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Nutrient modelling and a nutrient budget for Llangorse Lake

L. May, B. Dudley, B. M. Spears and T.W. Hatton-Ellis

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EXECUTIVE SUMMARY

Llangorse Lake is the largest natural lake in South Wales and is of European level importance in terms of the wildlife that it supports. However, the site has a history of eutrophication problems. These were believed to have been caused by high nutrient loads entering the lake from the surrounding catchment. This study aimed to determine the size and main sources of those loads.

The study found that phosphorus (P) and nitrate (NO_3-N) loads to Llangorse Lake were approximately 2 tonnes P y^{-1} and 74 tonnes NO_3-N y^{-1}, which is equivalent to an areal loading to the lake of 1.5 g P m^{-2} y^{-1} and 53 g NO_3-N m^{-2} y^{-1}. Most of the P and NO_3-N loads were found to enter the lake from only two of the inflow streams (i.e. those draining to Sites 2 and 6). These accounted for 85 per cent of the annual P load and 82 per cent of the annual NO_3-N load to the lake.

The hydrology of the Llangorse catchment seems to be very complex, with many areas affected by sub-surface flow. Streams to the north of the lake, for example, have very low flows and appear to be spring fed. In contrast, at Site 6, the upstream surface water catchment accounts for only 36 per cent of the lake catchment whereas the stream itself carries 67 per cent of annual hydraulic load to the lake. The flow at Site 6 is almost double that which can be accounted for by average levels of rainfall in this area. Although there is some evidence that higher rainfall in the upland areas of this subcatchment may account for some of this discrepancy, the results suggest that there may also be considerable sub-surface water flow in this area.

If the streams that flow into the lake have significant input from sub-surface flow, this will affect their hydrology and chemistry. As this sub-surface water may enter the drainage system from an area beyond the boundary of the topographically defined surface water catchment, this also has significant implications for catchment management aimed at reducing the nutrient loads to the lake. Any control measures put in place to reduce these loads may need to be applied to the catchment area that contributes to runoff and to that which generates sub-surface flow.

Most of the published literature concerning the eutrophication and recovery of Llangorse Lake has focused on P. This is probably for historical reasons. This study shows that the ecological water quality of the lake is actually determined by a delicate balance between P and NO_3-N availability. So, it is important to consider both of these nutrients in developing a catchment management plan for the area. The results suggest that catchment management planning should focus on the reduction of nutrient losses from agriculture and the better management of on-site sewage treatment systems such as septic tanks.

Some of the inflow streams showed evidence of occasional point source pollution in very wet weather. This suggests that there is a need, in some places at least, to control point sources of pollution that leak or overflow during heavy rainfall. However, most sources of nutrients within the catchment seem to be diffuse sources. These can only be addressed through catchment-wide nutrient budgeting, better animal husbandry and improved management of discharges related to sewage effluent. Catchment sensitive farming would probably be the best approach to this as other measures, such as making the area a nitrate vulnerable zone, would only address part of the problem. As many tourists visit the area, a move towards sustainable tourism should also be considered.

The results of this study suggest that the P load to the lake needs to be reduced from 2 tonnes P y^{-1} to 1.7 tonnes P y^{-1} to meet WFD water quality targets. Once this has been achieved, P concentrations in the open water will continue to be driven by recycling from the sediments for several years. During this period, it is essential to maintain the current situation whereby N-limitation controls algal biomass accumulation during the summer months, by

reducing N loads from the catchment. This will help prevent algal blooms occurring during the recovery period.

One final consideration in developing a catchment management plan is the possible impact of occasional flooding of the meadows around the lake in terms of transporting animal waste into the lake. Although flooding was once encouraged by local farmers as a way of carrying plant food to the pastures "both in solution and in very finely divided particles" (Griffiths, 1939), in these days of intensive agriculture, flooding of the meadows is more likely to carry nutrients from the meadows to the lake.

The most important findings from this study are:

- Phosphorus loads to the lake need to be reduced by about 15 per cent, and nitrate loads need to be maintained at or below the current level, for the lake to achieve good water quality
- More than 80 per cent of the nutrients are delivered to the lake by the two main inflow streams
- Sub-surface flow may significantly influence stream flow and nutrient delivery to the lake; if so, the water and nutrients may enter the lake from a catchment area wider than that defined on the basis of surface topography
- The lake appears to have a much shorter retention time than previously calculated
- Nutrient levels in the sediments are not likely to greatly slow the recovery of the lake once appropriate management is in place

The report concludes that Llangorse Lake is worth investing in as the prospects for recovery seem good if appropriate measures are taken to reduce nutrient delivery from the catchment. There seems to be a strong case for a catchment sensitive farming initiative, here, including provision for nitrate management by establishing a nitrate vulnerable zone (NVZ) in this area.

Residents in the area need to be made aware of the importance of proper maintenance of domestic sewerage systems and planning authorities need to take the sensitivity of the lake into account when considering new development proposals. It should not be assumed that replacing properly managed septic tanks with a mains sewerage system would necessarily improve the situation. This needs further investigation.

There is a strong possibility that land close to the lake shore may deliver large amounts of N and P to the lake when the area floods. Conservation bodies should consider strategic land purchase near the lake shore to extend areas of wet woodland and / or reedswamp. This would enable intensive agriculture, especially livestock grazing, to be excluded from areas that are sensitive to flooding, thereby reducing the nutrient load to the lake.

CRYNODEB GWEITHREDOL

Llyn Llan-gors yw'r llyn naturiol mwyaf yn Ne Cymru ac mae o bwysigrwydd Ewropeaidd yn nhermau'r bywyd gwyllt mae'n ei gynnal. Fodd bynnag, mae gan y safle hanes of broblemau gorfaethu. Credid i'r rhain gael eu hachosi gan lwythi mawr o faetholion mawr yn mynd i mewn i'r llyn o'r dalgylch o'i gwmpas. Nod yr astudiaeth hon oedd penderfynu maint a phrif ffynonellau'r llwythi hynny.

Canfu'r astudiaeth fod llwythi ffosfforws (P) a nitrad (NO_3-N) i Lyn Llan-gors oddeutu 2 dunnell fetrig P y^{-1} a 74 tunnell fetrig NO_3-N y^{-1}, sy'n gyfwerth â llwyth, yn ol arwynebedd y llyn, o 1.5 g P m^{-2} y^{-1} a 53 g NO_3-N m^{-2} y^{-1}. Canfuwyd bod y rhan fwyaf o'r llwythi P ac NO_3-N yn mynd i mewn i'r llyn trwy dwy o'r nentydd mewnlif yn unig (h.y. y rhai sy'n draenio i Safleoedd 2 a 6). Roedd y rhain yn gyfrifol am 85 y cant o'r llwyth P blynyddol ac 82 y cant o'r llwyth NO_3-N blynyddol i'r llyn.

Mae hydroleg dalgylch Llan-gors yn ymddangos yn gymhleth iawn, gyda llif is-wyneb yn effeithio ar lawer o fannau. Mae gan nentydd i'r gogledd o'r llyn, er enghraifft, lifoedd isel iawn ac ymddengys mai tarddellau sy'n eu porthi. O'i gyferbynnu, mae'r rhan o'r dalgylch i fyny'r nant o Safle 6 yn gyfrifol am gludo 67 y cant o'r llwyth hydrolig blynyddol i'r llyn er ei fod yn cynhyrchioly dim ond 36 y cant o ddalgylch y llyn. Mae'r llif yn Safle 6 bron dwbl yr hyn y gellir ei briodoli i gyfartaledd y glawiad yn yr ardal hon. Er bod rhywfaint o dystiolaeth y gall glawiad uwch yn rhannau ucheldirol yr is-ddalgylch hwn fod yn gyfrifol am rywfaint o'r anghysondeb hwn, mae'r canlyniadau'n awgrymu efallai bod yna hefyd lif dŵr is-wyneb sylweddol yn yr ardal hon.

Os oes cyfraniad sylweddol o lif is-wyneb i'r nentydd sy'n llifo i'r llyn, bydd hyn yn effeithio ar eu hydroleg a'u cemeg. Gan ei bod yn bosibl bod y dŵr is-wyneb hwn yn mynd i mewn i'r system ddraenio rywle y tu hwnt i derfyn y dalgylch a ddiffinnir yn dopograffigol, mae gan hyn hefyd oblygiadau sylweddol ar gyfer rheoli dalgylchoedd gyda'r nod o leihau'r llwythi maetholion i'r llyn. Mae'n bosibl y bydd angen i unrhyw fesurau rheoli a weithredir i leihau'r llwythi hyn gael eu gweithredu yn y dalgylch sy'n cyfrannu at ddŵr ffo ac yn y dalgylch sy'n creu llif is-wyneb.

Mae'r rhan fwyaf o'r llenyddiaeth gyhoeddedig sy'n ymdrin â gorfaethu ac adferiad Llyn Llan-gors wedi canolbwyntio ar P. Mae hyn am resymau hanesyddol, mae'n debyg. Mae'r astudiaeth hon yn dangos bod ansawdd dŵr ecolegol y llyn yn cael ei benderfynu mewn gwirionedd gan gydbwysedd sensitif rhwng argaeledd P ac NO_3-N. Felly mae'n bwysig ystyried y ddau faetholyn hyn wrth lunio cynllun rheoli dalgylch ar gyfer yr ardal. Mae'r canlyniadau'n awgrymu y dylai cynlluniau i reoli'r dalgylch ganolbwyntio ar ostwng lefel y maetholion a ollyngir gan amaethyddiaeth a gwella'r ffordd y rheolir systemau trin carthion lleol, megis tanciau septig.

Roedd rhai o'r nentydd mewnlif yn dangos tystiolaeth o lygredd achlysurol o ffynonellau pwynt ar dywydd gwlyb iawn. Mae hyn yn awgrymu bod angen, mewn rhai mannau o leiaf, rheoli llygredd of ffynonellau pwynt sy'n gollwng neu'n gorlifo pan geir glaw trwm. Fodd bynnag, ymddengys fod y rhan fwyaf o'r ffynonellau maetholion yn y dalgylch yn ffynonellau gwasgaredig. Ni ellir mynd i'r afael â'r rhain ond trwy gyllidebu maetholion ar draws y dalgylch, mabwysiadu ffyrd well i fagu anifeiliaid a rheoli gollyngiadau sy'n gysylltiedig ag elifion carthion yn well. Mae'n debyg mai ffermio sensitif i'r dalgylch fyddai'r dull gorau yma, gan na fyddai mesurau eraill, megis gwneud yr ardal yn barth perygl nitradau, ond yn mynd i'r afael â rhan o'r broblem. Gan fod llawer o dwristiaid yn dod i'r ardal, dylid hefyd ystyried symudiad tuag at dwristiaeth gynaliadwy.

Mae canlyniadau'r astudiaeth hon yn awgrymu bod angen lleihau'r llwyth P i'r llyn o 2 dunnell fetrig P y^{-1} i 1.7 tunnell fetrig P y^{-1} er mwyn cyrraedd targedau ansawdd dŵr y Gyfarwyddeb Fframwaith Dŵr. Ar ôl i hyn gael ei gyflawni, bydd ailgylchu o'r gwaddodion yn dal i ddylanwadu ar grynodiadau P yn y dŵr agored am nifer o flynyddoedd. Yn ystod y cyfnod hwn mae'n hanfodol cadw at y sefyllfa bresennol lle mae cyfyngiad ar N yn rheoli croniad y biomas algaidd yn ystod misoedd yr haf, trwy leihau llwythi N o'r dalgylch. Bydd hyn yn helpu i atal blwm algaidd rhag digwydd yn ystod cyfnod yr adferiad.

Un ystyriaeth olaf wrth lunio cynllun rheoli dalgylch yw'r effaith gallai llifogydd achlysurol gael ar y dolydd o gwmpas y llyn wrth gludo gwastraff anifeiliaid i'r llyn. Er bod llifogydd ar un adeg yn cael eu hybu gan ffermwyr lleol fel ffordd o gludo bwyd planhigion i'r porfeydd "both in solution and in very finely divided particles" (Griffiths, 1939), heddiw, gydag amaethyddiaeth ddwys, mae llifogydd ar y dolydd yn fwy tebyg o gludo maetholion o'r dolydd i'r llyn.

Canfyddiadau pwysicaf yr astudiaeth hon yw:

- Mae angen lleihau llwythi ffosfforws i'r llyn ryw 15 y cant, ac mae angen cadw llwythi nitradau ar y lefel bresennol neu yn llai, i'r llyn gael ansawdd dŵr da
- Mae'r ddwy brif nant mewnlif yn cyfrannu mwy nag 80 y cant o'r maetholion i'r llyn
- Mae'n bosibl bod llif is-wyneb yn dylanwadu'n sylweddol ar y llif dŵr a'r maetholion sy'n cyrraedd y llyn. Os felly, mae'n bosibl bod y dŵr a'r maetholion yn mynd i mewn i'r llyn o ddalgylch ehangach na'r un a ddiffinnir ar sail topograffeg arwyneb
- Ymddengys fod gan y llyn amser dargadw byrrach o lawer nag a gyfrifwyd o'r blaen
- Nid yw lefelau maetholion yn y gwaddodion yn debyg o arafu adferiad y llyn yn fawr unwaith y bydd rheolaeth briodol yn cael ei gweithredu

Mae'r adroddiad yn dod i'r casgliad ei bod yn werth buddsoddi yn Llyn Llan-gors gan fod rhagolygon adferiad yn ymddangos yn dda os gweithredir mesurau priodol i leihau'r maetholion o'r dalgylch. Ymddengys fod yna ddadl gref dros gynllun ffermio sensitif i'r dalgylch yma, gan gynnwys darparu ar gyfer rheoli nitradau trwy sefydlu parth perygl nitradau (PPN) yn yr ardal hon.

Mae angen rhoi gwybod i drigolion yr ardal ei bod yn bwysig cynnal a chadw systemau carthffosiaeth domestig yn briodol, ac mae angen i'r awdurdodau cynllunio ystyried sensitifrwydd y llyn wrth benderfynu ar gynigion datblygu newydd. Ni ddylid tybio y byddai gosod system carthffosiaeth prif gyflenwad yn lle tanciau septig a reolir yn briodol yn gwella'r sefyllfa o angenrheidrwydd. Mae angen ymchwilio ymhellach i hyn.

Mae yna bosibilrwydd cryf bod y tir sy'n agos at lan y llyn yn cyfrannu llawer iawn o N a P i'r llyn pan fo llifogydd arno. Dylai cyrff cadwraeth ystyried pryniadau tir strategol ger glan y llyn i ehangu'r darnau o goetir gwlyb a / neu gorsydd siglennaidd cyrs. Byddai hyn yn ei gwneud yn bosibl i amaethyddiaeth ddwys, yn enwedig pori gan anifeiliaid fferm, gael ei chadw allan o'r mannau lle ceir llifogydd, ac felly byddai'r llwyth maetholion i'r llyn yn lleihau.

1INTRODUCTION

Llangorse Lake is the largest natural lake in South Wales. There have been concerns about eutrophication problems here for many years. The problem is believed to have been caused by high nutrient loads entering the lake from the surrounding catchment. However, even after many years of study, the magnitude of these loads was unknown and the main sources of these inputs were unclear.

The ecological importance of Llangorse Lake has been recognised since 1954, when it was designated as a Site of Special Scientific Interest (SSSI). At 139 ha in area, the lake is the largest natural eutrophic lake in Wales, and supports a wide range of aquatic plants including eight species of *Potamogeton*, the rare hybrid yellow water-lily *Nuphar* x *spenneriana*, three different charophytes and a diverse marginal community. The lake is relatively well studied, with some aquatic plant records dating back to the late 19th century. Nevertheless, palaeolimnological evidence (Bennion *et al*., 2004) indicates that the lake formerly supported *Nitella* sp. and *Potamogeton praelongus*, though neither has been recorded during any field survey. In 1995 the lake was designated as a Special Area of Conservation (SAC) under the Habitats and Species Directive for its importance as a Natural Eutrophic Lake with *Magnopotamion* or *Hydrocharition* type vegetation.

In addition to aquatic macrophytes, the lake provides an important habitat for a wide range of invertebrates, including the variable damselfly *Coenagrion pulchellum* and the medicinal leech *Hirudo medicinalis*. The lake also supports a wide range of breeding and over-wintering wetland birds that are rare in Wales (e.g. Great Crested Grebes and Reed Warblers). Due to its relatively large size, it also represents one of the most important breeding and grazing sites in the country for these bird communities (Cundale, 1980). The lake also provides socio-economic benefits to the local community through its use as a recreational site for coarse fishing and water sports (Dickinson and Teeuw, 1999).

Although the lake is now considered to have European level importance in terms of its wildlife, achieving this status would have seemed improbable to lake managers in the 1970s. At that time, effluent from the Bwlch and Llangorse sewage treatment works entered the lake, making a significant contribution to soluble reactive phosphorus (SRP) levels that routinely peaked at 600 $\mu g\ l^{-1}$ during the second half of the year (Benson-Evans *et al*., 1999). During this period, the macrophyte community steadily declined and the frequency of algal blooms increased. By 1978, the only remaining submerged macrophyte was *Zannichellia palustris*, a species very tolerant of eutrophication (Wade 1999). During this period cyanobacteria, notably *Microcystis* and *Anabaena*, dominated algal blooms forming more than 96% of the total phytoplankton population (Benson-Evans *et al*., 1999).

It has always been assumed that phosphorus (P) was the main limiting nutrient in Llangorse Lake and that a reduction in P load would lead to a marked improvement in water quality. So, as a first step in addressing the eutrophication problem, a P budget for the lake was drawn up by the Welsh Water Authority in the 1970s (Turner *et al*., 1981) This suggested that the total phosphorus (TP) load to the lake was 1 - 1.5 tonnes y^{-1}, of which 0.4 - 0.6 tonnes y^{-1} came from the sewage treatment works at Llangorse and Bwlch. As a result of this initial assessment, Turner *et al*. (1981) predicted that, if these sources of P were diverted away from the lake, the lake would become ‘oligotrophic’ or ‘in the critical or transitional region between oligotrophic and eutrophic’. As a result of this study, the effluent from Llangorse STW was diverted away from the lake in 1981 and that from Bwlch STW in 1992 (Wade 1999).

