inferred water column TP values are 7, 4 and 3 µg/L for 2012, 1940 and 1900 respectively.

5. CONCLUSIONS

Although the Loweswater catchment is characterised by low intensity farming and low population density the lake has shown signs of eutrophication in recent years, an observation supported by evidence from historical and palaeoecological data (Bennion *et al.,* 2000; Maberly *et al*., 2006). Land use and farming practices have changed over the past 200 years which have led to increased nutrient loading to the lake with significant increases occurring in the mid part of the last century. Agricultural intensification is likely to be a significant cause of the problem as well as inadequate septic tank management (Bennion *et al*. 2000, Bennion & Winchester 2010). It is suggested that Loweswater has shifted from being a mesotrophic lake to a borderline mesotrophic-eutrophic system (Maberly *et al.,* 2006).

Local management efforts, led by the Loweswater Care Project, has sought to reduce the primary sources of nutrients reaching the lake, but total phosphorus (TP) concentrations in the lake remain higher than desired. The extent to which P recycling from the sediments can be a cause of the continued enrichment of the water is assessed in this study. As Loweswater is a productive lake, compared with other lakes in the region, oxygen depletion occurs towards the bottom of the water column following summer stratification resulting in anoxic conditions during this period (Maberly, *et al.,* 2006). The consequences of this can include release of phosphorus from the sediment into the water column (Mortimer, 1941, 1942) which, in turn, can increase algal production. The long retention time characterising this lake means that cyanobacterial blooms in particular may be favoured. Therefore a better understanding of the concentrations and internal cycling of P in Loweswater is necessary to address the longer term management of the lake.

To address this we determined the spatial distribution of phosphorus (P) concentrations both above and below the thermocline using surface sediment samples taken from a range of depths. To establish changes in sediment concentrations (as well as sediment flux) through time we used evidence from dated sediment cores. Seasonal water chemistry data from the outflow and from the water column during periods of overturn in the spring and autumn were used to determine P fluxes. These data were used to model P flux within the lake and provide forecasts of future sediment P release.

Measurements of temperature and dissolved oxygen (DO) down the water column confirmed that the site was stratified in summer with major changes in DO occurring below a depth of 8 m. The deeper waters were almost entirely anoxic with DO concentrations of less than 1 mg l^{-1} compared with values around 9-10 mg l^{-1} towards the surface. At this time the maximum TP value was recorded at the lake bottom (19.9 µg l^{-1}). This is unambiguous evidence for P release from the lake bed during summer stratification. In question, however, is whether enough P is released to impact the lake as a whole, and we now have sufficient information to show that the effect is minor. This evidence arises from two independent sources; 1) inflow stream data, and 2) lake water column P profiles; both interpreted in the context of a mass balance model for the P fluxes.

First, analysis of the stream water P fluxes, presented above, shows that P influx remain high enough to explain the elevated lake water P concentrations, despite considerable efforts to reduce catchment P sources. This is based only on the 2013 data from Dub Beck.

Second, an analysis of the water column P profiles shows that P release from the sediment is only a minor contribution to the P load. While our sediment core data reveals a substantial pool of P in the sediment (equivalent to about 7 years of inflow), very little of this should be released each year to the water column. The precise amount released cannot be estimated from the sediment record, but can be measured by observing changes to the water column P profiles across the period during which thermal stratification is established. Assuming the data from April and July 2013 is representative for the lake, and that all the difference between the two profiles is due to sediment P release (an upper limiting case, but a reasonable estimate of the actual value), then the hypsometric curve and the difference in the P concentrations in lake water profiles can be used to estimate the total P release. This comes to 21 kg P for the whole lake. The estimated total P input to the lake for the year is 225 kg P. Thus in 2013 more than 90% of the P came from the catchment and only ~10% from the sediment.

These two observations support the assertion of Maberly et al. (2006) that the Loweswater spring bloom is driven by nutrients derived directly from the catchment (62% from the improved grassland in the Dub Beck catchment with other significant contributions from cattle slurry, farmyard manure and septic tanks) rather than as a result of internal cycling although the sediment derived nutrients may be more important during summer when anoxic conditions at depth facilitate P release by reducing the redox potential at the sediment - water interface (Mortimer, 1941, 1942), an inference supported by the higher TP values observed during the summer months.

As with all modelling exercises there are uncertainties inherent in the approach. In this case the model output is based on a single year of input data for the inflow P flux calculations and it would be preferable to have a longer data series to inform the modelling. Inflow fluxes are highly dependent on flow conditions and here, in the absence of flow data from Dub Beck, we used data from a nearby stream. Further, the monthly sampling has resulted in most sampled being taken in low flow conditions, thus missing storm flow conditions. Finally, stream input information is restricted to Dub Beck, and contributions from the other stream is unknown.

However, the results from the P flux modelling are clear and we can conclude that the priority is for P loading to the lake to be reduced by better catchment management and that lake manipulation is not warranted. Integrated catchment management supported by modelling together with local stakeholder engagement should provide the most effective means of improving the condition of the lake (Norton et al., 2011, 2012)

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7. APPENDICES

7.1 Appendix 1 - Loweswater Catchment Restoration Fund – ENSIS Fieldwork report 16th & 17th October 2012

Present: Ben Goldsmith & James Shilland (ENSIS @ UCL)

Aim: To take 4 short cores (2 deep water >10 m and 2 shallow < 8m)
To collect DO / Temp data from the deep point
To collect water samples down a depth profile for chemical analysis
To collect 20 surface sediments (10 from >10m and 10 from <10m)

Cores: **All taken using a Renberg gravity corer**

Code	Date	Location	Water Depth	Time	Length
LOWS3	16/10/2012	NY1266621691	16.8	14:52	c. 20 cm
LOWS4	16/10/2012	NY1255021761	15.9	15:07	18 cm
LOWS5	16/10/2012	NY1213022058	7.4	15:25	c. 30 cm
LOWS6	16/10/2012	NY1298621392	6.3	15:50	c. 30 cm

Aim is to slice all four cores at 2.5 mm intervals for the top 5 cm, 5 mm between 5 – 15 cm and at 1 cm intervals thereafter. LOWS4 sliced on site – other 3 cores transported to UCL for extrusion.