Diversion of the two STW outfalls had a positive effect on the lake. Annual mean in-lake TP concentrations fell from about 160 $\mu g\ l^{-1}$ in the mid 1980s to about 120 $\mu g\ l^{-1}$ by the mid 1990s. This was closely followed by a steady recovery in the macrophyte community and, in terms of species richness at least, this has now reached its former levels. Moreover, there has been a significant decline in cyanobacterial blooms, with the phytoplankton becoming increasingly dominated by Chlorophyta and diatoms (Benson-Evans *et al*., 1999). However, the submerged plant community continues to show signs of instability (Duigan *et al*., 2006) and is dominated by species characteristic of strongly eutrophic water bodies (Wade 1999; Duigan *et al*., 2006). Although the TP concentration was reduced by 25 per cent, this was not sufficient to meet the Special Area of Conservation (SAC) target TP concentration of 35 µg l^{-1} (JNCC, 2005). These initial results suggested that significant sources of P had not been accounted for in the initial budget.

Recently, a CCW condition assessment (Burgess *et al*., 2006) found that the lake was in unfavourable condition due to continuing signs of nutrient enrichment, apparently from diffuse sources in the catchment. Some of these increases in nutrient load are thought to be associated with increased sediment loads resulting from agricultural intensification within the catchment (Chambers, 1999).

As a result of this, the Countryside Council for Wales (CCW) initiated the current study, which aimed to provide a more comprehensive nutrient budget for the lake and its catchment on which management decisions could be based. The specific objectives of this study were to:

1. Review existing data and information on the water quality of Llangorse Lake.
2. Conduct a field study to investigate the nutrient budget of the lake.
3. Model the nutrient delivery from the catchment to the lake, with particular focus on phosphorus delivery, to give an indication of source apportionment.
4. Prepare a draft catchment management plan.

In contrast to earlier work, this study focuses on both phosphorus and nitrate. Targets for in-lake nutrient concentrations are discussed in detail in Section 7.2.1.

The results of this study are reported in relation to current climatic conditions. However, it should be noted that climate change will almost certainly affect nutrient delivery and in-lake ecosystem responses in future. The nature of these changes cannot be predicted with any certainty at the site specific level, but some general conclusions can be drawn from the fact that warmer, wetter winters and hotter, drier summers are predicted for this area in the future (UKCIP, 2002). Eisenrich *et al*. (2005) suggest that such changes could result in:

- higher sediment and nutrient loads in winter and lower nutrient loads in summer, due to seasonal changes in runoff
- higher flushing rates in winter and increased water retention times in summer, due to seasonal changes in the level of rainfall
- increased rates of nutrient cycling in both the catchment and the lake, due to the effect of increased temperatures on the biological processes involved in this process
- more nutrients from sewage-related sources as a result of an increased numbers of visitors being attracted to the area by the hotter, drier summers

Changes in the timing and magnitude of nutrient delivery, as described above, will affect both the chemistry and ecology of the lake. However, these responses are very complex and there are insufficient quantitative data available for Llangorse Lake to enable accurate predictions to be made on a site specific basis. However, a more general review of climate change impacts on lakes in the Netherlands by Mooij *et al*., (2005) suggests that climate change is likely to:

- have a negative impact on biodiversity, including a reduction in the numbers of aquatic bird species
- increase phytoplankton dominance, causing higher turbidity and loss of macrophytes

The authors conclude that these adverse effects can be limited by, amongst other things, reducing nutrient loads.

2THE STUDY SITE

Lake

Llangorse Lake (51° 55' N; 3°15' W) is a nutrient rich lake that lies at an altitude of 155 m above sea level in the Brecon Beacons National Park, South Wales. It is the largest natural lake in this part of Wales, with a maximum length of 2.5 km, a maximum breadth of 0.8 km, a maximum depth of 7.75 m (Cragg *et al*., 1980) and a surface area of 139 ha (Duigan *et al*., 1999). The lake is reported to have a volume of 3.6 x 10^6 m^3 and a water residence time of 104 days (Turner *et al*., 1981). However, data collected during the present study suggests that the water residence time is much less than this, i.e. about 55 days (see Section 5.1). The lake is widely used for recreational activities such as fishing, sailing, water-skiing and windsurfing and is of great economic importance to the local community because it attracts large numbers of visitors to the area.

Llangorse Lake has a long history of algal blooms and other water quality problems associated with elevated inputs of nutrients from external sources (eutrophication). The earliest record of an algal bloom, dates back to 1188 and the earliest record of large amounts of sediment being delivered to the lake by the River Llynfi after heavy rainfall dates back to the mid 1500s (Griffiths, 1939). That said, the situation became much worse in the 1950s, when the submerged macrophytes began to decline. This coincided with a switch in the diatom community from non-planktonic to planktonic forms (Bennion & Appleby, 1999).

Catchment

The catchment of Llangorse Lake covers an area of about 2,200 ha. Land use, here, is described in detail by Dickinson & Teeuw (1999). In summary, the area is predominantly under agricultural use for flocks of sheep and herds of dairy and beef cattle, especially in the low lying areas around the shores of the lake. Most of the land cover in the area is improved pasture, although there are small areas of unimproved pasture, moorland, woodland, and arable land rotated with improved pasture.

In terms of resident population, the catchment has one small town, i.e. Llangorse, which has about 460 inhabitants, and a small number of scattered farms and minor hamlets (Dickinson & Teeuw, 1999). The total number of people living within the catchment is unclear, but about 1200 adults are believed to live within the parish of Llangorse and approximately 110 children attend the local primary school (Llyn Syfaddan Parish Profile). So, for the purposes of this part of the project, the size of the local population has been estimated to be about 1500 people. As the sewage works at Llangorse and Bwlch, combined, serve an estimated 500 people (Wade, 1999; CCW, *pers. comm*.), this suggests that about 1000 people living within the catchment depend upon septic tank systems for the treatment of their domestic sewage and waste water.

In addition to the above, the catchment hosts a large number of visitors at certain times of the year. Wade (1999) suggested that many of these stay within the area served by Llangorse sewage treatment works (STW), the effluent from which has been diverted to the lake outflow. However, in recent years there have been a number of conversions of farm buildings into holiday accommodation outside the area that is served by this STW. This will have increased the nutrient load to the lake from private, on-site, sewage treatment facilities such as septic tanks.

3LITERATURE REVIEW

The ecology and environmental history of the lake have already been extensively described elsewhere (Monteith, 1996; Bennion & Appleby, 1999; Chambers, 1999; Duigan *et al*., 1999; Benson-Evans *et al*., 1999; Wade, 1999; Bennion *et al*., 2004) and are not described further here. Instead, this literature review focuses on long term changes in water quality, sediment accumulation rate, land use within the catchment and macrophyte species richness.

3.1Water quality

Llangorse Lake is a shallow eutrophic lake that has been subject to natural and cultural eutrophication for many years. Analysis of the diatom record from the lake sediments suggests that it has been affected by eutrophication since at least the middle of the 19th century (Bennion & Appleby, 1999). The long-term data show that phosphorus levels within the lake were very high between the early 1900s and the mid-1980s, reaching annual mean in-lake concentrations of 150-160 $\mu g\ l^{-1}$ (Figure 3.1). After that, P concentrations began to fall as a result of treated effluent from the Llangorse and Bwlch sewage treatment works (STWs) being diverted away from the lake (Wade, 1999).

At the time of diversion, the Llangorse STW served a local population of 360 people plus up to 600 seasonal visitors (Wade, 1999), while the Bwlch STW served about 130 people (CCW, *pers. comm*.). If it is assumed that the sewage output from seasonal visitors to the area equated to about 150 people, then these STWs served a population equivalent of about 640 people. If this figure is combined with the published *per capita* P export coefficient for sewage effluent from secondary treatment processes, i.e. 1 kg P y^{-1} (Harper, 1992), these values suggest that the reduction in P load to the lake that was probably achieved by diverting these sources was 0.6 tonnes P y^{-1}.

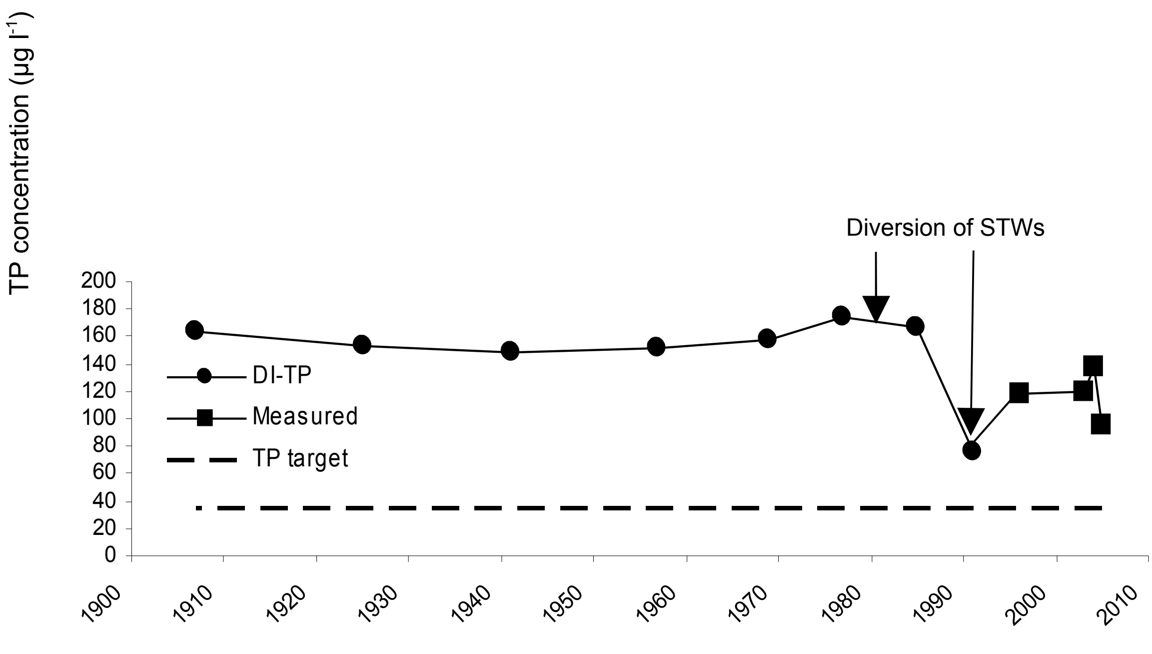

Figure 3.1. Variation in annual mean in-lake TP concentration in Llangorse Lake. TP data comprise: diatom inferred TP estimates (DI-TP: circles) for 1907-1991 (from Bennion and Appleby, 1999); measured annual average TP concentrations for 1995 to 2005 (squares) from SAC (2005). Dashed line represents the SAC target TP concentration of 35 $\mu g\ l^{-1}$. Arrows indicate years in which the STW effluents were diverted away from the lake.

3.2Sedimentation rate

In the absence of nutrient-laden inputs of treated sewage effluent, sediments generated from erosion and runoff from the catchment are likely to be the main inputs of nutrients to the lake. Data obtained from the literature suggest that the rate of sediment accumulation within the lake has increased in recent years (Figure 3.2) and there is evidence that the accumulation rate over the past 150 yrs has been 2.5 times higher than over the previous 150 years (Chambers 1999). This is thought to be due to increased erosion from the catchment due to agricultural intensification (Jones *et al.*, 1991).

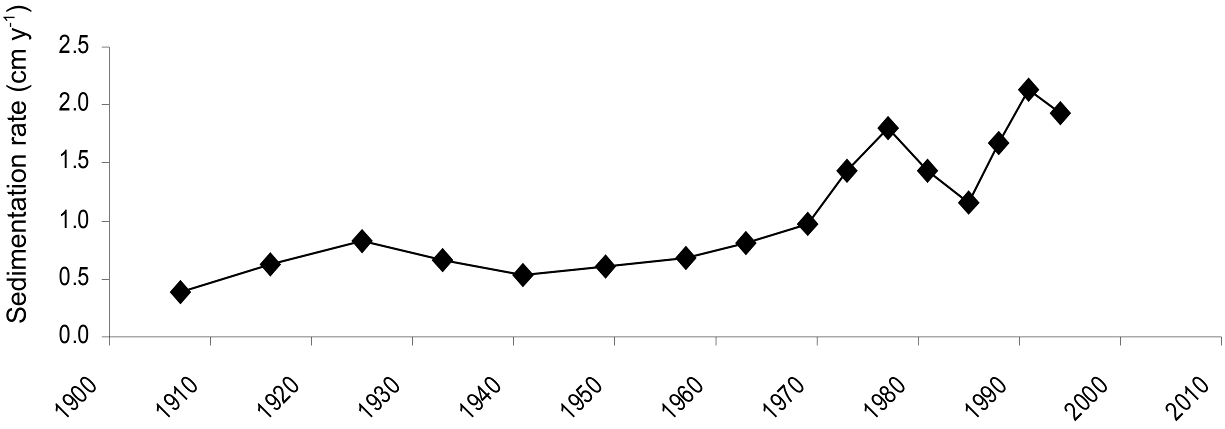

Figure 3.2. Variation in within lake sedimentation rate in Llangorse Lake (data from Chambers, 1999).

The elevated sediment accumulation rate probably contributes to the accumulation of P within the lake sediments. If so, this is an important issue in relation to restoring the lake to good ecological status, as it will tend to prolong the recovery of the lake by fuelling the cyclical uptake and release of P between the sediment and the water column (internal loading). However, the increase in sedimentation rate has not been mirrored by a corresponding increase in open water TP concentrations (compare Figure 3.1). Initially, this suggests that these sediments were not, in fact, transporting increasing amounts of particulate P into the lake. However, this is unlikely to be the case because they are derived from agricultural soils that are likely to be heavily laden with P. A possible explanation is that, while sediment and thus particulate P loads to the lake have been increasing, dissolved P loads have been decreasing due to the diversion of treated sewage effluent away from the lake. It is also possible that the sediment entering the lake may simply be deposited onto the lake bed and therefore not contribute directly to changes in the water column TP signal. The overall 25 per cent reduction in annual mean in-lake TP concentration recorded in the lake is probably the net effect of a combination of these processes.

3.3Land use

Apart from sediment transport, one of the main sources of nutrients to the lake is runoff from the catchment. This is related to land use, which is a combination of land cover and land management practices. Although there was little change in land cover between the years 1937 and 1993 (+2% arable, -2% improved grassland, -1% moorland, and -1% woodland and scrub), there was a rapid increase in livestock numbers in the area between 1940 and 1988 (>50 % increase in cattle and 100% increase in sheep), as farming practices underwent increasing intensification (Dickinson and Teeuw, 1999). There is insufficient detail in the published data to enable the impact of these changes on the nutrient load to the lake to be determined with any great accuracy. However, pro-rata estimates of the number of livestock within the Llangorse catchment, based on the areas of each of the three parishes that contribute to this (i.e. Cathedine and 70% of Llangorse and Llangasty Talyllyn), suggest that there may be about 1000 cattle and about 9000 sheep. Using P and N export coefficients derived from data for the Slapton catchments in England (Burt *et al.*, 1996), the nutrient loads to the lake from these sources can be estimated to be about 490 kg P y^{-1} and 21,400 kg N y^{-1} (see Sections 7.3.1 and 7.3.2).

3.4Macrophyte species diversity

The long-term changes in open water TP concentration recorded in Llangorse Lake (Figure 3.1) appear to have had a marked effect on the ecology of the lake. The sediment diatom record suggests that a marked change in dominance from epiphytic to planktonic diatom species probably occurred in the 1950s (Bennion & Appleby, 1999). This probably reflects a more general switch to a plankton dominated system that may have reduced water transparency (Wade, 1999).

It is believed that this reduction in water transparency may have caused a decline in the submerged macrophyte community between the mid to late 1960s and the early 1980s (Bennion & Appleby, 1999). Over this period, species diversity and areal coverage declined until there were only a few stands comprising two species in the lake by 1982. The submerged flora only began to recover after effluent from the STWs was diverted away from the lake. The species composition of both submerged and emergent macrophyte communities recovered completely, or almost completely, by the 1990s (Wade, 1999, Figure 3.3).

In addition to the impact on macrophytes and diatoms, changes in the nutrient load to the lake also affected the phytoplankton communities in the lake. Cyanobacteria blooms were common in the 1960s and 1970s, but Chlorophyta became increasingly dominant after the diversion of the STW effluent (Benson-Evans *et al.*, 1999). Apart from the changes in nutrient load from point sources, changes are thought to be related to land use change and subsequent increase in soil erosion and turbidity (Benson-Evans *et al.*, 1999). Bennion & Appleby (1999) suggest that inwash of sediments may have caused loss of habitat for epiphytic and benthic diatom taxa.

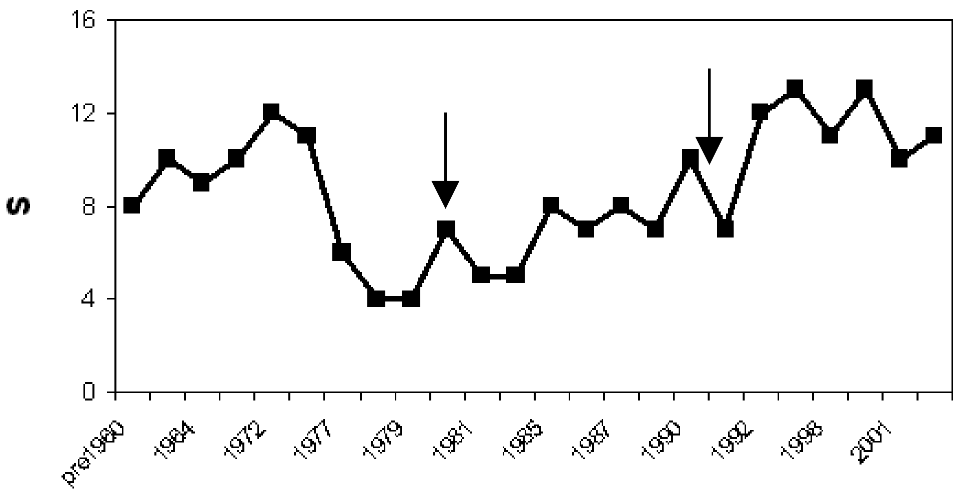

Figure 3.3 Aquatic plant species richness (S) for Llangorse Lake between 1960 and the present day, excluding *Lemna* and the non-native *Elodea* spp. and *Nymphoides peltata*. Only floating-leaved species grew in the lake during the late 1970s. Arrows indicate dates of STW diversion. Data based on Wade (1999). Note that survey intervals varied.

4METHODOLOGY

4.1Estimating the nutrient load to the lake by field survey

The nutrient load to the lake was estimated from nutrient concentrations and flows measured on the inflow streams. Nutrient concentrations were also measured in the outflow to provide an indication of lake water quality. The monitoring sites were chosen to include the main drainage channels into and out of the lake and with sampling points located as close to the lake as practically possible. Eight sampling sites were selected; the locations of these are shown in Table 4.1 and Figure 4.1.

Table 4.1 Locations of sampling points on the inflows and outflow of Llangorse Lake.

Site code	Site name	Location		Type
		Easting	Northing	
1	Afon Llynfi (outflow)	312565	227129	outflow
2	Lower Pendre Farm	313083	227050	inflow
3	Tynewydd Farm	313714	226799	inflow
4	Cathedine Fawr Farm	314137	226274	inflow
5	Lower Cathedine Farm	314107	225581	inflow
6	Afon Llynfi (inflow)	313749	225313	inflow
7	Neuadd Farm	313551	225407	inflow
8	National Trust Woodland	312821	226170	inflow

4.1.1Sampling regime and exceptions

Water and flow sampling was conducted at fortnightly intervals for one year, starting on 10/10/06. All sampling and flow gauging was conducted by Forest Enterprise research staff under sub-contract to CEH. On several occasions it was either impossible or unsafe to sample Sites 1 and 7, due to local flooding. The dates on which these sites were not sampled were 5/12/06, 19/12/06, 2/1/07 and 13/3/07.

4.1.2Hydraulic load to the lake

Digital outlines of the surface water subcatchments upstream of all sampling sites, apart from Site 8, were derived from a 50 m digital terrain model (DTM) and supplied by CEH Wallingford. At Site 8, the topography was too featureless for an upstream subcatchment to be defined.

Gauging boards were installed at each sampling location to enable stream depth to be measured on each visit. Where possible, the gauging boards were calibrated against rates of flow measured on 19/12/06, 13/2/06, 17/5/07, 7/6/07, 18/6/07 and 21/8/07. However, on some occasions and at some sites, flow measurement was impossible because the flows were too low or because there was extensive overbank flooding. This was especially true of Site 8, where flows were too small to be measured.

Figure 4.1 Aerial view of Llangorse Lake showing approximate locations of the sampling sites.

It should be noted, however, that the gauging board at Site 2 (close to the town of Llangorse) disappeared at an early stage of the project. So, flows at this site have been estimated from a regression equation relating measured flows at this site to those of the site that it was most closely correlated to, i.e. Site 6. The regression equation used was:

$$Q_2 = 0.3053 \times Q_6 - 0.0167 \ (r^2 = 0.97)$$

where Q is the rate of flow ($m^3 \ s^{-1}$) at Sites 2 and 6, respectively.

As the flushing rate of a lake is important in determining the ecological response to nutrient inputs, this was determined from the annual hydraulic load to the lake and the estimated lake volume of $3.6 \times 10^6 \ m^3$ (Turner *et al.*, 1981). The annual hydraulic load was determined as the sum of the measured inflows.

Rainfall data for the period 21/6/06 to 11/6/07 were made available to the project by Forest Research. The data comprised readings taken at 10-minute intervals by a tipping bucket rain gauge situated at Abergavenny (SO 311 178). There was a period of missing data between 19/7/06 and 4/10/06 and no data were available beyond 11/6/07 due to vandalism of the rain gauge and theft of its associated datalogger. For this reason, annual rainfall for this area was estimated over the 1-year period for which data were available rather than the 1-year period that corresponded to sample collection and flow monitoring in this project. This is likely to have underestimated the rainfall over the study period, which spanned a period of exceptionally heavy rainfall and severe flooding in late July 2007.

4.1.3Nutrient concentration in the lake inflows

Water chemistry samples were collected in duplicate at each site with a 500 ml capacity plastic measuring jug. The raw water samples were sub-sampled and filtered, where necessary, in the field immediately after collection to prevent deterioration. This was carried out as follows:

- 15 ml was transferred directly into a polypropylene sample tube for total phosphorus (TP) determinations
- 38 ml was filtered into a sample tube for total soluble phosphorus (TSP) and soluble reactive phosphorus (SRP) determinations, using a disposable cartridge filter (30 mm diameter, 1.2 µm pore-size, cellulose acetate filter in polypropylene housing; both Whatman® Puradisc FP30 and Sartorius Minisart filters were used) attached to a 60 ml capacity plastic syringe
- 12 ml was filtered, as above, into a third tube for nitrate (N) determinations

Each filter was initially 'rinsed' by passing 10 ml of sample water through it and discarding the filtrate prior to collecting the remainder in the sample tube. To reduce costs, only one filter cartridge was used at each site on most occasions, with care being taken to ensure that the filter was rinsed between samples. However, at times of high turbidity, the filter became clogged with small particles and a new filter had to be used for the second sample.

The samples were frozen on the day of collection and stored in a domestic freezer at approximately -18°C for up to 2 months before chemical analysis. The samples were defrosted immediately prior to being analysed for nutrient content.

4.1.3.1Phosphorus determinations

Tubes of filtered water (50 ml) were defrosted, sub-sampled and analysed for SRP and TSP, and the set of defrosted 15 ml tubes of unfiltered water were analysed for TP. SRP concentrations were determined following the method of Murphy and Reilly (1962), in which a filtered sample is reacted with acidic ammonium molybdate to form a yellow phospho-molybdate complex. This is then reduced with ascorbic acid to a more stable and more intensely-coloured blue complex. The reaction is catalysed by antimony, and the blue colour is formed in amounts proportional to the amount of SRP present. The optical absorbance of the sample solutions at a wavelength of 882 nm was directly measured against that obtained for known standard solutions of SRP using a Philips PU8670 spectrophotometer fitted with a 40mm flow-cell.

TP was determined using a sulphuric acid-potassium persulphate digestion on unfiltered samples to convert all forms of phosphorus to SRP. This was then measured in a similar way to that described above. The method used was as described for TP by Wetzel and Likens (2000), with an added acidification step (0.1 ml of 30% H_2SO_4 was added to the samples before addition of persulfate). TSP was determined in the same way as TP (but using a filtered sample).

The concentration of total particulate phosphorus (TPP) was calculated as the difference between TP and TSP concentrations.

4.1.3.2Nitrate determinations

Filtered water samples in the 15 ml tubes were defrosted and analysed for nitrate (NO_3-N). Samples were analysed on a SEAL AQ2 analyser (SEAL Analytical Limited, Burgess Hill, West Sussex, UK). Nitrate was determined by the sulphanilamide/NEDD (N-1-naphthylethyene diamine dihydrochloride) reaction which produces a reddish-purple dye. This was measured spectrophotometrically at 546 nm.

4.1.4Phosphorus concentrations in the sediments

Sediment samples were collected on 16/1/07 and 19/7/07. On each of these dates, duplicate samples were collected at each of two open water sites (Table 4.2; Figure 4.1) with a Jenkin surface-sediment sampler (Ohnstadt & Jones, 1982; Macan, 1970; Collins *et al*., 1973). Each sediment core was sectioned at 1 cm intervals to a sediment depth of 4 cm, at 2 cm intervals to a depth of 10 cm and at 5 cm intervals to a depth of 15 cm to provide a vertical profile of sediment material. The core 'slices' were frozen within 5 hours of collection and stored at about -18ºC.

Prior to analysis, the core slices were defrosted and their water content was determined by weighing before and after drying. Duplicate 50 mg subsamples of the dried material were then each mixed with 5 ml of distilled water and the resultant suspension was analysed for TP content following the methods described above for TP analysis.

Table 4.2 Locations of sampling points for sediments within Llangorse Lake

Site code	Site name	Location	
		Easting	Northing
20	Sediment 1	313886	226036
21	Sediment 2	312948	226628

4.2 Historical variations in nutrient concentrations in the inflow and outflow

4.2.1Inflow data provided by the Environment Agency

Variations in nutrient concentrations in the main inflow since 1996 were assessed from historical data provided by the Environment Agency (EA). As individual years may not be fully representative of the overall situation, average conditions over two three year periods, namely 1996-1999 (past) and 2004-2007 (present/recent), were compared. It should be noted that the EA sampling point for the inlet does not correspond exactly with the sampling point used in the present study.

Monthly average values for each period were calculated for NO_3-N, PO_4-P, NO_3-N:PO_4-P ratio, dissolved oxygen percent saturation (DO%), suspended sediments, and water temperature. The water chemistry was determined by the EA using their standard analytical methods. To take account of gaps in the data, monthly values were derived only where it was possible to calculate an average of at least two values from separate years.

4.2.2Outflow data provided by the Environment Agency

The comparative approach described above (Section 4.2.1) was also used for the outflow determinands. Here, the EA sampling point was about 100 m further downstream than that used in the present study. Monthly average values for each period were calculated for NO_3-N, NH_4-N, TN, PO_4-P, TP, and the TN:TP ratio. There were insufficient data to provide similar analyses of chlorophyll-a concentration in the outflow, so single period values over the periods 1996-1999 and 1996-2007, respectively, were calculated. Analytical methods for water chemistry are consistent with EA standard methodologies. Again, there were gaps in the data and monthly values represent averages of at least two values from separate years. The outflow data were used as a proxy for in-lake conditions. However, it should be noted that concentrations may have been altered in the stretch of river between the "true" lake outlet and the EA sample point.

5RESULTS

5.1Hydrology

The catchment and subcatchments of Llangorse Lake are shown in Figure 5.1, and their absolute and relative sizes are summarised in Table 5.1. These data correspond to the surface water catchment and subcatchments as defined from the surrounding topography. It should be noted that they do not reflect any sub-surface flow within the catchment that contributes to streamflow at each site.

The annual rainfall in this area was estimated to be about 1150 mm y^{-1}. The corresponding annual hydraulic loads to and from the lake are summarised in Table 5.1. The data show that the only significant inflows to the lake are at Sites 2 and 6 (Figure 5.2). These accounted for 18 per cent and 67 per cent of the estimated annual hydraulic load to the lake, respectively, over the study period. The remaining inflows were very small streams that tended to dry up completely during periods of very low rainfall (e.g. late March/early April 2007) and maintain low, and relatively constant, flows at other times of the year. This suggested that they were probably spring fed.

The estimated annual rainfall over the catchment (1150 mm y^{-1}) was combined with the long term average annual evapo-transpiration rate for the Llangorse area (600 mm y^{-1}; Hydrological Review, 2005) to give an expected hydrologically effective rainfall (HER) value for the catchment of about 550 mm $y^{-1.}$ This value is calculated as rainfall minus evapo-transpiration and is generally taken to reflect the measured downstream flow in catchments whose hydrology is dominated by surface runoff. However, this does not hold for catchments where the hydrology is significantly influenced by sub-surface flow. Measured values for HER were derived from the flow monitoring data for each inflow to Llangorse Lake by dividing the estimated annual flow in each stream by the area of the surface water catchment upstream of each gauging site. It was found that some of the streams had flows that were significantly higher than could be accounted for by rainfall alone (i.e. values > 600 mm), while others had much lower flows than would have been expected on the basis of rainfall (values < 600 mm) (Table 5.1). This gave a strong indication that streamflow across the catchment is strongly influenced by sub-surface flow.

Flows at Site 6 appeared to be particularly strongly affected by sub-surface flow. This inflow accounted for 67 per cent of the annual hydraulic load to the lake in 2006/2007, while draining only 36 per cent of the surface water catchment. This suggested that, here, more than half of the flow may have been generated by water travelling across the catchment as sub-surface flow and appearing in the drainage channel only when it reached the relatively impermeable layer of clay that lies just south of the lake (Figure 5.1). Whether that sub-surface flow is generated from within the area bounded by the surface water catchment, or whether it originates from a catchment that extends beyond this, is unclear. It is also possible that some of this additional water came from heavier rainfall across land at higher elevation (up to 600 masl) that forms part of this subcatchment. However, this could not be confirmed as it was not possible to obtain any current or historical rainfall records for this area during this study.

Rates of flow in the outflow were difficult to measure directly because of the frequent high flows that occurred in this area. However, the water balance shown in Table 5.1 suggests that the lake received about 25,015,700 m^3 of water from the inflow streams during the 1-year period of study. When combined with the estimated volume of the lake, 3.6 x 10^6 m^3 (Turner *et al*., 1981), this gives a revised water residence time for the lake during 2006/07 of about 55 days, which contrasts with the previously published value of 104 days (Turner *et al*., 1981). This updated value has been used throughout this report.

5.2Nutrient concentrations in inflowing streams

This section presents the results of analyses for concentrations of phosphorus (P) and nitrate (NO_3-N) in the inflow streams of Llangorse Lake. Nutrient concentrations in the outflowing Afon Llynfi are included in the figures for comparison, but are described later in the text (Section 5.5). In the interests of clarity, results from the outflow and the two streams that contributed most of the hydraulic load (Sites 2 and 6, which represented about 85 per cent of the total flow) are presented separately from the other results. It should be kept in mind that, although patterns in concentrations in these other five streams are interesting, their lower flows will result in very low nutrient loads to the lake from these sources in comparison with the two dominant streams.

5.2.1Phosphorus concentrations

Phosphorus concentrations varied in streams across the catchment and throughout the study period. In general, the highest concentrations of SRP, TSP, and TP were found at Site 2 and the lowest at Site 4. Figure 5.3 shows values of SRP, SUP and TPP, averaged across all sampling dates, for each site. Overall values for SRP:TP ratio at each site ranged from 0.52 at Site 4 to 0.82 at Site 3, while the overall average was 0.66. In a predominantly surface water fed stream, such a high value would usually be taken to indicate quite high levels of pollution from animal waste or sewage effluent. However, this may not be the case for a catchment where water movement is dominated by sub-surface flow because much of the TPP may have been filtered out of the drainage water as it travelled through the soils, increasing the SRP:TP ratio. That said, values as high as 0.77 and 0.82, as determined for Sites 2 and 3, respectively, are unlikely to occur unless there is some contamination from such sources.

Table 5.1 Area of surface water subcatchment upstream of each sampling site and the annual hydraulic load to Llangorse Lake accounted for at each site. ‘Very low’ indicates flows too low to be measured accurately.