DO / Temp Profile @ NY1263321705

Depth	DO	Cond	pH	Temp
0	9.75	48.0	6.18	10.5
1	9.75	48.0	6.24	10.5
2	9.72	48.0	6.26	10.5
3	9.72	48.0	6.29	10.5
4	9.67	48.0	6.30	10.5
5	9.68	48.0	6.32	10.5
6	9.63	48.0	6.32	10.5
7	9.62	48.0	6.35	10.5
8	9.56	48.0	6.36	10.5
9	9.56	48.0	6.38	10.5
10	9.59	48.0	6.37	10.5
11	9.57	48.0	6.38	10.5
12	9.46	48.0	6.39	10.5
13	9.49	48.0	6.40	10.5
14	9.53	48.0	6.42	10.5
15	9.52	48.0	6.43	10.5
16	9.46	48.6	6.44	10.5
10	9.53	48.0	6.43	10.5
5	9.48	48.0	6.46	10.5
0	9.55	48.0	6.49	10.5

Water Sample Profile @ NY1263321705

Van Dorn sampler: 1 x 250 ml NLS Nuts sample at each depth
1 x 1000 ml NLS Gen sample at each depth

Depth	NLS Sample No.	Depth	NLS Sample No.
1	214701	9	214697
3	214700	11	214696
5	214699	13	214695
7	214698	15	214694

Surface sediments – All Renberg tops taken 0-5 mm

Code	Date	Location	BG Waypoint	Water Depth
LOWSSS1	17/10/2012	NY1199422015	151	4.3
LOWSS2	17/10/2012	Check bag	NONE	4.1
LOWSS3	17/10/2012	NY1235822053	152	6.0
LOWSS4	17/10/2012	NY1232921980	153	11.3
LOWSS5	17/10/2012	NY1229921762	154	13.0
LOWSS6	17/10/2012	NY1208221907	156	6.8
LOWSS7	17/10/2012	NY1254721904	157	7.0
LOWSS8	17/10/2012	NY1246521824	158	14.8
LOWSS9	17/10/2012	NY1238221742	159	14.0
LOWSS10	17/10/2012	NY1236321438	160	6.4
LOWSS11	17/10/2012	NY1262921703	162	16.0
LOWSS12	17/10/2012	NY1258621645	163	15.3
LOWSS13	17/10/2012	NY1261721425	164	15.3
LOWSS14	17/10/2012	NY1254021283	165	8.4
LOWSS15	17/10/2012	NY1278721347	167	12.6
LOWSS16	17/10/2012	NY1285521526	168	12.0
LOWSS17	17/10/2012	NY1280621657	169	12.4
LOWSS18	17/10/2012	NY1300821432	170	5.4
LOWSS19	17/10/2012	NY1301421358	171	4.8
LOWSS20	17/10/2012	NY1283221298	172	7.2

Photos: 926-969
928 – 935 LOWS4
936 – 940 LOWS6
968 -969 LOWSSS18 core – take in 5.4 m water.

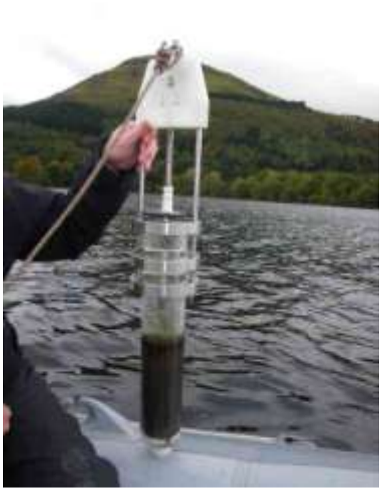
Notes:
Weather – mix of sunshine and very heavy showers – calm to breezy
Secchi depth 3.10 m
Used ENSIS RAB with 4hp stroke engine – JS to clean / dry all kit at UCL
Launched from Watergate Farm track with permission from NT warden Mark Astley

Bathymetric survey data were collected using the boat-mounted Lowrence GPS / Echo sounder – data were collected only from the northwest half of the lake on this occasion due to the memory card filling up; the remainder of the lake will be surveyed on a subsequent visit.

Photos

Loweswater from Watergate track

Van Dorn water sampler



Renberg corer

Core LOWS4 from 15.9 m

LOWS6 from 6.3 m

Bathymetric survey 1

Bathymetric survey 2 – In a downpour

7.2 Appendix 2 - Loweswater Catchment Restoration Fund – ENSIS Fieldwork report 29th April

Present: Ben Goldsmith & Ewan Shilland (ENSIS @ UCL)

Aim:
To take 1 short core at c. 11 m
To collect DO / Temp data from the deep point
To collect water samples down a depth profile for chemical analysis

Cores: **Taken using a Renberg gravity corer**

Two cores were collected (one as a back-up) – this is additional to the four cores taken in October and will be processed at no charge to WCRT.

Code	Date	Location	Water Depth	Time	Length
LOWS7	29/04/2013	NY1252121886	11.3	13:10	24 cm
LOWS8	29/04/2013	NY1252921890	11.1	13:15	28 cm

Cores will be extruded at 2.5 mm intervals for the top 5 cm, 5 mm between 5 – 15 cm and at 1 cm intervals thereafter. Both cores transported to UCL for extrusion.

DO / Temp. Profile @ NY1268321686 – 16.2 m water depth

Depth m	DO mgl^{-1}	Cond μScm^{-1} (Ambient)	Cond μScm^{-1} (@ 25°C)	pH	Temp °C
0	13.74	44.2	62.8	7.32	8.1
1	13.50	44.3	62.9	7.27	8.1
2	13.48	44.2	62.8	7.24	8.1
3	13.42	44.2	62.8	7.24	8.1
4	13.39	44.3	62.9	7.24	8.1
5	13.40	44.2	62.8	7.24	8.1
6	13.39	44.2	62.8	7.26	8.1
7	13.35	44.2	62.8	7.24	8.1
8	13.38	44.2	62.8	7.24	8.1
9	13.40	44.2	62.8	7.24	8.1
10	13.39	44.2	62.8	7.27	8.1
11	13.42	44.2	62.8	7.26	8.1
12	13.40	44.2	62.8	7.26	8.1
13	13.41	44.2	62.8	7.26	8.1
14	13.44	44.2	62.8	7.26	8.1
15	13.44	44.2	62.8	7.28	8.1
16	13.21	44.5	63.2	7.24	8.1
10	13.41	44.2	62.8	7.28	8.1
5	13.40	44.2	62.8	7.24	8.1
0	13.71	44.2	62.8	7.29	8.1

As expected, the water column was well mixed. The water was relatively clear, but had a noticeable green tinge to it. Secchi depth was recorded as 3.8 m.