Site	Subcatchment area		Estimated annual hydraulic load		Estimated hydrologically effective rainfall (mm)
	km^2	%	m^3	% of total	
2 (Nant Cwy)	5.81	25.7	4,391,605	18	760
3 (Hoel Ddu)	1.39	6.16	2,195,064	9	1580
4 (Cwm)	0.71	3.14	701,604	3	990
5	0.15	0.65	Very low	0	0
6 (Afon Llynfi)	8.07	35.74	16,087,887	67	1990
7 (Cathedine)	0.54	2.38	639,562	3	1190
8	Topography too flat		Very low	0	0
Ungauged area	5.93	26.23	Unknown	0	0
Total	22.59	100	24,015,722	100	1060

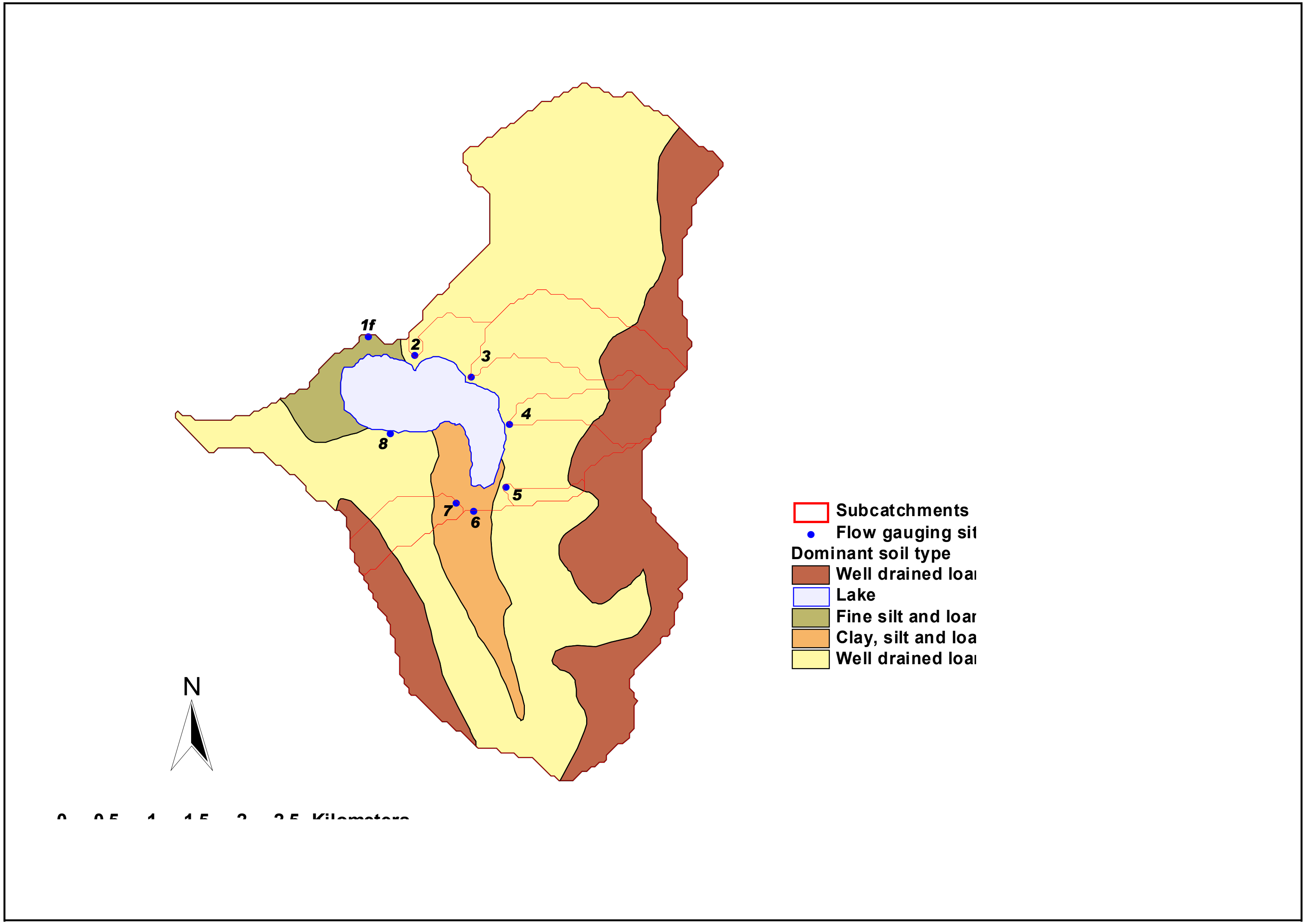

Figure 5.1 Catchment of Llangorse Lake showing soil types, subcatchment outlines and location of flow gauges

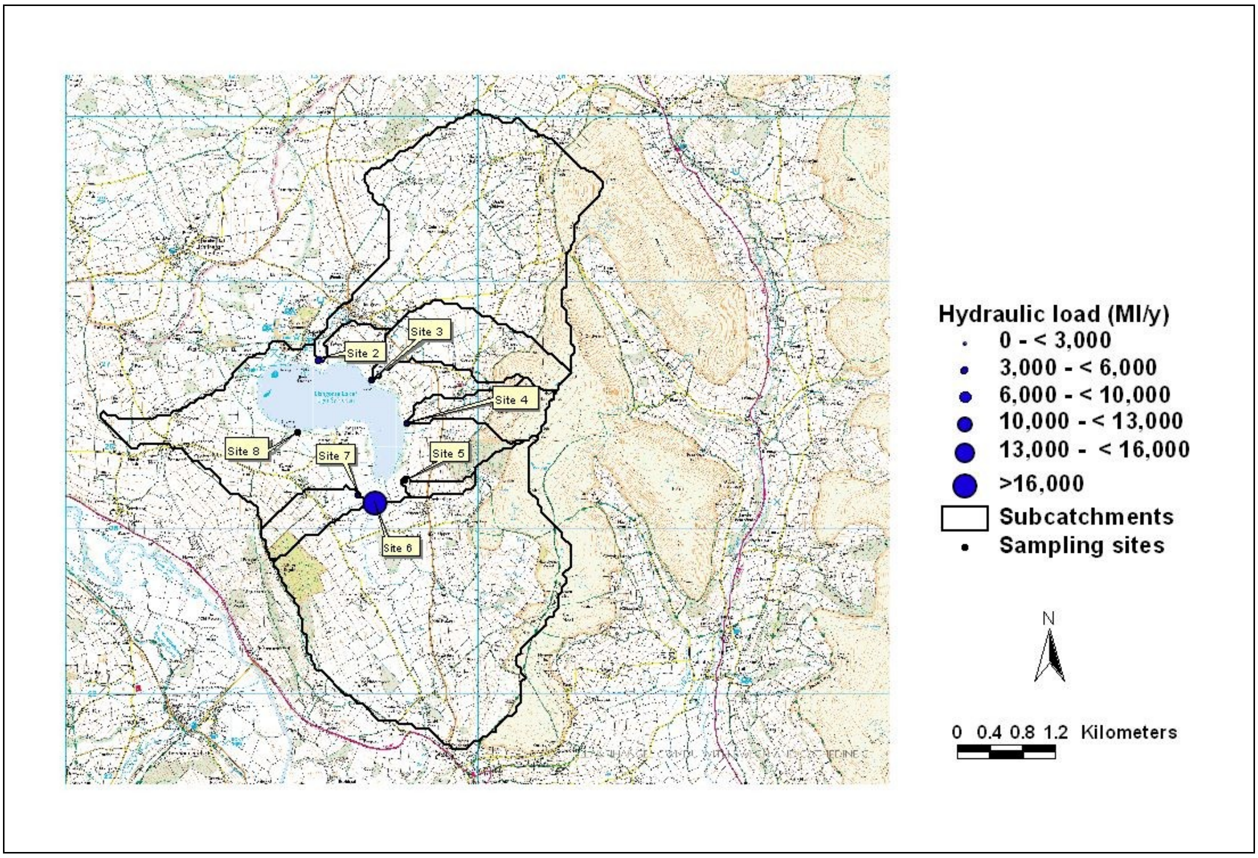

Figure 5.2 Hydraulic load from input streams to Llangorse Lake showing the relative importance of each input.

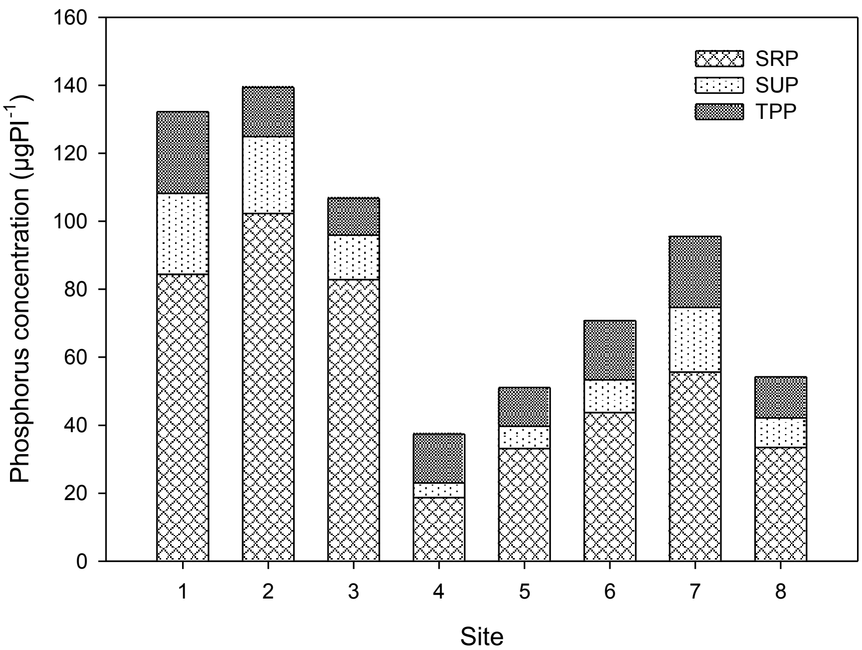

Figure 5.3 Average concentrations of soluble reactive (SRP), soluble unreactive (SUP), and total particulate (TPP) fractions of phosphorus in the outflow (Site 1) and inflow streams of Llangorse Lake. Values are averages of fortnightly samples taken between 10/10/06 to 25/9/07. The total height of each stacked bar represents the average concentration of total phosphorus (TP) at each site. See the text and Table 4.1 for locations of sampling sites.

5.2.1.1 Soluble reactive phosphorus (SRP)

In-stream SRP concentrations are presented in Figures 5.4 and 5.5. Concentrations of SRP varied between 8.3 µg P l^{-1} at Site 4 on 27/2/07 and 500 µg P l^{-1} at Site 2 on 31/7/07. The latter very high value for SRP was more than double the next highest value (223 µg P l^{-1} at Site 3 on 5/12/06). It should be noted that the end of July 2007 was the height of the period of extensive flooding throughout England and Wales. A discussion of why this particularly wet period may have resulted in such high concentrations of SRP at Site 2 is included in Section 6.

Apart from the single very high concentration recorded at Site 2, the pattern of change over time was similar across all of the inflow streams (Sites 2-8). So, the relative order of stream SRP concentrations did not change to any great extent over time (for example, the concentration of SRP at Site 3 was always higher than at Site 4). The highest concentrations were observed in early December 2006 and during the summer of 2007.

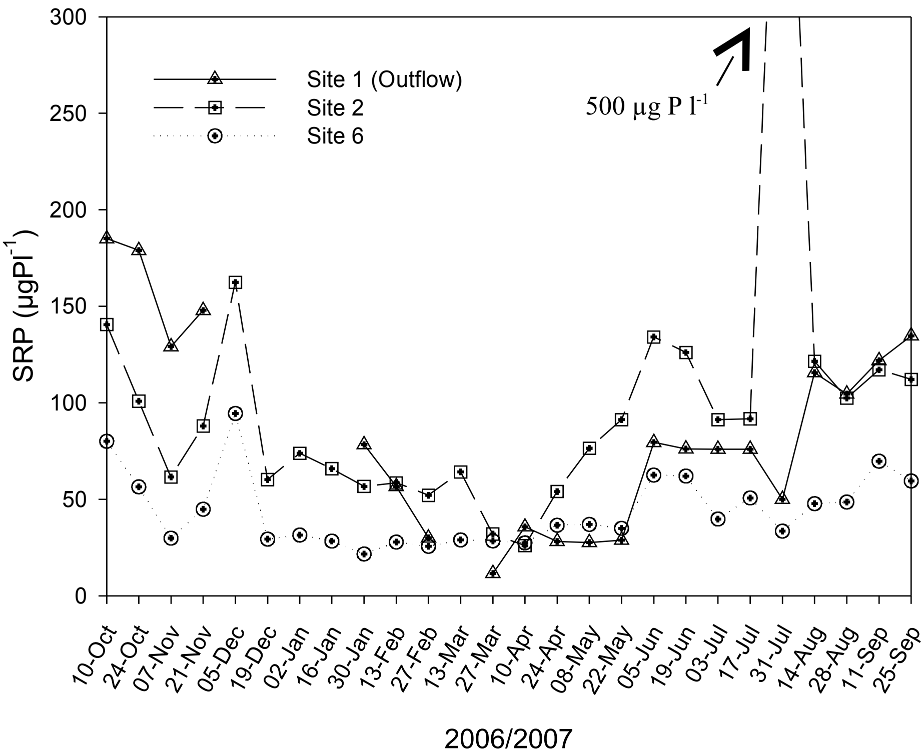

Figure 5.4 Concentrations of soluble reactive phosphorus (SRP) in the main inflow streams to Llangorse Lake (Sites 2 and 6) and in the lake outflow (Site 1). See the text and Table 4.1 for locations of sampling sites.

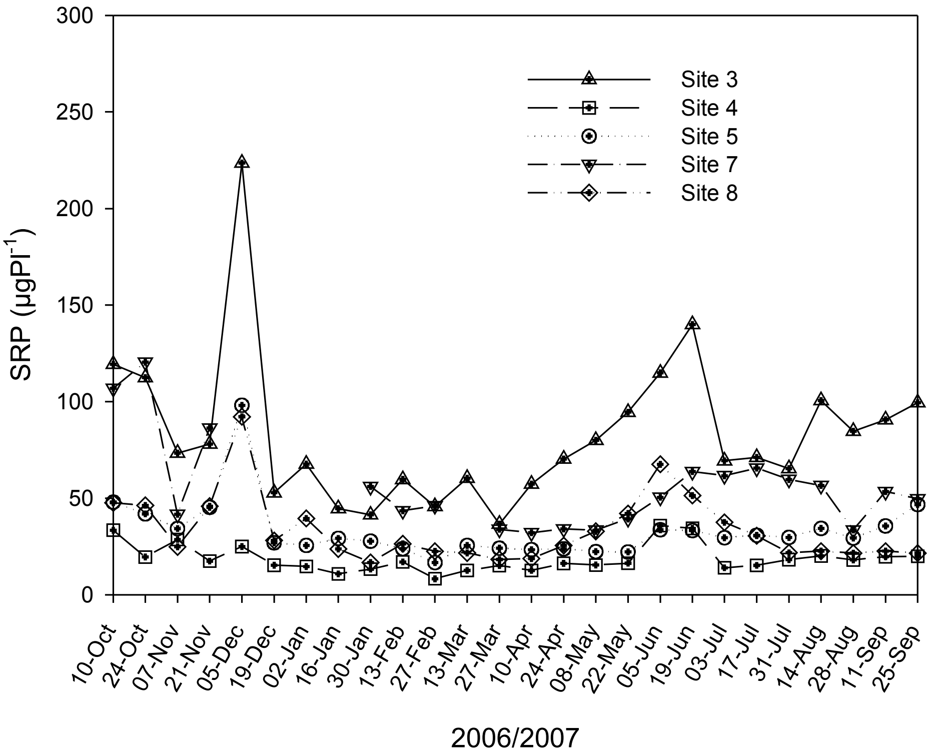

Figure 5.5 Concentrations of soluble reactive phosphorus (SRP) in the inflow streams to Llangorse Lake at Sites 3-5, 7 and 8. See the text and Table 4.1 for locations of sampling sites.

5.2.1.2Total particulate phosphorus (TPP)

TPP results are presented in Figures 5.6 and 5.7. Concentrations of TPP were generally lower than those of SRP and were sometimes undetectable. The highest concentrations of TPP were found in a sample from Site 2 (106 µg P l^{-1} on 24/11/2007). Periods of low flow corresponded to very low or undetectable concentrations of TPP across all measured sites (e.g. 7/11/2006 and 10/4/2007) and, conversely, periods of high flow were related to elevated concentrations of TPP across all or most sites (e.g. 5/11/2006 and 24/4/2007). This is consistent with the transport of phosphorus-rich stream sediment or eroded soil that requires sufficiently high flow to keep the material suspended. It is important to note that, even when elevated during periods of high stream flow, concentrations of TPP rarely exceeded those of SRP.

5.2.1.3Total phosphorus (TP)

TP results are presented in Figures 5.8 and 5.9. Variation in TP concentrations, as might be expected from the sum of all phosphorus fractions, roughly followed those of concentrations of SRP, which has already been identified as the dominant phosphorus component (Section 5.2.1.1). Across the study, TP varied between 19 µg l^{-1} (at Site 6 – the Afon Llynfi inflow – on 7/11/2006) and 500 µg l^{-1} (at Site 2 on 31/7/2007). The sample with the highest concentration of TP had the same measured amount of SRP, indicating that the P content of the sample was entirely in the soluble reactive form and suggesting that it was due to contamination from sewage effluent or animal waste. As was the case for SRP, this concentration of TP was unusual within the dataset, as the next highest measurement was much lower (272 µg l^{-1} at Site 3, on 5/12/2006).

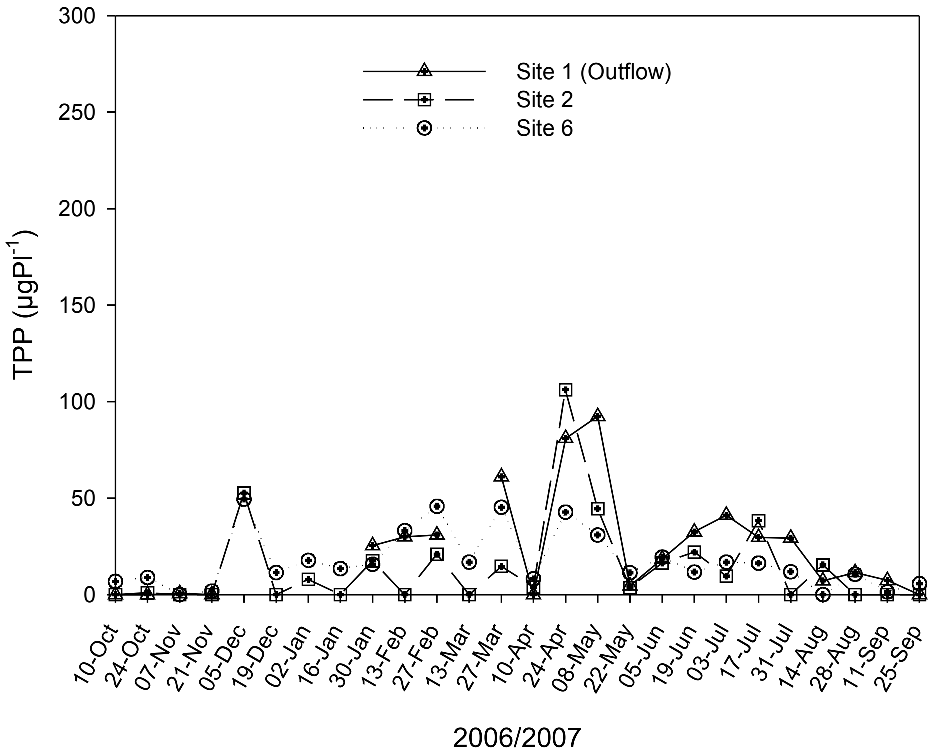

Figure 5.6 Concentrations of total particulate phosphorus (TPP) in the main inflow streams to Llangorse Lake (Sites 2 and 6) and in the lake outflow (Site 1). See the text and Table 4.1 for locations of sampling sites.