Water Sample Profile @ NY1263321705 – every 2 m

Van Dorn sampler: 1 x 250 ml NLS Nuts sample at each depth
1 x 1000 ml NLS Gen sample at each depth

Depth m	NLS Sample No.	Nitrate nitrogen mgl^{-1}	Orthophosphate (as P) μgl^{-1}	Total Phosphorus (as P) μgl^{-1}
1	214702	0.368	1.09	10.7
3	214703	0.365	1.4	10.6
5	214704	0.363	1.2	10.4
7	214705	0.366	1.1	10.6
9	214706	0.365	1.1	9.8
11	214707	0.358	<1.0	10.4
13	214708	0.354	<1.0	9.4
15	214709	0.367	1.03	9.6

Samples delivered to NLS Star Cross 30/04/2013 – Analysed 1st – 7th May 2013.

Notes:
Weather – mix of sunshine and very heavy showers – calm to breezy

Secchi depth 3.80 m

Used ENSIS Redcrest 3 with electric engine – BG cleaned and disinfected all kit at UCL and ALL dried.

Launched from roadside layby – met with Vikki Salas and Andrew Shaw – NT warden Mark Astley notified.

Macrophyte Data 2012

Loweswater was surveyed by ENSIS in 2012 as part of the EA Water Framework Directive monitoring. JNCC Common Standards Methodology was used to collect data from 4 100 m shoreline transects, each with a boat transect from shore to open water. The results therefore provide fixed point monitoring data rather than a full survey of the site – nonetheless, the Loweswater survey is considered to offer a representative picture of the aquatic flora of the site. More details will be reported in the final report.

Site Condition Assessment: Loweswater (01/08/2012)

Lake Details		**Survey Details**		
Lake Name	Loweswater	Survey Date		
01/08/2012				
SSSI Name		Surveyors	BG & LG	
SAC Name		Shore Surveys	4	out of
Grid Ref	NY124217	Wader Surveys	4	4
WBID	28986	Boat Surveys	3	sections

Section Summaries

Section	**1**	Maximum depth of colonisation (cm)	300 cm
		Notes: Slightly turbid	
Section	**2**	Maximum depth of colonisation (cm)	-
		Notes: No plants loose gravel and steep shelving - shaded	
Section	**3**	Maximum depth of colonisation (cm)	330 cm
Section	**4**	Maximum depth of colonisation (cm)	360 cm

Section Locations

		Shore Survey GPS Co-ords		Boat Survey GPS Co-ords	
		start	end	start (shore)	end (lake)
Section	**1**	NY1203322293	NY1210622274	NY1205622278	NY1201222120
Section	**2**	NY1223821795	NY1229621708	NY1227421760	-
Section	**3**	NY1280821267	NY1290721266	NY1285721255	NY1285721255
Section	**4**	NY1266321861	NY1258821920	NY1261721891	NY1258821920

Site Condition Assesment: Loweswater (01/08/2012)

Dissolved Oxygen Profile

GPS Location	NY1265621705
Maximum Depth (m)	16.6 m
Secchi Depth (cm)	260 cm

Notes:

Depth (m)	DO (mg/l)	Temp (°C)
0	9.89	16.1
1	9.75	16.1
2	9.74	16.1
3	9.69	16.1
4	9.71	16.1
5	9.65	16

6	9.63	16
7	9.56	15.9
8	7.3	14.9
9	6.52	14.4
10	6.2	14.2
10.5	0.8	12.1
11	0.21	11.8
12	0.14	11.6
13	0.15	11.3
14	0.16	11.1
15	0.19	10.8
16	0.19	10.8

Site Condition Assessment: Loweswater (01/08/2012)

Species Abundance - Boat Survey

Total number of sample plots	60
Total number of vegetated sample plots	25

	Occurrence	
Plant Species	*n*	%
Elodea canadensis	8	32
Isoetes lacustris	23	92
59		
Littorella uniflora	10	40
90		
Lobelia dortmanna	5	20
41		
Myriophyllum alterniflorum	4	16
Nitella flexilis agg.	1	4
Potamogeton alpinus	2	8

Species Abundance - Wader Survey

Total number of sample plots	60
Total number of vegetated sample plots	39

	Occurrence	
Plant Species	*n*	%
Eleocharis palustris	5	13
Isoetes lacustris	23	
Littorella uniflora	35	
Lobelia dortmanna	16	
Myriophyllum alterniflorum	3	8

Note: Species abundance % = ((number of plots / total number of vegetated sample plots) * 100) *n*

Site Condition Assesment: Loweswater (01/08/2012)

Plant Scores

Total plant species 34 **Filamentous algae (%)** 13.3 % WADER 5.7 % BOAT

SURVEY SCORES

PLANT SPECIES	PERIMETER	WADER	BOAT	COVER %	DAFOR	ABUNDANCE
Isoetes lacustris	0.025	0.0944	0.2527	30.62	A	4
Littorella uniflora	0.1	0.1775	0.0591	17.28	F	3
Juncus effusus	0.4625	0	0	11.56	F	3
Salix sp.	0.375	0	0	9.38	O	2
Lobelia dortmanna	0.025	0.0714	0.0399	8.18	O	2
Eleocharis palustris	0.2125	0.0169	0	6.16	O	2
Mosses unid	0.2125	0	0	5.31	O	2
Elodea canadensis	0.025	0	0.0379	4.42	R	1
Ranunculus flammula	0.175	0	0	4.38	R	1
Phalaris arundinacea	0.175	0	0	4.38	R	1
Filipendula ulmaria	0.15	0	0	3.75	R	1
Hydrocotyle vulgaris	0.1375	0	0	3.44	R	1
Galium palustre	0.1375	0	0	3.44	R	1
Juncus acutiflorus	0.125	0	0	3.12	R	1
Carex nigra	0.125	0	0	3.12	R	1
Myriophyllum alterniflorum	0	0.0074	0.0238	2.75	R	1
Viola palustris	0.0875	0	0	2.19	R	1
Mentha aquatica	0.075	0	0	1.88	R	1
Potamogeton alpinus	0.025	0	0.0121	1.84	R	1
Oenanthe crocata	0.0625	0	0	1.56	R	1
Caltha palustris	0.05	0	0	1.25	R	1
Angelica sylvestris	0.05	0	0	1.25	R	1
Lotus pedunculatus	0.05	0	0	1.25	R	1
Persicaria hydropiper	0.05	0	0	1.25	R	1
Potentilla anserina	0.05	0	0	1.25	R	1
Potentilla erecta	0.05	0	0	1.25	R	1
Senecio aquaticus	0.05	0	0	1.25	R	1
Alnus glutinosa	0.025	0	0	0.62	R	1
Carex viridula subsp. oedocarpa	0.025	0	0	0.62	R	1
Scutellaria galericulata	0.025	0	0	0.62	R	1
Cardamine pratensis	0.025	0	0	0.62	R	1
Valeriana dioica	0.025	0	0	0.62	R	1
Lychnis flos-cuculi	0.025	0	0	0.62	R	1
Nitella flexilis agg.	0	0	0.0042	0.42	R	1

7.3 Appendix 3 - Loweswater Catchment Restoration Fund – ENSIS Fieldwork report 19th July

Present: Ben Goldsmith & Pete Smyntek (ENSIS @ UCL)

Aim: To collect DO / Temp data from the deep point
To collect water samples down a depth profile for chemical analysis

DO / Temp. Profile @ NY1272021670 – 16.5 m water depth

Depth m	DO mgl^{-1}	Cond μScm^{-1} (@ 25°C)	pH	Temp °C
0	9.25	71	7.62	23.3
1	8.71	71	7.62	23.3
2	9.05	72	7.68	22.8
3	9.50	72	7.68	21.5
4	10.14	72	7.68	18.0
5	9.22	71	7.52	16.8
6	8.75	70	7.22	16.1
7	8.12	71	7.17	15.6
8	7.26	71	7.01	15.0
9	5.51	72	6.91	13.7
10	4.07	73	6.71	12.1
11	3.65	72	6.74	11.2
12	2.30	72	6.62	10.9
13	1.20	73	6.64	10.7
14	0.54	79	6.66	10.5
15	0.21	88	6.84	10.4
16	0.23	87	6.79	10.4
10	4.26			12.0
5	9.31			16.8
0	9.30			23.3

Following the fine summer weather the site was fully stratified with major changes in temperature and dissolved oxygen below depth of 8 m. The deepest waters were almost entirely anoxic. The water was clear: Secchi depth was recorded as 4.9 m.

Water Sample Profile @ NY1272021670 – every 1 m

Van Dorn sampler: 1 x 250 ml NLS Nuts sample at each depth
1 x 1000 ml NLS Gen sample at each depth

Depth m	Nitrate nitrogen mgl^{-1}	Orthophosphate (as P) μgl^{-1}	Total Phosphorus (as P) μgl^{-1}
0.5	0.0072	6.20	17.20
2	0.0084	10.30	17.70
4	0.0685	4.70	11.30
6	0.104	2.80	14.90
7	0.117	2.20	9.60
8	0.128	2.90	11.40
9	0.147	1.60	13.40
10	0.216	3.00	11.00
11	0.274	2.50	9.70
12	0.284	3.20	8.80
13	0.285	2.10	10.10
14	0.198	4.03	12.30
15	0.0858	3.20	19.90
16	0.046	3.50	21.40

Samples delivered to NLS Star Cross 22/08/2013 – Analysed 23rd July 2013.

Notes:

Weather – Warm with 6/8 cloud – calm

Secchi depth 4.90 m

Used ENSIS Redstart 3 with electric engine – Previously used at Red Tarn, Helvellyn – BG cleaned and disinfected all kit with Virkon Aq prior to and after use at Loweswater. Launched from roadside layby – met with Vikki Salas and Mark Astley.

7.4 Appendix 4 - Data from the Radiometric Dating of Four Sediment Cores (LOWS3, LOWS4, LOWS5 and LOWS6) Taken from Loweswater, England

Table 8.4,1. ^{210}Pb concentrations in core LOWS3 taken from Loweswater, England.

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.38	0.0297	529.37	41.76	36.28	9.67	493.09	42.86	147.5	11.6
2.13	0.3033	545.15	32.51	57.22	6.71	487.93	33.2	1489.6	104.3
4.13	0.7289	426.31	30.36	57.77	6.82	368.54	31.12	3300.3	187
6.25	1.2159	337.94	20.71	53.28	4.89	284.66	21.28	4882	244.5
8.25	1.7063	217.57	16.16	51.64	4.51	165.93	16.78	5960.8	269.5
10.25	2.2038	149	16.52	48.48	4.48	100.52	17.12	6610.1	284.1
12.25	2.7745	107.18	13.96	58.28	4.12	48.9	14.56	7018.9	299.1
13.25	3.1195	102.7	7.88	51.78	2.37	50.92	8.23	7191.1	304
15.5	3.8956	90.36	12.71	50.83	3.81	39.53	13.27	7540.2	312
17.5	4.4582	75.86	10.96	46.89	3.36	28.97	11.46	7731.3	322
19.5	5.6326	43.48	7.21	50.65	2.51	-7.17	7.63	7859.3	338.6

Table 8.4.2. Artificial fallout radionuclide concentrations in core LOWS3.

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.38	271.41	11.51	0	0
2.13	417.91	10.78	0	0
4.13	592.94	12.4	0	0
6.25	859.66	10.31	0	0
8.25	403.25	6.42	3.39	1.73
10.25	218.37	5.37	5.32	1.8
12.25	91.27	3.32	0	0
13.25	70.15	1.84	0	0
15.5	31.85	2.62	0	0
17.5	25	2.23	0	0
19.5	10.25	1.38	0	0

Table 8.4.3. ^{210}Pb chronology of core LOWS3 taken from Loweswater, England.