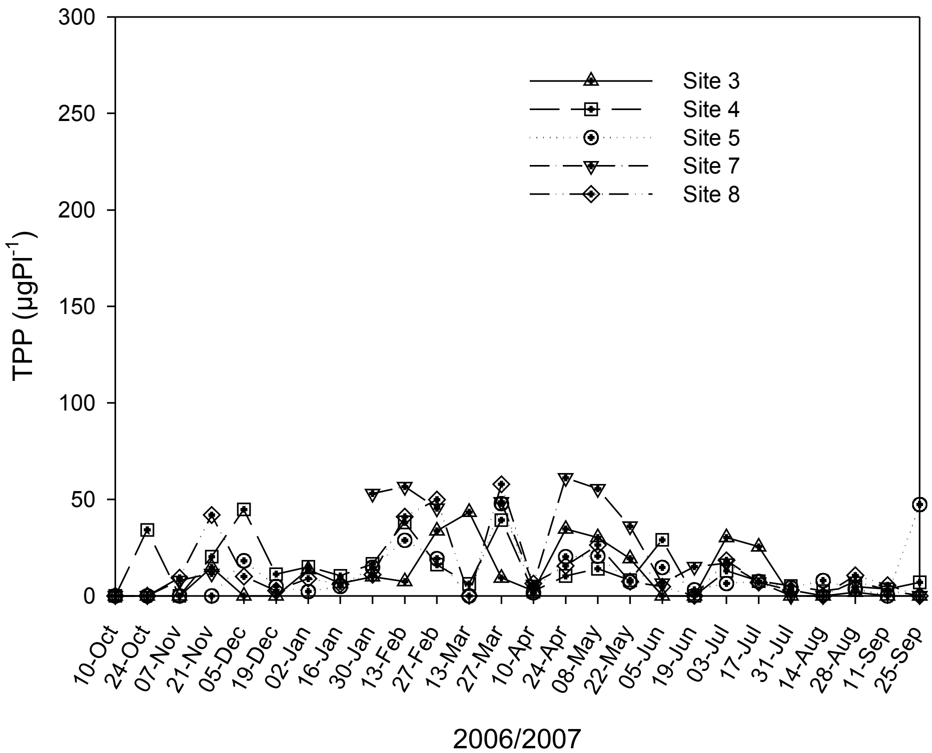

Figure 5.7 Concentrations of total particulate phosphorus (TPP) in the inflow streams to Llangorse Lake at Sites 3-5, 7 and 8. See the text and Table 4.1 for locations of sampling sites.

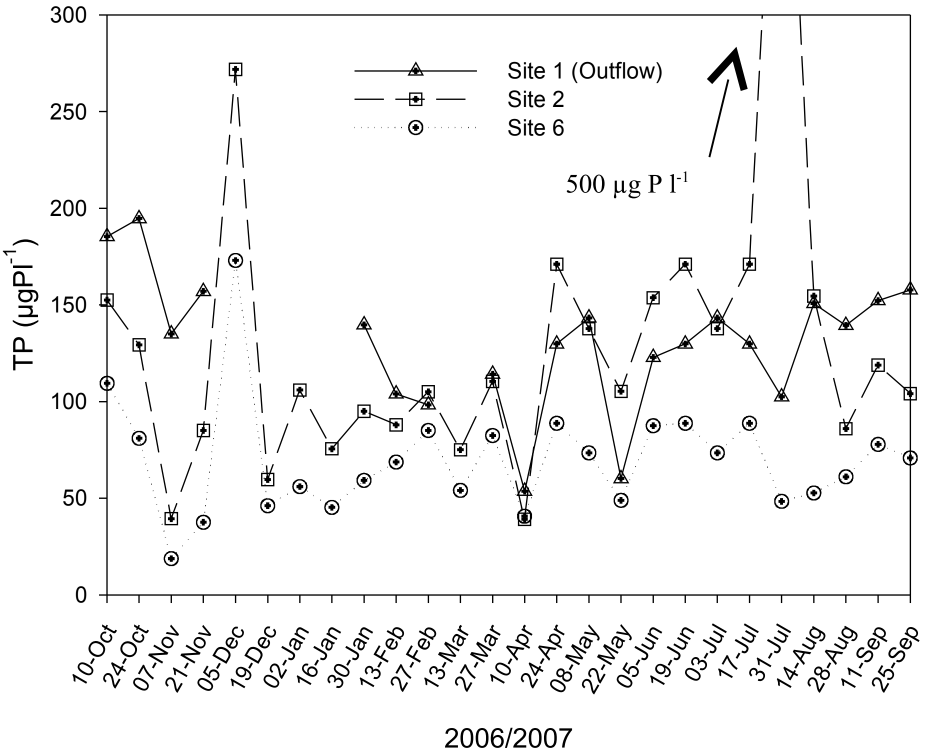

Figure 5.8 Concentrations of total phosphorus (TP) in the main inflow streams to Llangorse Lake (Sites 2 and 6) and in the lake outflow (Site 1). See the text and Table 4.1 for locations of sampling sites.

5.2.2Nitrate concentrations

Concentrations of nitrate (NO_3-N) are presented in Figures 5.10 and 5.11. Averaged across the study period, the highest concentrations were measured at Site 2 and the lowest at Site 7. The highest observed concentration in the inflow streams was 8.5 mg NO_3-N l^{-1}, measured at Site 3 on 30/1/2007, and the lowest was 0.9 mg NO_3-N l^{-1}, measured at Site 7 on 19/6/2007. Overall, there was less variation among NO_3-N concentrations in the inflow streams than was observed for the various P fractions. Three periods when nitrate concentrations were elevated across most of the sites were noted. These were 30/1/07 to 27/2/07, 24/4/07 to 19/6/07, and 31/7/07 to 11/9/07.

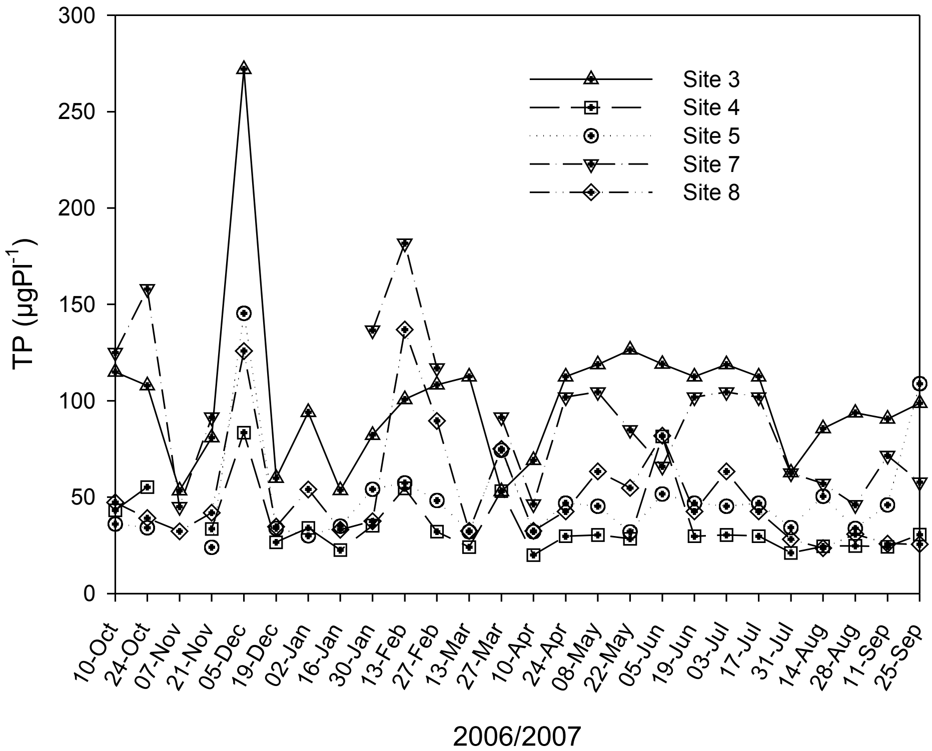

Figure 5.9 Concentrations of total phosphorus (TP) in the inflow streams to Llangorse Lake at Sites 3-5, 7 and 8. See the text and Table 4.1 for locations of sampling sites.

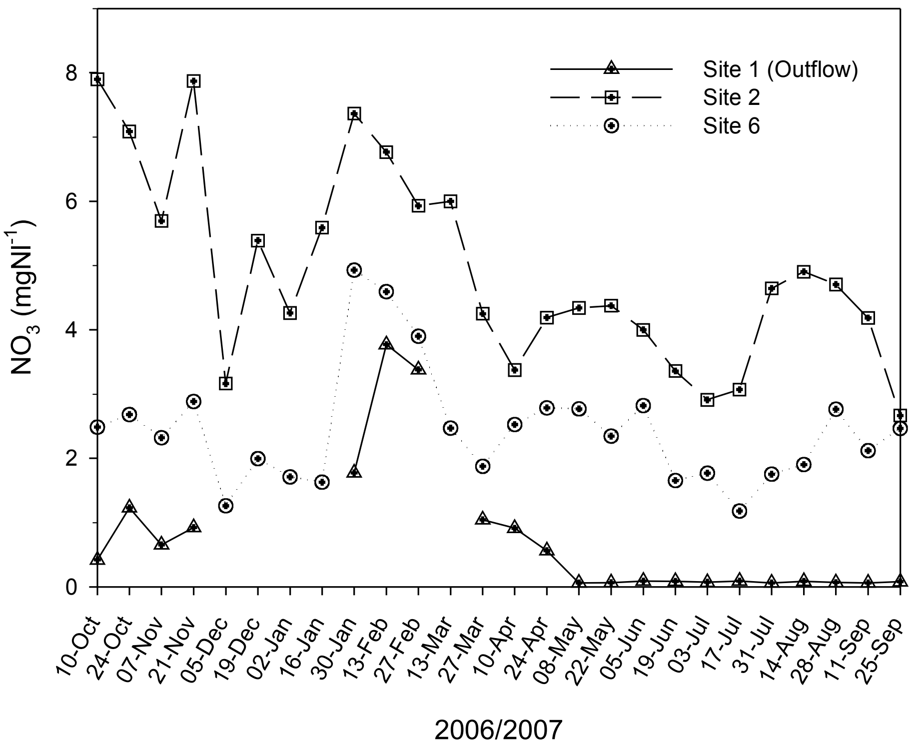

Figure 5.10 Concentrations of nitrate (NO_3-N) in the main inflow streams to Llangorse Lake (Sites 2 and 6) and in the lake outflow (Site 1). See the text and Table 4.1 for locations of sampling sites.

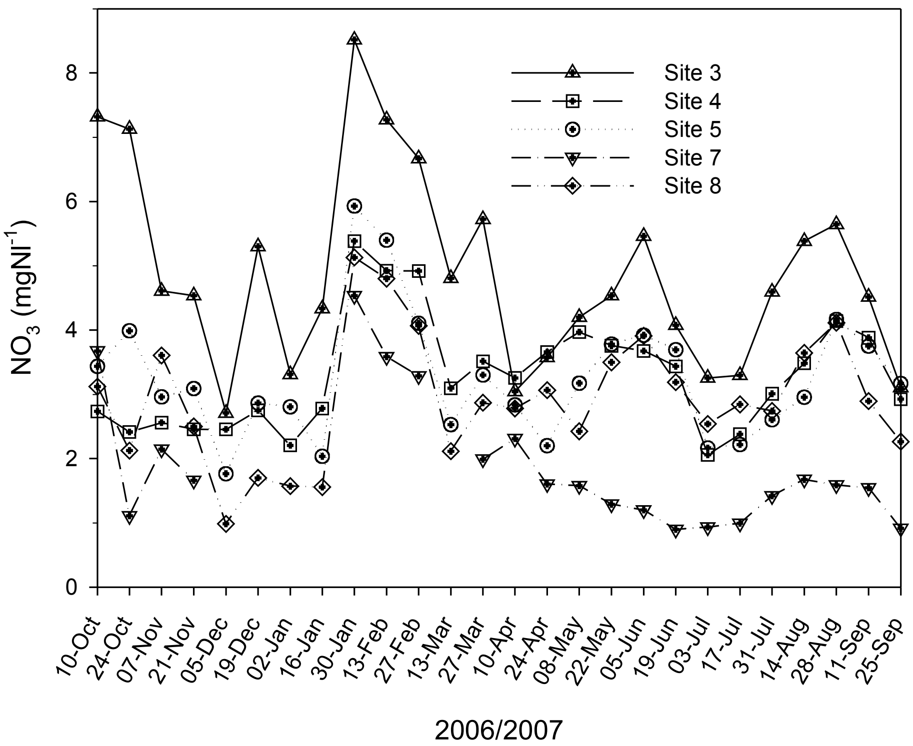

Figure 5.11 Concentrations of nitrate (NO_3-N) in the inflow streams to Llangorse Lake at Sites 3-5, 7 and 8. See the text and Table 4.1 for locations of sampling sites

5.3Nutrient loads

Fortnightly nutrients loads to the lake from each sampled inflow were determined by multiplying measured nutrient concentration by the corresponding flow value. These values were then averaged over the year and multiplied by 365 to give an estimated annual load. The results of these calculations are shown in Table 5.2.

Table 5.2 Annual loads of SRP, TP and NO_3-N at each of the sampling sites.

Site	SRP load		TP load		NO_3-N load	
	kg y^{-1}	%	kg y^{-1}	%	kg y^{-1}	%
Site 2	477	34%	616	29%	22,326	30%
Site 3	187	13%	230	11%	9,849	13%
Site 4	14	1%	26	1%	2,277	3%
Site 6	711	50%	1,166	56%	38,438	52%
Site 7	35	2%	60	3%	1,148	2%
Total	1,423	100%	2,098	100%	74,038	100%

The data showed that, in terms of annual load, most of the nutrients entering the lake were coming from subcatchments 2 (29 - 30%), 3 (11 - 13%) and 6 (50 - 56%), with the contribution from subcatchments 4 and 7 being very low (Table 5.2). The location and relative contribution of each of these sources is illustrated in a spatial context in Figures 5.12 – 5.14.

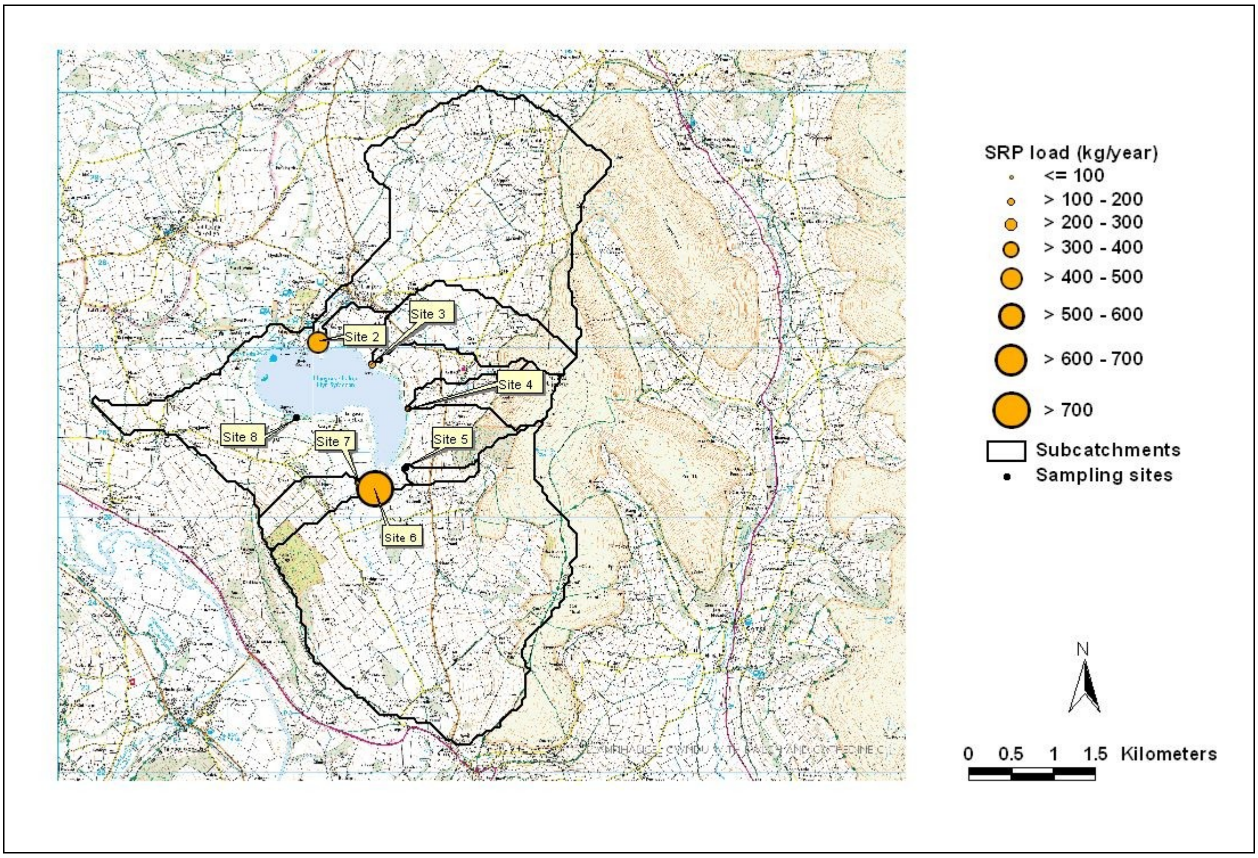

Figure 5.12 SRP load from input streams to Llangorse Lake showing the relative importance of each input.

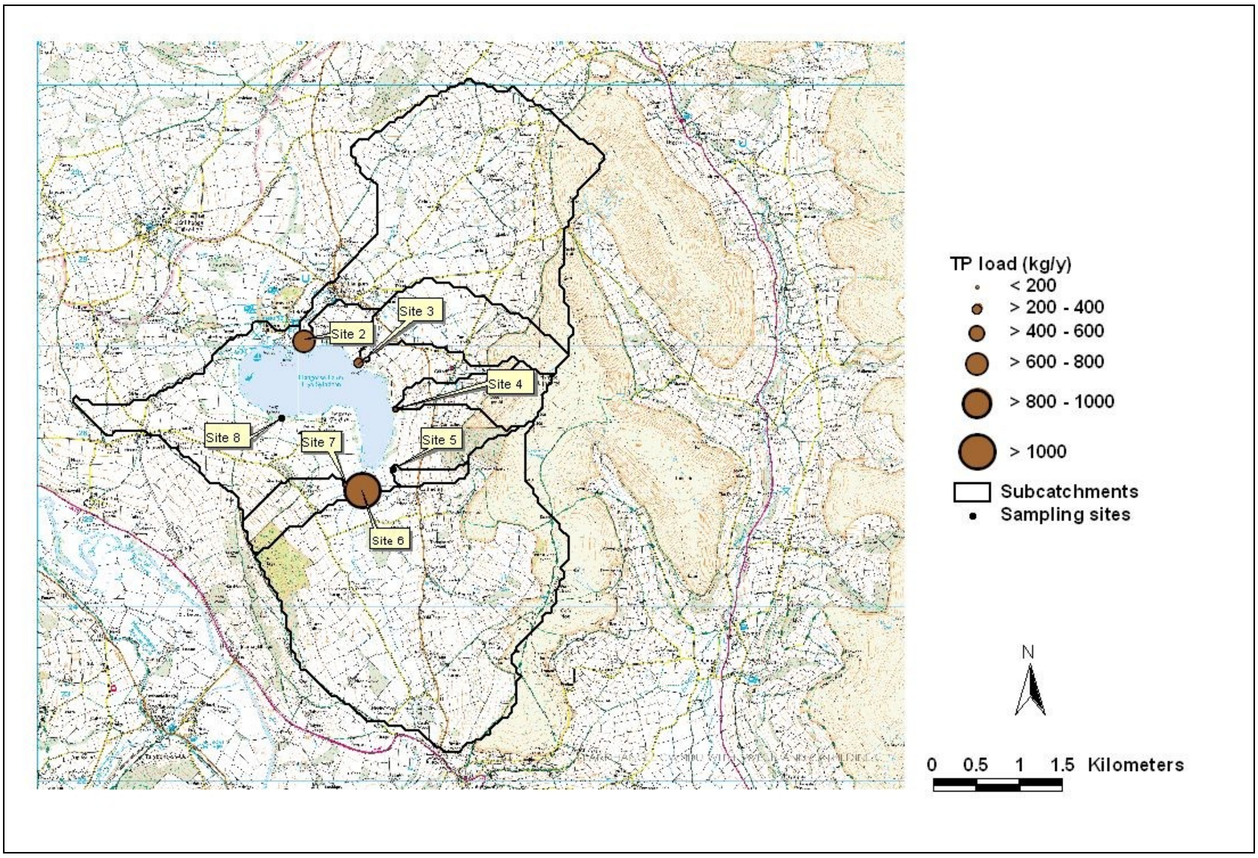

Figure 5.13 TP load from input streams to Llangorse Lake showing the relative importance of each input.

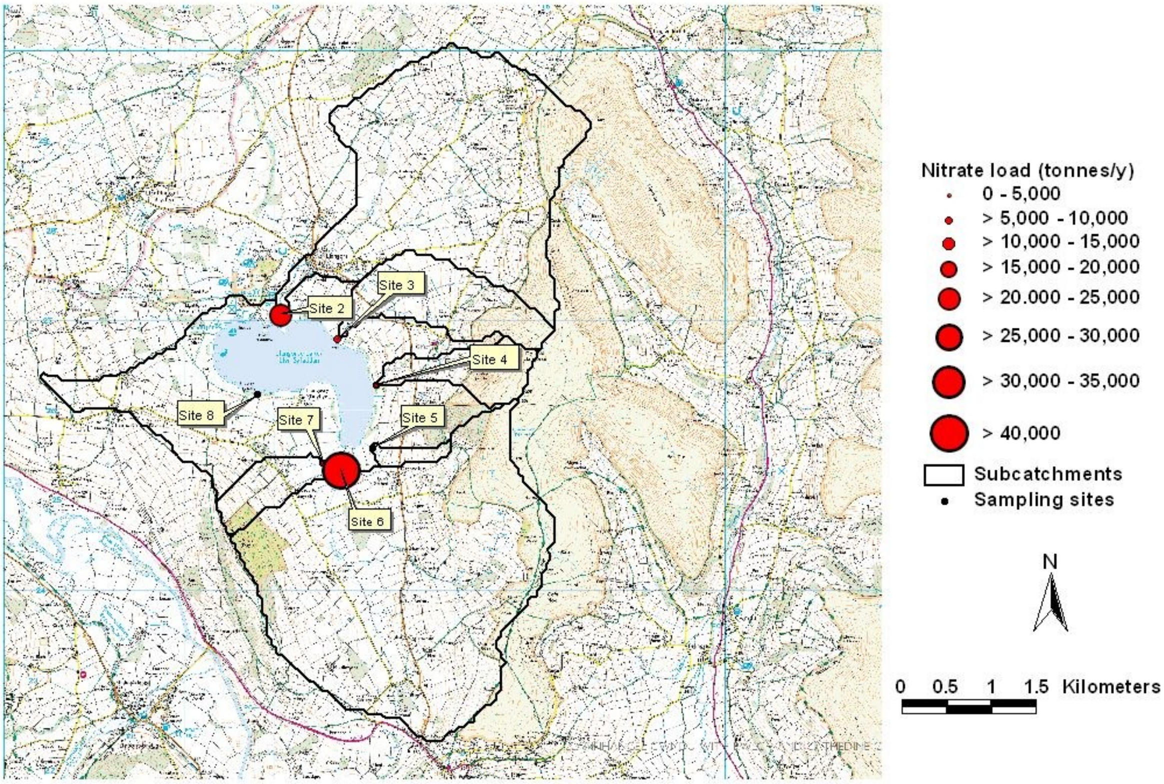

Figure 5.14 Nitrate-N load from input streams to Llangorse Lake showing the relative importance of each input.

In total, the annual load of N and P to the lake from the catchment was 1.4 tonnes of SRP, 2.1 tonnes of TP, and 74 tonnes of NO_3-N. These values equate to aerial loadings for the lake of 1 g P m^{-2} of SRP, 1.5 g P m^{-2} of TP, 53 g N m^{-2} of NO_3-N.

A single, average, annual export coefficient, expressed as kg ha^{-1}, was determined for the loss of SRP, TP and NO_3-N from each subcatchment by dividing the annual export of each nutrient fraction by the area of the upstream surface water catchment (Table 5.3). At Sites 2, 4 and 6, these values were much higher than would have been expected for almost any type of agricultural land use. For example, export coefficients for N and P for the Slapton Ley catchment, calculated from data given by Burt *et al*. (1996), are only about 0.3 kg P ha^{-1} y^{-1} and 12 kg N ha^{-1} y^{-1} for permanent grassland, and 0.6 kg P y^{-1} and 15 kg N ha^{-1} y^{-1} for arable land. The elevated nutrient export rates calculated from the Llangorse Lake data suggests either significant point source impacts on the chemistry of the streams, excessive application of fertiliser to the land or a nutrient load that originates from a much wider area than is accounted for by the surface water catchment alone. The reality is probably a combination of all of these.

Figures 5.15 to 5.18 show seasonal variation in nutrient loads to the lake from the feeder streams. In general, most of the P load enters the lake from subcatchment 6 throughout the year, with lesser amounts from subcatchments 2 and 3. However, the P load from subcatchment 2 increased suddenly during a period of very heavy rainfall in late July, significantly exceeding that from any of the other subcatchments on 31/7/07. The sudden increase in P load was, primarily, due to an increase in SRP load. This appears to have been due to a pollution event from a point source rich in dissolved P and may reflect storm overflow from the sewage works at Llangorse during a period of exceptionally heavy rainfall. However, this was not a significant event in terms of the total annual P load to the lake and, given its close proximity to the outflow and the very heavy rainfall over that period, was probably washed through the lake and into the outflow very quickly. The corresponding P concentration data from the outflow showed a significant reduction in concentration on this date, probably due to dilution as a result of the short term increase in lake flushing rate.

Table 5.3 Average nutrient export coefficients per subcatchment

Site	Nutrient export coefficients (kg $ha^{-1}y^{-1}$)		
	SRP	TP	NO_3-N
Site 2	0.82	1.06	38.45
Site 3	1.34	1.65	70.79
Site 4	0.19	0.37	32.13
Site 6	0.88	1.44	47.61
Site 7	0.65	1.10	21.31

In terms of seasonal variations in NO_3-N loads from each subcatchment, the main contribution of nitrate to the lake came from Sites 6, 2 and 3, in that order (Figure 5.17). There is little evidence of the pollution event recorded for P on 31/7/07 being reflected in the nitrate loading data for subcatchment 2. In general, the increases and decreases in NO_3-N load from each subcatchment followed similar temporal patterns, apart from subcatchment 3 where occasional increases in NO_3-N load occurred at this site alone (7/11/06, 2/1/07 and 17/7/07) (Figure 5.17). These may indicate minor, local, point source pollution events. At the whole catchment scale, NO_3-N loads were between 100 and 200 kg d^{-1}, except during periods of very low flows in March/April and August/September 2007 (Figure 5.18).

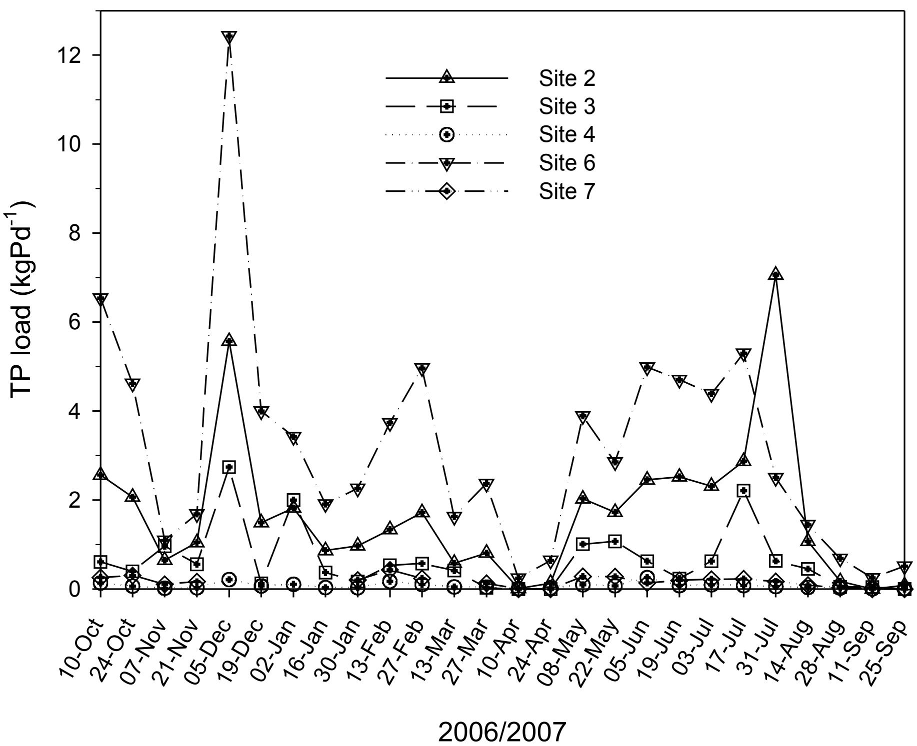

Figure 5.15 Loads of total phosphorus (TP) from the inflow streams to Llangorse Lake.

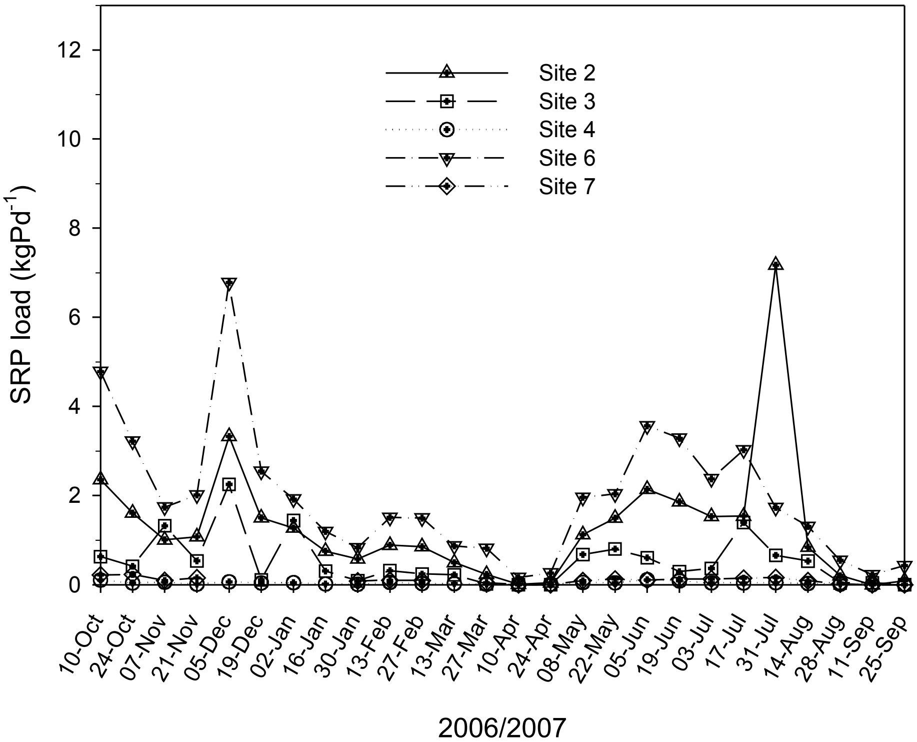

Figure 5.16 Loads of soluble reactive phosphorus (SRP) from the inflow streams to Llangorse Lake.

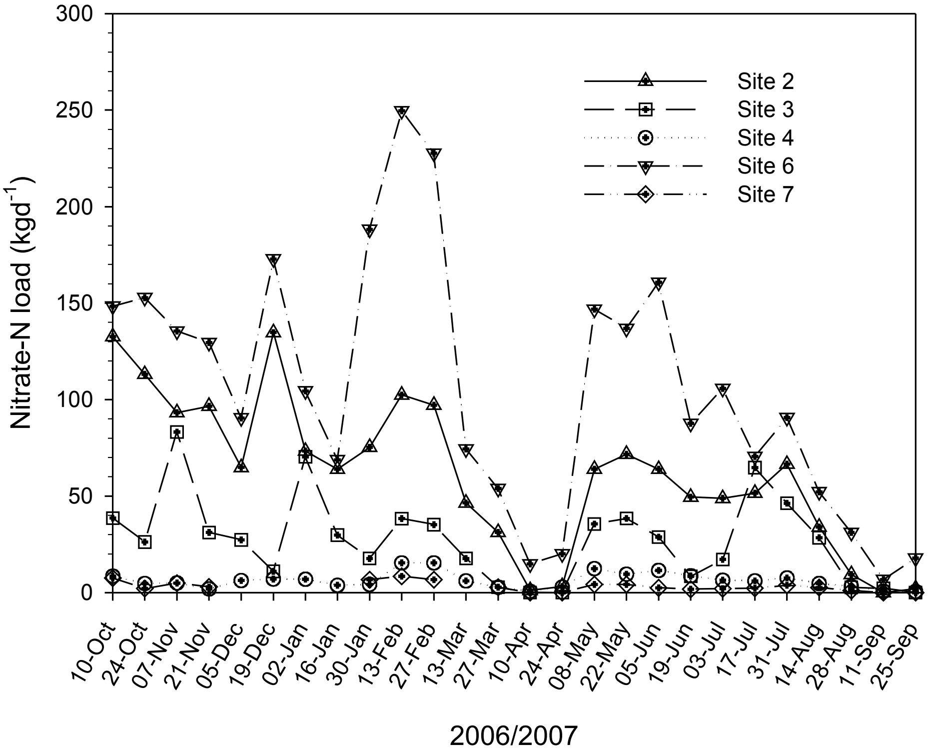

Figure 5.17 Loads of nitrogen (as nitrate) from the inflow streams to Llangorse Lake.

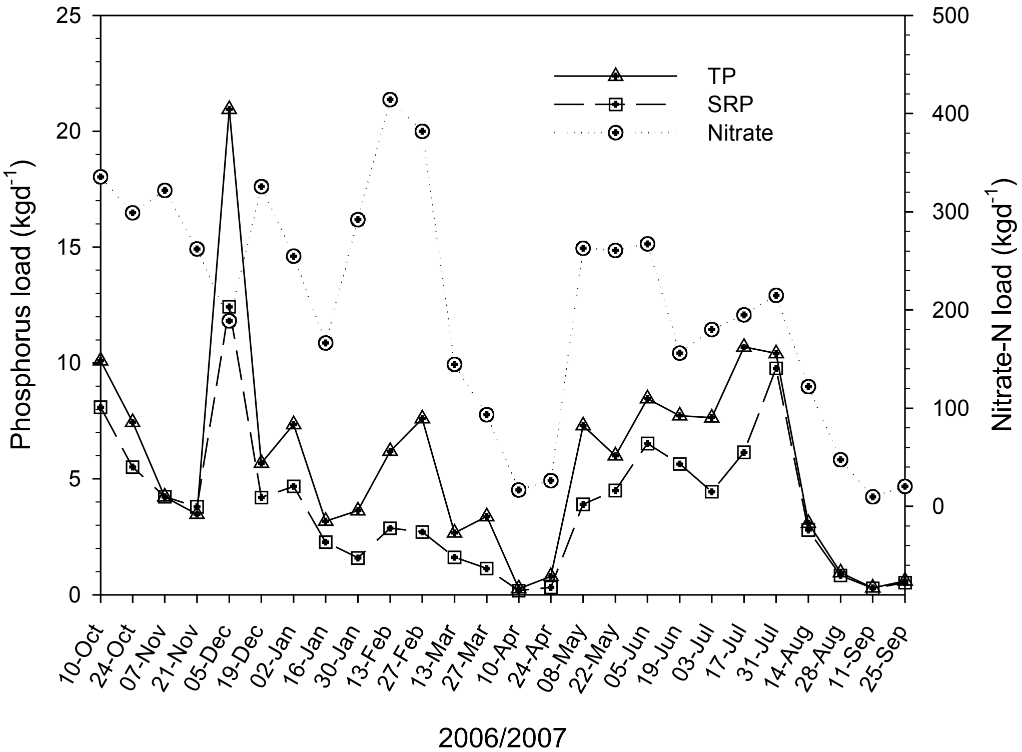

Figure 5.18 Total loads of phosphorus (as SRP and TP) and nitrate-N from all measured inflows to Llangorse Lake.