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2012	0				
0.38	0.0297	2011	1	2	0.0485	0.341	9.7
2.13	0.3033	2005	7	2	0.0405	0.217	8.4
4.13	0.7289	1994	18	2	0.0383	0.173	10.3
6.25	1.2159	1981	31	2	0.0323	0.136	10.8
8.25	1.7063	1966	46	3	0.0352	0.142	15
10.25	2.2038	1952	60	5	0.0379	0.142	22.8
12.25	2.7745	1939	73	7	0.052	0.17	36.3
13.25	3.1195	1932	80	8	0.0394	0.114	30.3
15.5	3.8956	1907	105	15	0.0232	0.074	57.9
17.5	4.4582	1873	139	19	0.016	0.026	68.9

Table 8.4.4. ^{210}Pb concentrations in core LOWS4 taken from Loweswater, England.

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.38	0.0211	510.52	38.95	49.88	10.01	460.64	40.22	97.7	7.7
2.13	0.2425	555.9	36.23	44.14	7.85	511.76	37.07	1173.2	83.7
4.13	0.6009	436.35	23.97	46.14	5.16	390.21	24.52	2779.7	159.1
6.25	1.1208	308.23	31.32	34.37	6.8	273.86	32.05	4488.1	222.2
7.25	1.3857	279.68	15.73	53.83	3.38	225.85	16.09	5148	244.6
8.25	1.6164	242.68	12.25	54.05	3.09	188.63	12.63	5624.8	248.4
10.25	2.0711	189.84	18.88	46.81	4.99	143.03	19.53	6374	258.4
11.25	2.3017	158.72	15.1	53.67	3.92	105.05	15.6	6657.8	264.2
12.25	2.5569	172.16	16.31	52.49	4.59	119.67	16.94	6944.1	267.6
12.75	2.7005	126.89	8.24	51.03	2.03	75.86	8.49	7082.2	269
13.25	2.8458	104.29	7.41	51.21	2.17	53.08	7.72	7174.9	269.3
14.25	3.1473	108.74	11.98	51.88	2.92	56.86	12.33	7340.5	270.6
15.5	3.5258	90.75	15.25	55.39	3.77	35.36	15.71	7511.8	274.9
17.5	4.2723	42.02	11.41	56.45	2.93	-14.43	11.78	7552.6	290.6

Table 8.4.5. Artificial fallout radionuclide concentrations in core LOWS4.

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.38	250.75	10.36	0	0
2.13	343.49	10.42	4.8	2.82
4.13	542.87	8.89	3.68	2.07
6.25	744.11	14.07	4.8	2.86
7.25	513.02	6.18	0	0
8.25	397.85	4.66	4.94	1.26
10.25	225.16	6.01	6.56	2.09
11.25	183.93	4.48	4.39	1.59
12.25	147.5	4.44	4.6	1.81
12.75	93.19	1.77	1.56	0.71
13.25	76.94	1.74	0	0
14.25	65.79	2.39	0	0
15.5	25.46	2.49	0	0
17.5	12.48	1.74	0	0

Table 8.4.6. ^{210}Pb chronology of core LOWS4 taken from Loweswater, England.

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2012	0				
0.38	0.0211	2012	0	2	0.0505	0.443	9.6
2.13	0.2425	2007	5	2	0.0389	0.252	8.4
4.13	0.6009	1997	15	2	0.0382	0.179	8
6.25	1.1208	1983	29	2	0.035	0.139	13
7.25	1.3857	1975	37	2	0.0333	0.135	10
8.25	1.6164	1968	44	3	0.032	0.14	10.8
10.25	2.0711	1953	59	4	0.0259	0.114	18.2
11.25	2.3017	1944	68	5	0.0269	0.111	21.3
12.25	2.5569	1932	80	7	0.0162	0.061	25.8
12.75	2.7005	1924	88	9	0.0198	0.069	29.8
13.25	2.8458	1917	95	11	0.0229	0.077	36.8
14.25	3.1473	1899	113	18	0.0123	0.041	60.2
15.5	3.5258	1853	159	25	0.0047	0.014	82.8

Table 8.4.7. ^{210}Pb concentrations in core LOWS5 taken from Loweswater, England.

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.38	0.0501	395.2	35.08	48.31	8.54	346.89	36.1	177.2	15.6
2.25	0.3375	418.37	31.07	52.1	6.68	366.27	31.78	1201.7	92.6
3.13	0.5037	283.15	27.62	42.75	8.38	240.4	28.86	1698.6	113.6
4.25	0.736	261.23	20.42	43.06	4.75	218.17	20.97	2230.8	130.1
5.25	0.9663	142.21	15.62	56.63	5.21	85.58	16.47	2557.1	139.1
6.25	1.2067	199.01	16.56	64.21	4.92	134.8	17.28	2817.5	145.3
7.25	1.472	132.9	15.98	44.97	4.86	87.93	16.7	3108.5	152.6
8.25	1.7136	139.55	14.01	43.76	3.51	95.79	14.44	3330.3	158.2
9.25	1.9196	82.83	12.11	49.12	4.06	33.71	12.77	3452.8	161.2
10.25	2.1372	71.33	9.53	47.27	2.81	24.06	9.94	3515.1	163.3
11.25	2.3946	63.46	10.34	50.87	3.51	12.59	10.92	3560.7	165.3
12.25	2.6569	74.53	12.02	41.62	3.59	32.91	12.54	3616.1	167.9
13.25	2.9272	43.75	6.36	45.9	2.22	-2.15	6.74	3657.7	170.7

Table 8.4.8. Artificial fallout radionuclide concentrations in core LOWS5.

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.38	275.47	12.59	0	0
2.25	471.37	13.87	0	0
3.13	618.35	15.16	3.91	2.6
4.25	666.86	11.51	2.7	1.76
5.25	453.9	8.68	4.49	1.56
6.25	391.83	8.68	5.16	1.79
7.25	168.25	5.81	0	0
8.25	110.4	4.24	0	0
9.25	85.3	3.87	2.21	1.33
10.25	56.39	2.61	0	0
11.25	50.32	2.73	0	0
12.25	35.38	2.9	0	0
13.25	18.87	1.39	0	0

Table 8.4.9. ^{210}Pb chronology of core LOWS5 taken from Loweswater, England.

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2012	0				
0.38	0.0501	2010	2	2	0.0312	0.208	11.4
2.25	0.3375	1999	13	2	0.0208	0.126	10.3
3.13	0.5037	1992	20	2	0.0253	0.127	13.6
4.25	0.736	1982	30	2	0.0203	0.093	12.4
5.25	0.9663	1973	39	3	0.0398	0.169	21.3
6.25	1.2067	1965	47	4	0.0193	0.076	17
7.25	1.472	1951	61	5	0.0192	0.076	24.1
8.25	1.7136	1934	78	8	0.0104	0.047	27.5
9.25	1.9196	1918	94	11	0.0183	0.086	51
10.25	2.1372	1906	106	15	0.0176	0.074	62.5
11.25	2.3946	1893	119	21	0.0223	0.086	107
12.25	2.6569	1863	149	26	0.0033	0.012	136.3

Table 8.4.10. ^{210}Pb concentrations in core LOWS6 taken from Loweswater, England.

Depth	Dry Mass	Pb-210						Cum Unsupported	
		Total		Supported		Unsupp		Pb-210	
cm	g cm^{-2}	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq Kg^{-1}	±	Bq m^{-2}	±
0.38	0.0395	462.81	36.16	58	9.39	404.81	37.36	165.2	13.3
1.13	0.1361	501.66	33.11	46.01	8.45	455.65	34.17	580.3	38.4
2.25	0.3119	410.8	32.27	42.19	8.13	368.61	33.28	1302.3	74.4
3.13	0.4725	241.76	25.79	39.69	8.83	202.07	27.26	1747.1	93.9
4.25	0.7031	206.56	18.66	53.3	5.6	153.26	19.48	2154.2	110
5.25	0.9268	218.45	16.94	47.23	5.24	171.22	17.73	2516.8	119.5
6.25	1.1399	165.91	14.05	53.43	3.86	112.48	14.57	2814.7	125.9
7.25	1.3415	132.75	14.68	46.6	4.75	86.15	15.43	3013.7	129.9
8.25	1.548	126	13.62	54.94	4.73	71.06	14.42	3175.5	133.8
9.25	1.7649	73.55	11.25	54	4.27	19.55	12.03	3262.1	137.2
10.25	1.9963	72.15	7.59	49.36	2.43	22.79	7.97	3311	139.5
11.25	2.2534	51.5	7.18	55.1	2.66	-3.6	7.66	3335.7	140.9
12.25	2.524	59.42	12.11	54.61	2.79	4.81	12.43	3337.3	143

Table 8.4.11. Artificial fallout radionuclide concentrations in core LOWS6.

Depth	Cs-137		Am-241	
cm	Bq Kg^{-1}	±	Bq Kg^{-1}	±
0.38	348.38	13.95	0	0
1.13	395.96	13.46	0	0
2.25	515.06	14.84	0	0
3.13	602.51	14.8	0	0
4.25	480.38	9.63	5.19	1.66
5.25	339.89	7.74	0	0
6.25	204.43	5.58	3.87	1.38
7.25	122.37	4.93	0	0
8.25	93.6	4.09	0	0
9.25	54.92	3.26	0	0
10.25	43.38	1.99	0	0
11.25	34.5	1.72	0	0
12.25	23.36	1.87	0	0

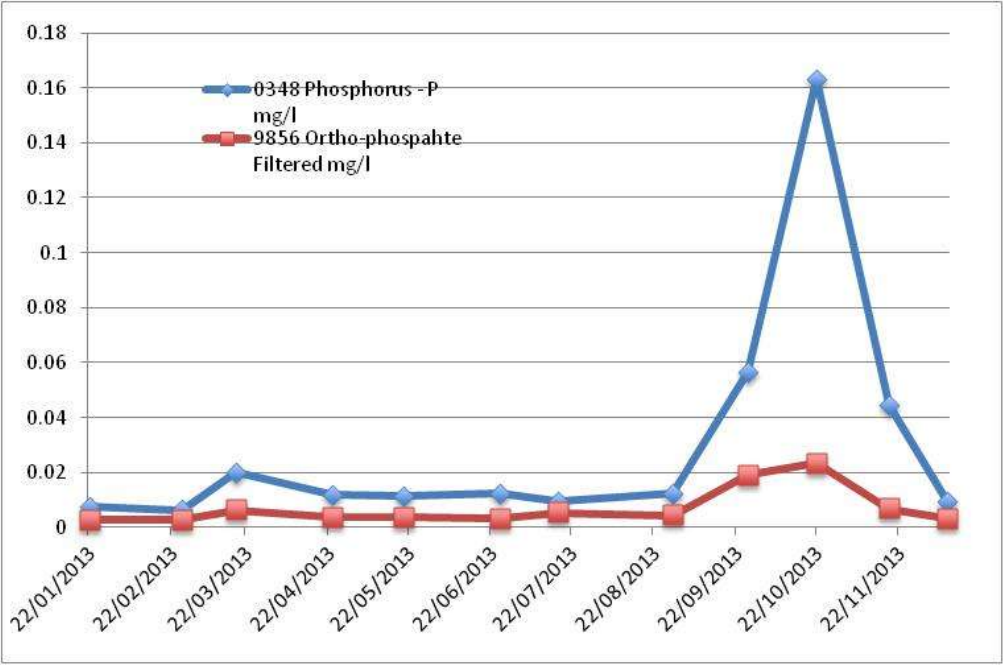
Table 12. ^{210}Pb chronology of core LOWS6 taken from Loweswater, England.