5.4Nutrients in sediments

Sediment phosphorus content was measured to give an estimate of the potential importance of internal loading (nutrient release from the sediment) to the overlying water. This is an important factor in determining the length of the recovery process once catchment sources have been reduced. In this study, investigation of the potential for nutrient recycling from the sediment was minimal due to resource constraints.

Little seasonal variation was observed in the sediment TP profiles of the two sampled sites (Figure 5.19). TP was observed to peak at around 3 cm depth at all sites, except Site 2 in winter. In general, TP concentrations decreased with depth at depths below 3 cm. This is probably a result of P release from redox sensitive Fe-P complexes in deeper anoxic sediments being capped by shallower aerobic sediments (Farmer *et al.,* 1994). The observed peak at 3 cm probably represents vertical migration of P from deeper sediments to shallower sediments where it is bound within Fe complexes under aerobic conditions. It, therefore, appears that the mixed/aerobic upper layer of sediment in Llangorse Lake is about 3 cm deep. The absence of this peak at Site 2 in winter suggests local disturbance of this upper layer whereby the upper gradient is “reset” by some form of mixing. The elevated surface concentrations at Site 2 in winter may have resulted from the re-settling from the water column of P-rich sediment under aerobic conditions following a mixing event. Site 2 is in a much more exposed part of the lake than Site 1 and is probably far more prone to wind-induced mixing.

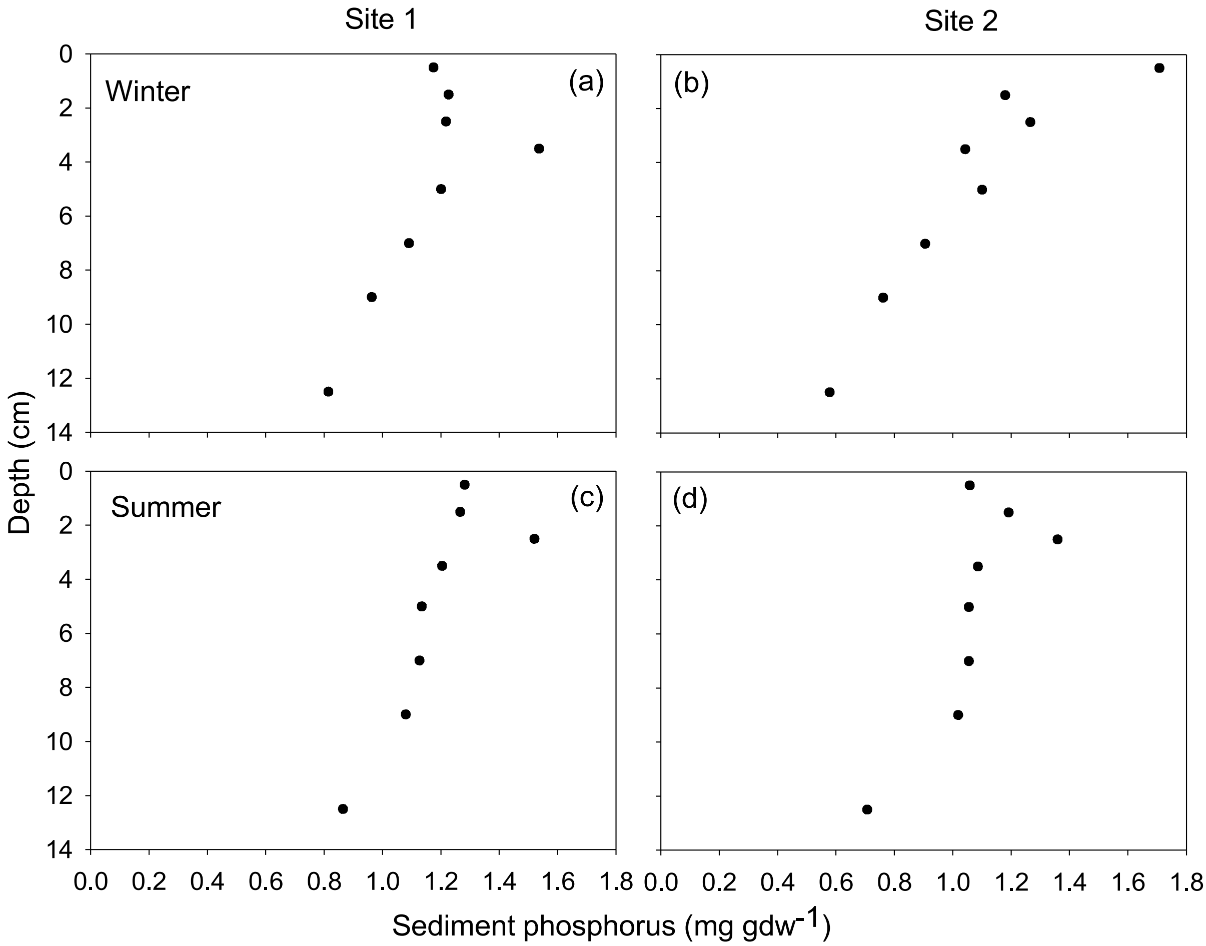

Figure 5.19 Concentrations of TP in the sediments of Llangorse Lake, expressed as mg P per gram dry weight of sediment. Values are averages of two replicate cores, at each of two sites (see Table 4.2 for locations); samples were collected on 16/1/2007 (Winter) and 19/7/2007 (Summer).

The sediment TP concentrations in Llangorse Lake are modest by comparison with other lakes (Figure 5.20). Sas (1989) classified the sediment TP concentration in the upper 0-15 cm of lake sediments in relation to the estimated recovery time following reduction of external P loading. At concentrations of less than 1 mg TP g^{-1}dw, internal loading is expected to be negligible with moderate summer sediment-P release events. At concentrations between 1 mg TP g^{-1}dw and 2.5 mg TP g^{-1}dw, net annual sediment-P release will be high, initially, with recovery expected within a 5 year period; a high summer release event would be expected to occur that will be affected by pH, dissolved oxygen and microbial activity. At concentrations in excess of 2.5 mg TP g^{-1}dw, net annual sediment-P release will occur for more than 5 years; in this situation, sediment-P release is expected all year round and will be greatly influenced by pH, dissolved oxygen and microbial activity. At present, Llangorse Lake appears to be close to the boundary of the first and second classification. However, it should be noted that these estimated recovery times only apply once the external loading has been reduced enough to promote this level of recovery.

It is interesting to note that, if the results given above are extrapolated, the top 3 cm of sediment across the entire lake area contains more than 12 tonnes of TP. In contrast, the equivalent figure for the TP content of the whole lake when the concentration is its average level of about 130 µg l^{-1} (see Section 5.5) is only about 0.5 tonnes.

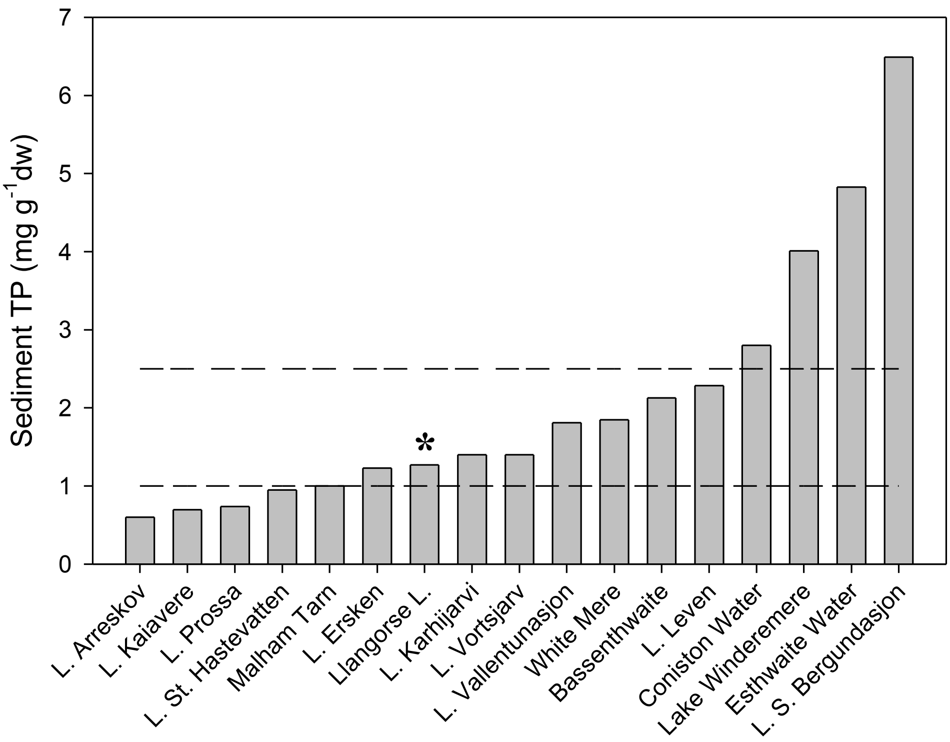

Figure 5.20 Comparison of TP concentrations in the surface sediments of a range of lakes. The value used for Llangorse Lake (marked with a *) is an average of all values recorded in this study from sediment depths of 0 - 3.5 cm. Thresholds for different recovery patterns are shown as dashed horizontal lines (see text for details).

5.5Nutrient concentrations in the lake

Although no samples were collected from the lake itself, nutrient concentrations in the Afon Llynfi just downstream of the lake outflow were monitored during the project. These have been taken to represent nutrient concentrations in the lake itself for the purposes of this project.

The data show that NO_3-N concentrations in the lake increased from October 2006 to February 2007, reaching a peak of 3.77 mg l^{-1} on 13/2/07 (Figure 5.21). Then, NO_3-N concentrations fell steadily from 13/2/07 to 8/5/07. After this, concentrations were very low (< 0.1 mg N l^{-1}) for the rest of the monitoring period.

In contrast, TP concentrations in the outflow remained relatively constant throughout the study period, with most values being between 100 and 150 µg l^{-1} (Figure 5.21) and the average concentration over the study period being 130 µg l^{-1}. However, the P fractions within these values varied. SRP concentrations tended to fall steadily from October 2006 to March 2007 and then build up again over the period April to September 2007. In contrast, TPP tended to increase throughout the spring, reaching a maximum of 116 µg l^{-1} on 8/5/07 (Figure 5.22). It then declined suddenly in late May before increasing to a secondary and much smaller peak of 54 µg l^{-1} on 3/7/07. This was followed by a steady decline to 23 µg l^{-1} by the end of September. It should be noted, however, that the values recorded on 10/4/07 and 24/4/07 may not reflect the lake water quality very well. This is because they represent a period when rates of flow in the inflows were especially low following 3-4 weeks of almost no rainfall, so there was likely to be little or no flow from the lake into the Afon Llynfi at that time.

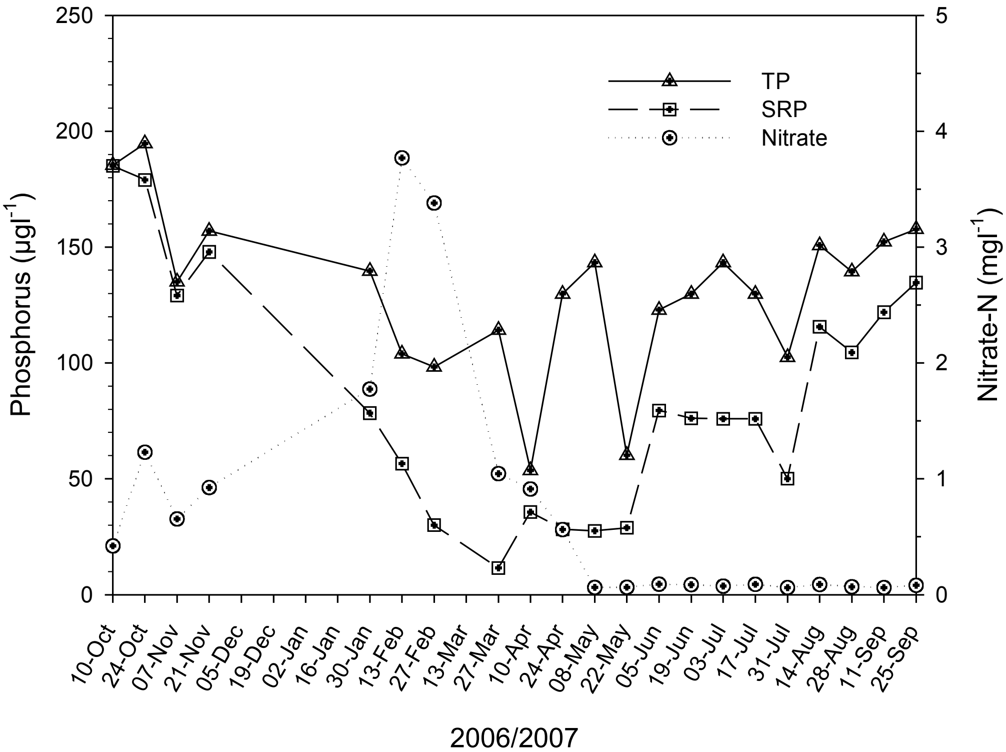

Figure 5.21 Concentrations of nitrate, soluble reactive (SRP) and total phosphorus (TP) in the outflow of Llangorse Lake. SRP and nitrate are the nutrient fractions that are most readily available to support algal growth.

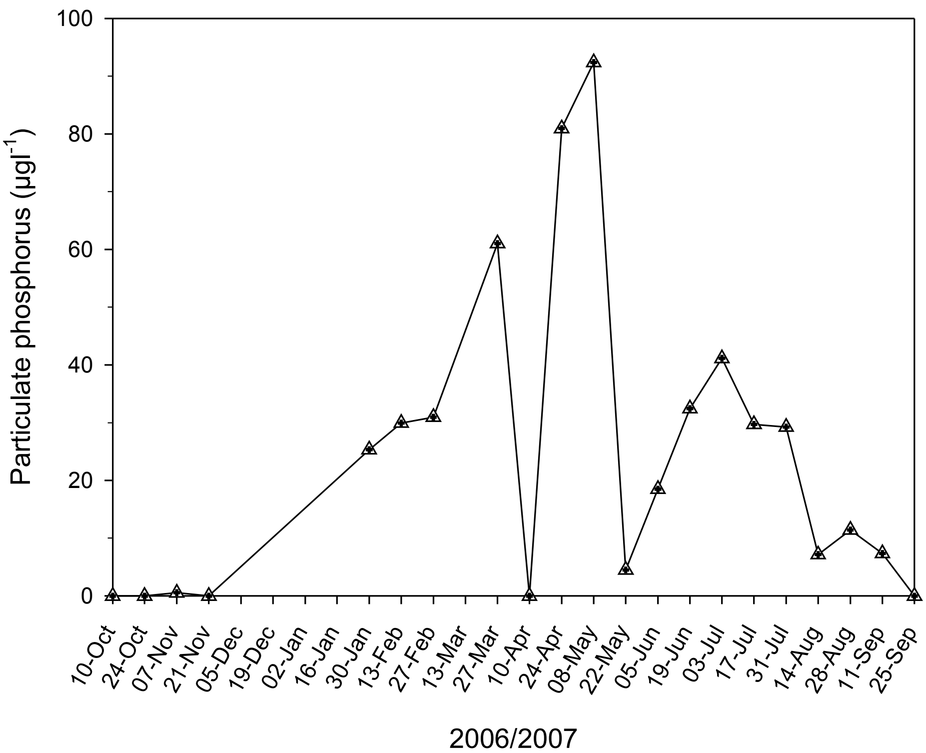

Figure 5.22 Concentrations of total particulate phosphorus (TPP) in the outflow of Llangorse Lake.

When all of the outflow chemistry data are considered together, and an assumption is made that most of the TPP in the outflow is related to algal biomass from the lake, a pattern begins to emerge of the way in which the lake probably functions (Figure 5.22). The data suggest that SRP levels are high over the winter period and that these begin to decline in spring as soluble P becomes incorporated into increasing levels of algal biomass (TPP). However, by early May, nitrate levels in the lake fall to very low levels and, from then onwards, algal growth appears to be controlled by nitrogen limitation. This prevents the algae using the P that becomes available through inputs from the catchment and recycling from the sediments. For this reason, P (especially SRP) accumulates and TP/SRP concentrations become very high (approximately 140 µg l^{-1}) by the end of the summer period. If in late summer/autumn, N were to become more available either from catchment sources or lake sediments, this in combination with already high SRP levels would create a very high risk of algal bloom formation.