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2012	0				
0.38	0.0395	2010	2	2	0.0244	0.202	10.2
1.13	0.1361	2006	6	2	0.0188	0.129	8.9
2.25	0.3119	1996	16	2	0.0172	0.102	10.6
3.13	0.4725	1988	24	2	0.0244	0.125	14.8
4.25	0.7031	1979	33	2	0.0239	0.112	14.6
5.25	0.9268	1967	45	3	0.0148	0.068	13.8
6.25	1.1399	1952	60	4	0.0143	0.069	18.2
7.25	1.3415	1937	75	6	0.0115	0.057	25.5
8.25	1.548	1914	98	10	0.0069	0.033	37.2
9.25	1.7649	1888	124	19	0.0113	0.05	83.4
10.25	1.9963	1851	161	24	0.003	0.012	106.6

7.5 Appendix 5 Loweswater water chemistry data

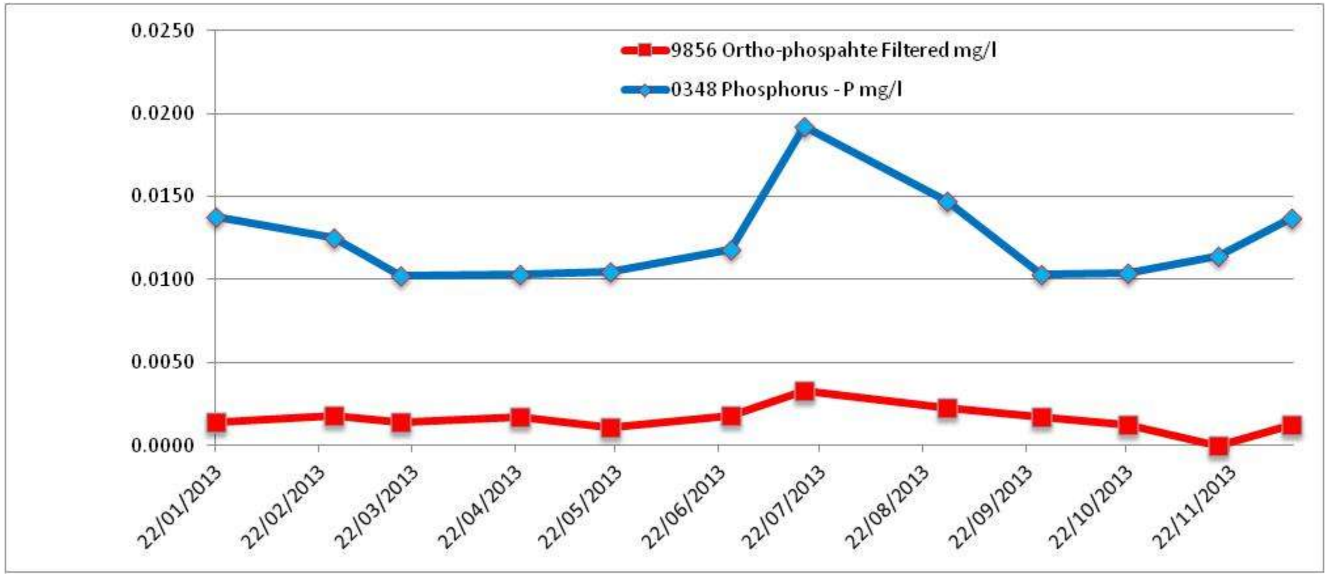
i) Inflow Dub Beck at Waterend, Loweswater

DATE	TIME	0061 pH PHUNITS	0072 Colour Filt HAZEN	0076 Temp Water CEL	0077 Conductivity @ 25C	0111 Ammonia (N) mg/l	0116 Nitrogen Total Oxidised	0117 Nitrate-N mg/l	0119 Ammonia Un-ionised mg/l	0158 Hardness mg/l	0162 Alkalinity pH 4.5 mg/l	0172 Chloride Ion mg/l	0182 Silicate Reactive Filtered	0348 Phosphorus - P mg/l	7610 Alkalinity Grans Plot (4.5) mg/l	7887 Chlorophyll ug/l	9686 Nitrogen - N mg/l	9856 Ortho-phospahte Filtered mg/l	9901 Oxygen Dissolved %satn	9924 Oxygen Dissolved mg/l	9943 Nitrogen Total Oxidised	9993 Ammonia Filtered N mg/l
22/01/2013	11:00	7.16	8.3	2.5	65	0.036	0.94	0.936	0.00006	30.4	24	10.3	2.92	0.0076	21.2	< .5	1.06	0.0026	98.9	13.5	0.886	0.017
26/02/2013	10:56	6.89	7	3	95.7	< .03	0.89	0.886	< .00003	30.1	20	9.7	2.64	0.0063	21.1	< .5	1.03	0.0028	101	13.6	0.913	0.0111
18/03/2013	11:04	7.17	13	3.6	82.3	0.061	0.73	0.726	0.0001	24.7	19	10.2	1.91	0.0201	16.3	1.5	1.08	0.0063	94.5	12.5	0.751	0.0653
23/04/2013	11:19	6.98	11	8.7	93	< .03	0.89	0.886	< .00005	27.4	17	11.4	1.74	0.0118	15.7	0.88	1.03	0.0037	100	11.6	0.876	0.0078
20/05/2013	10:51	7.32	14	10.5	86.3	< .03	0.92	0.916	< .00012	26.6	20	9.1	1.86	0.0113	18.5	2.5	0.97	0.0037	98	10.9	0.708	0.0046
25/06/2013	11:07	7.18	12	11.4	102	< .03	0.55	0.546	< .00009	37.8	32	8	2.6	0.0123	30.9	4.4	0.85	0.00307	98.2	10.7	0.557	0.0247
17/07/2013	11:07	7.13	12	16.2	116	< .03	0.59	0.586	< .00012	42.4	36	8.9	3.4	0.0095	34.3	1.8	0.83	0.0054	104.9	10.3	0.613	0.0132
29/08/2013	11:49	6.98	19	13.6	117	< .03	0.54	0.536	< .00007	37.7	35	9.5	3.18	0.0123	32.6	0.91	0.84	0.0045	92.6	9.6	0.593	0.0119
26/09/2013	12:00	6.99	14	13.4	6	< .03	0.74	0.736	< .00007	32.1	29	9.3	3.17	0.0564	24.5	0.79	0.99	0.0191	96.4	10	0.713	0.0122
22/10/2013	11:17	6.45	46	12.6	67	< .03	0.81	0.806	< .00002	17.3	13	9.7	1.84	0.163	10.3	19.5	1.55	0.0233	89.9	9.53	0.774	0.0284
18/11/2013	10:31	6.65	24	8.2	84	< .03	0.89	0.886	< .00002	22.2	15	11.1	2.12	0.0446	12.9	3.6	1.32	0.0069	93	10.9	0.911	0.0153
10/12/2013	11:18	6.99	10	8.1	99	< .03	0.91	0.906	< .00005	28.8	19	11.6	2.82	0.0096	18.3	< .5	1.01	0.0032	96.6	11.4	0.853	0.0168



ii) Lake sample

DATE	TIME	0061 pH PHUNITS	0067 Trans-parency m	0072 Colour Filt HAZEN	0076 Temp Water CEL	0077 Cond-uctivity @ 25C uS/cm	0158 Hardness mg/l	0172 Chloride Ion mg/l	0348 Phosphorus - P mg/l	7610 Alkalinity Grans Plot (4.5) mg/l	7887 Chlorophyll ug/l	9686 Nitrogen - N mg/l	9856 Ortho-phospahte Filtered mg/l	9901 Oxygen Dissolved %satn %	9943 Nitrogen Total Oxidised Filtered mg/l	9993 Ammonia Filtered N mg/l
22/01/2013	10:45	7.48	4.00	10.00	3.4	65.0	16.6	9.0	0.0138	10.4	4.3	0.64	0.0014	96.6	0.4160	0.0058
26/02/2013	10:44	7.65	3.20	7.40	2.9	62.0	16.1	8.6	0.0125	10.2	10.8	0.63	0.0018	103.0	0.3950	< .002
18/03/2013	10:48	7.48	3.20	6.80	3.8	62.0	16.4	8.8	0.0102	10.8	6.2	0.59	0.0014	100.4	0.3650	0.0056
23/04/2013	10:38	7.31	3.70	6.70	7.5	65.0	16.6	8.5	0.0103	10.2	3.7	0.59	0.0017	103.0	0.3480	0.0044
20/05/2013	10:53	7.72	3.80	7.00	11.1	64.0	17.2	8.5	0.0105	10.9	6.9	0.57	0.0011	102.4	0.2970	0.0021
25/06/2013	10:36	7.80	3.20	6.00	15.3	68.0	17.3	8.6	0.0118	11.7	12.2	0.43	0.0018	99.3	0.1350	0.0286
17/07/2013	10:42	8.86	5.90	5.80	22.0	69.0	17.9	8.7	0.0192	12.5	5.0	0.40	0.0033	114.7	0.0333	0.0184
29/08/2013	11:06	7.71	2.40	8.10	17.6	66.0	17.2	8.4	0.0147	11.4	6.3	0.40	0.0023	99.9	0.1110	0.0029
26/09/2013	12:00	7.33	2.30	8.10	14.3	67.6	17.0	8.1	0.0103	11.9	5.7	0.45	0.0017	97.3	0.1510	0.0224
22/10/2013	10:47	7.03	3.40	7.50	11.8	66.0	17.8	8.4	0.0104	12.0	7.3	0.46	0.0012	97.4	0.1810	0.0093
18/11/2013	10:33	7.28	3.00	9.30	8.3	66.0	16.9	8.0	0.0114	11.2	9.3	0.49	< .001	96.6	0.2560	< .002
10/12/2013	10:55	7.37	0.00	8.70	6.9	70.0	17.4	8.7	0.0137	11.0	7.8	0.64	0.0012	96.5	0.2750	0.0041



iii) Dub Beck at NY 132 212, outflow from lake

DATE	TIME	0061 pH PHUNITS	0072 Colour Filt HAZEN	0076 Temp Water CEL	0077 Cond-uctivity @ 25C uS/cm	0158 Hardness mg/l	0172 Chloride Ion mg/l	0182 Silicate Reactive Filtered mg/l	0348 Phosphorus - P mg/l	7610 Alkalinity Grans Plot (4.5) mg/l	7887 Chlorophyll ug/l	9686 Nitrogen - N mg/l	9856 Ortho-phospahte Filtered mg/l	9943 Nitrogen Total Oxidised Filtered mg/l	9993 Ammonia Filtered N mg/l
22/01/2013	09:56	7.58	9.9	3.1	65	16.6	8.5	1.78	0.0114	10.4	4.8	0.63	0.0011	0.42	0.003
26/02/2013	09:23	7.47	7.3	2.2	63	16.3	8.8	0.62	0.0106	10.5	8.7	0.64	< .001	0.405	0.0021
18/03/2013	10:10	7.34	7.6	4	62	16.8	8.2	0.2	0.011	10.5	6.6	0.62	< .001	0.369	0.00304
23/04/2013	09:44	7.28	6.8	7.5	65	17.4	8.7	< .2	0.0117	10.4	4.8	0.59	0.003	0.352	0.012
20/05/2013	10:00	7.74	7.3	11.5	65	16.7	8.9	0.22	0.0172	11.3	21.5	0.59	0.0032	0.284	0.0068
25/06/2013	09:53	7.51	5.4	15.1	66	17.2	8.5	< .2	0.0127	11.7	12.4	0.51	0.00202	0.134	0.0265
17/07/2013	09:55	7.42	6.5	21.4	69	18.1	8.7	0.38	0.0198	12.7	10.4	0.56	0.0054	0.0157	0.0266
29/08/2013	09:40	7.35	8.4	17.1	66	17.3	8	0.62	0.0092	11.2	7.1	0.4	< .001	0.105	0.0087
26/09/2013	10:45	7.14	8.1	13.6	67	17.3	7.9	1.2	0.0106	12	6.6	0.49	< .001	0.153	0.0265
22/10/2013	09:52	6.64	15	12.1	67	17.3	8.3	2.07	0.0147	11.4	7.2	0.55	0.00204	0.195	0.0144
18/11/2013	09:29	6.94	9.8	8.3	66	16.7	8.5	1.67	0.0125	11.1	9.3	0.53	< .001	0.256	0.0109
10/12/2013	10:08	7.08	7.6	6.8	67	17.4	8.8	1.77	0.0159	10.9	7.3	0.61	0.0013	0.287	0.0075