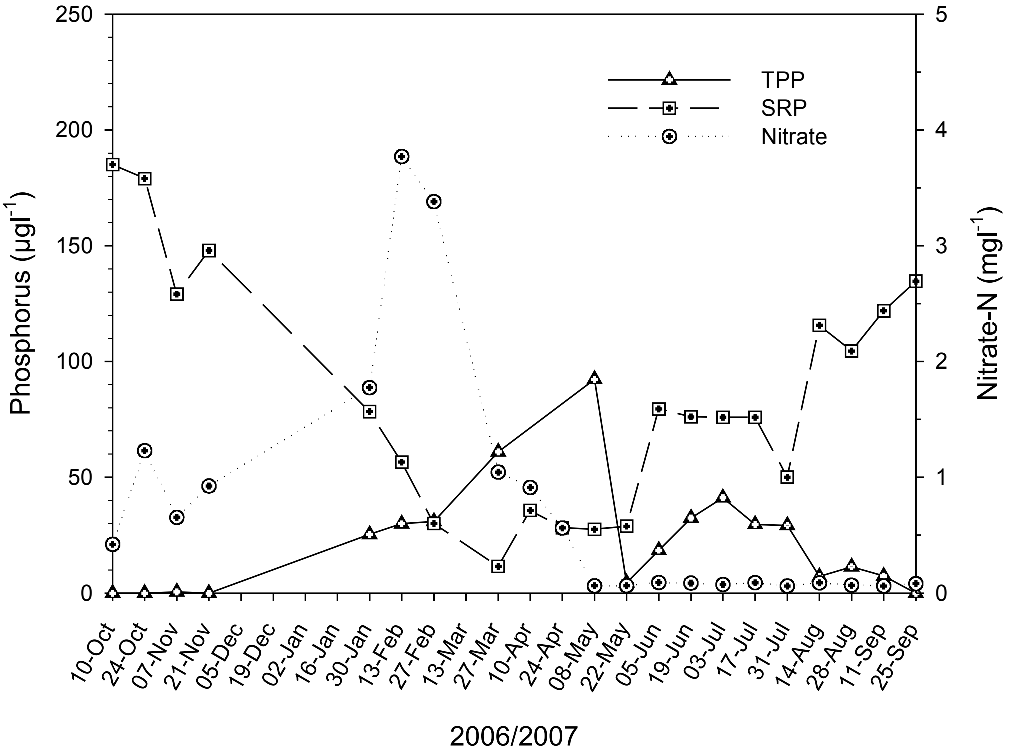

Figure 5.23 Concentrations of soluble reactive phosphorus (SRP), nitrate, and total particulate phosphorus (TPP) at the outflow of Llangorse Lake, after removing two, low-flow, samples (10/4/07 and 24/4/07) from the TPP data.

5.6 Historical variations in nutrient concentrations in the inflow and outflow

5.6.1 Inflow data provided by the Environment Agency

Comparisons of average monthly values of NO_3-N, PO_4-P and NO_3-N:PO_4-P in the inflow for the periods 1996-1999 and 2004-2007 are shown in Figure 5.24. The data show that average monthly NO_3-N concentrations (Figure 5.24a) have decreased by about 1 mg l^{-1} (about 30%) in recent years, with NO_3-N concentrations appearing to be high in winter and low in summer over both periods. In contrast, PO_4-P concentrations (Figure 5.24b) have fallen in both winter and autumn in recent years, while remaining high during spring and summer. The NO_3-N:PO_4-P ratio (Figure 5.24c) suggests that the chemistry of this inflow stream shows the potential for P limitation of algal growth throughout the year, although it should be noted that the changes in the concentrations outlined above have resulted in a nutrient loading to the lake from this stream with a higher N:P ratio during the winter/spring of recent years.

(b)

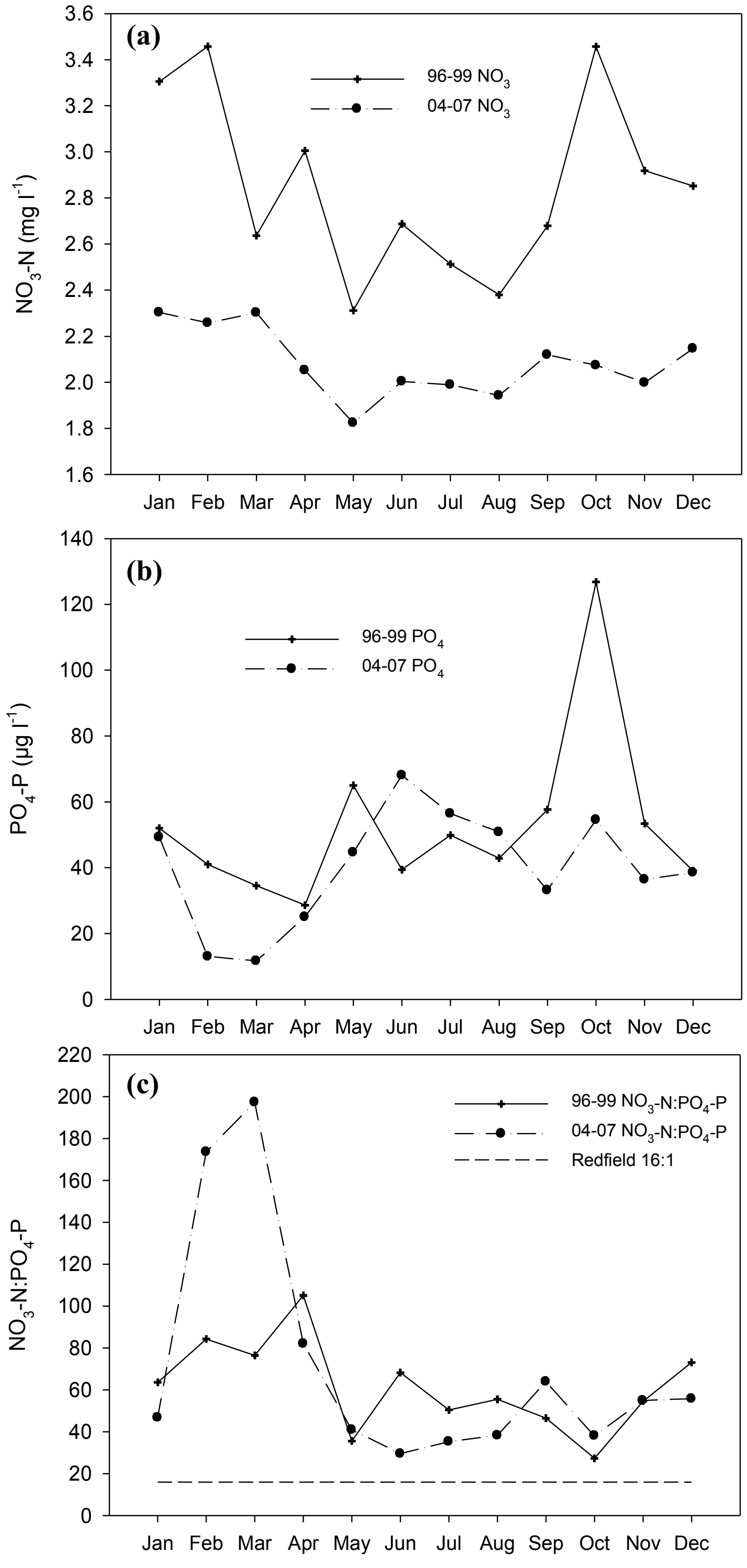

Figure 5.24 Variation in average monthly (a) NO_3-N concentrations, (b) PO_4-P concentrations and (c) NO_3-N:PO_4-P ratio in the main inflow to Llangorse Lake over the periods 1996-1999 and 2004-2007. Values were estimated using data provided by the EA. The dashed line in (c) represents the 16N:1P Redfield ratio, the optimal N:P ratio for phytoplankton growth (Redfield *et al.,* 1963).

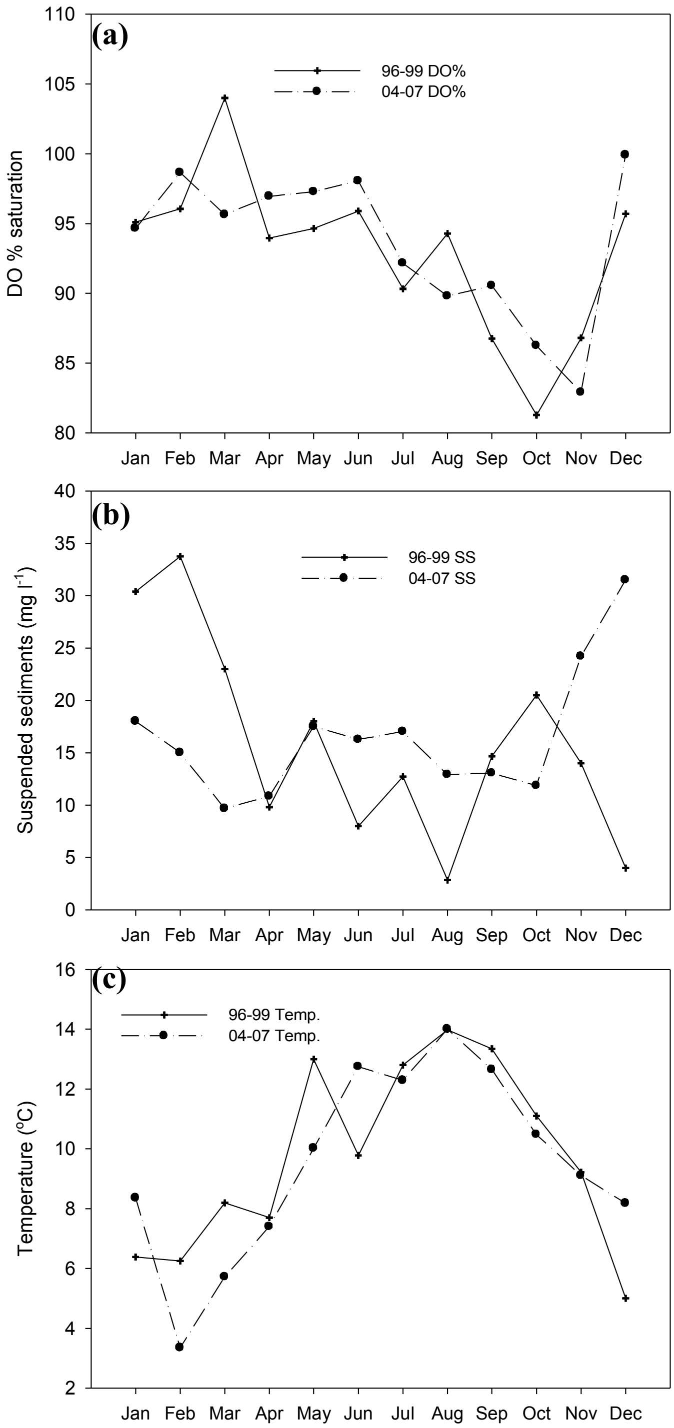

Figure 5.25 Variation in average monthly (a) dissolved oxygen, (b) suspended sediment concentration and (c) water temperature in the inflow over the periods 1996-1999 and 2004-2007. Values were estimated using data provided by the EA.

Historical comparisons (1996-1999 *cf.* 2004-2007) of average monthly values of dissolved oxygen expressed as percent saturation (DO%), suspended sediment concentration, and water temperature in the inflow are shown in Figure 5.25. Average monthly DO% (Figure 5.25a) appears to be similar across the two periods considered. In general, DO% is highest in winter/spring and lowest in summer/autumn. Suspended sediment (SS) concentrations

(Figure 5.25b) tended to be high in winter and low in summer, with concentrations appearing to have reduced in January-March and increased during November-December in recent years. There was little variation in SS concentrations over the remainder of the year. Water temperature (Figure 5.25c) shows good agreement between the two periods considered and varies seasonally, as expected.

5.6.2Outflow data provided by the Environment Agency

Historical comparisons of average monthly values of NO_3-N, NH_4-N and TN in the outflow for the periods 1996-1999 and 2004-2007 are shown in Figure 5.26a-c. These outflow concentrations have been assumed to reflect "in-lake" conditions at the time of sampling.

The seasonal trend in NO_3-N concentrations (Figure 5.26a) is similar over both of the periods considered, with NO_3-N concentrations being higher in winter and lower in summer. This is probably the result of more denitrification occurring during the warmer summer months, when the process is driven by an inverse relationship with dissolved oxygen concentration, and a direct relationship with temperature and microbial activity (Risgaard-Petersen *et al.,* 1994). This hypothesis is supported by changes in DO concentrations observed during both time periods (Figure 5.28a). In terms of concentration, Figure 5.26a suggests that the NO_3-N levels in the lake have reduced across all seasons in recent years, apart from in summer when concentrations were too close to zero to be able to fall any further. This overall reduction in N concentrations probably reflects the reduction in N-loading from the catchment that was highlighted in Section 5.6.1.

Little seasonality could be detected in the NH_4-N signal during either period (Figure 5.26b). However, seasonal variations in TN concentrations were evident (Figure 5.26c) and these showed a similar pattern to those observed for NO_3-N. Further comparisons indicated that TN did not decrease as much as NO_3-N during the summer, and that autumn values for TN have increased while those for NO_3-N have decreased in recent years. The reason for this switch is unclear. What is clear is that the contribution of NH_4-N to TN was low during both of the periods considered, although NH_4-N will be of greater ecological importance in the lake during the summer months when NO_3-N concentrations are reduced to almost zero.

Average monthly values of PO_4-P, TP and TN:TP in the outflow for 1996-1999 and 2004-2007 are shown in Figure 5.27. The seasonality of PO_4-P (Figure 5.27a) follows the classic trend observed in many shallow lakes (Sas, 1989), with PO_4-P concentrations being maintained over the winter period by a combination of light- and temperature-limited phytoplankton growth before a reduction in concentration that marks the onset of the spring phytoplankton bloom. Concentrations remain low until summer/autumn, when P release from the sediments, driven by temperature related microbial remineralisation and consumption of dissolved oxygen, results in the release of Fe-P complexes into the overlying water under conditions of anoxia (Figure 5.28a). The peak PO_4-P concentration that corresponds to this internal loading of P has reduced in recent years (Figure 5.27a). This is also reflected in the results of the sediment TP analysis (see Section 5.4). The variation in water column TP concentration (Figure 5.27b) follows that of PO_4-P. In general, both PO_4-P and TP concentrations in the lake have reduced in recent years, but this reduction is insufficient to result in the lake reaching "good" ecological status based on its average TP concentration at present (Carvalho *et al.,* 2006).

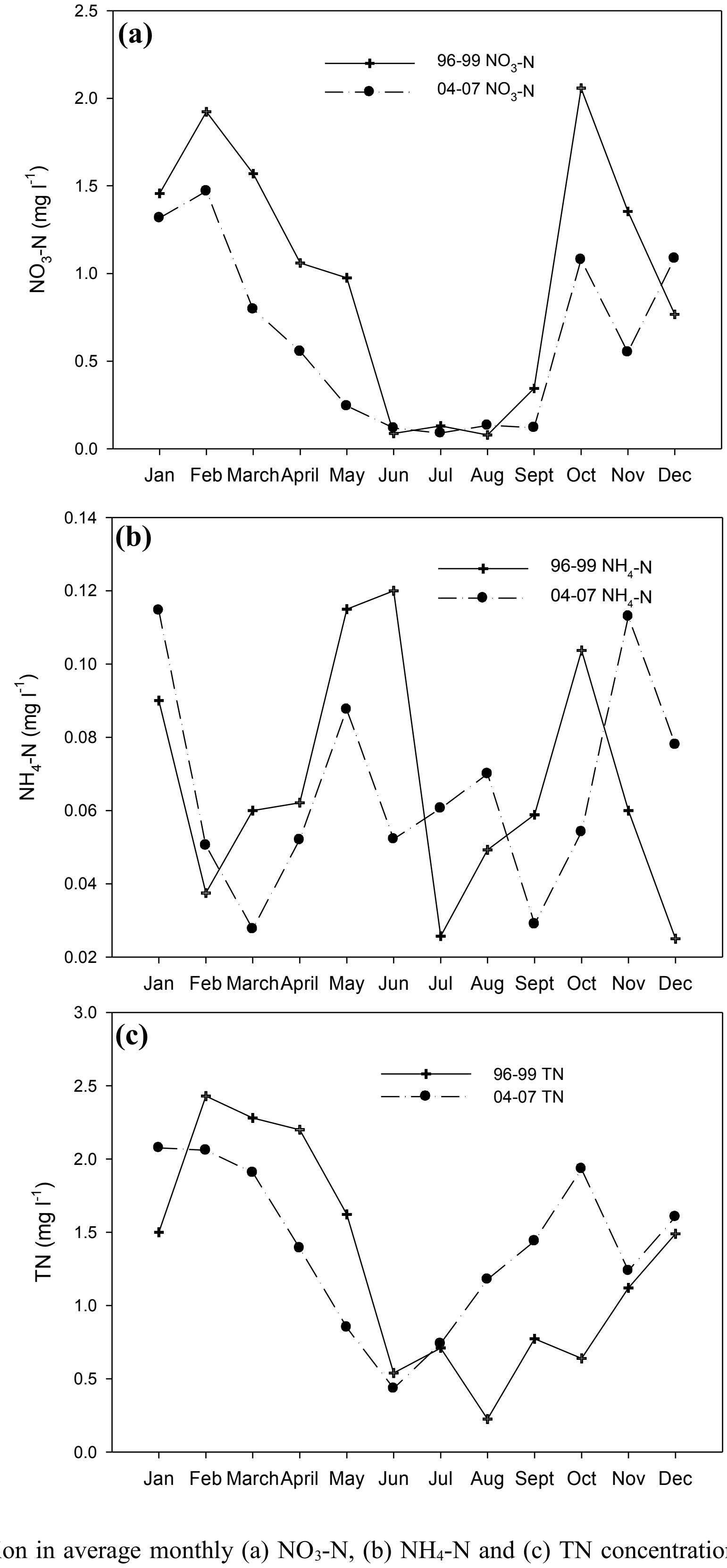

Figure 5.26 Variation in average monthly (a) NO_3-N, (b) NH_4-N and (c) TN concentrations in the outflow during the periods 1996-1999 and 2004-2007. Values were estimated using data provided by the EA.

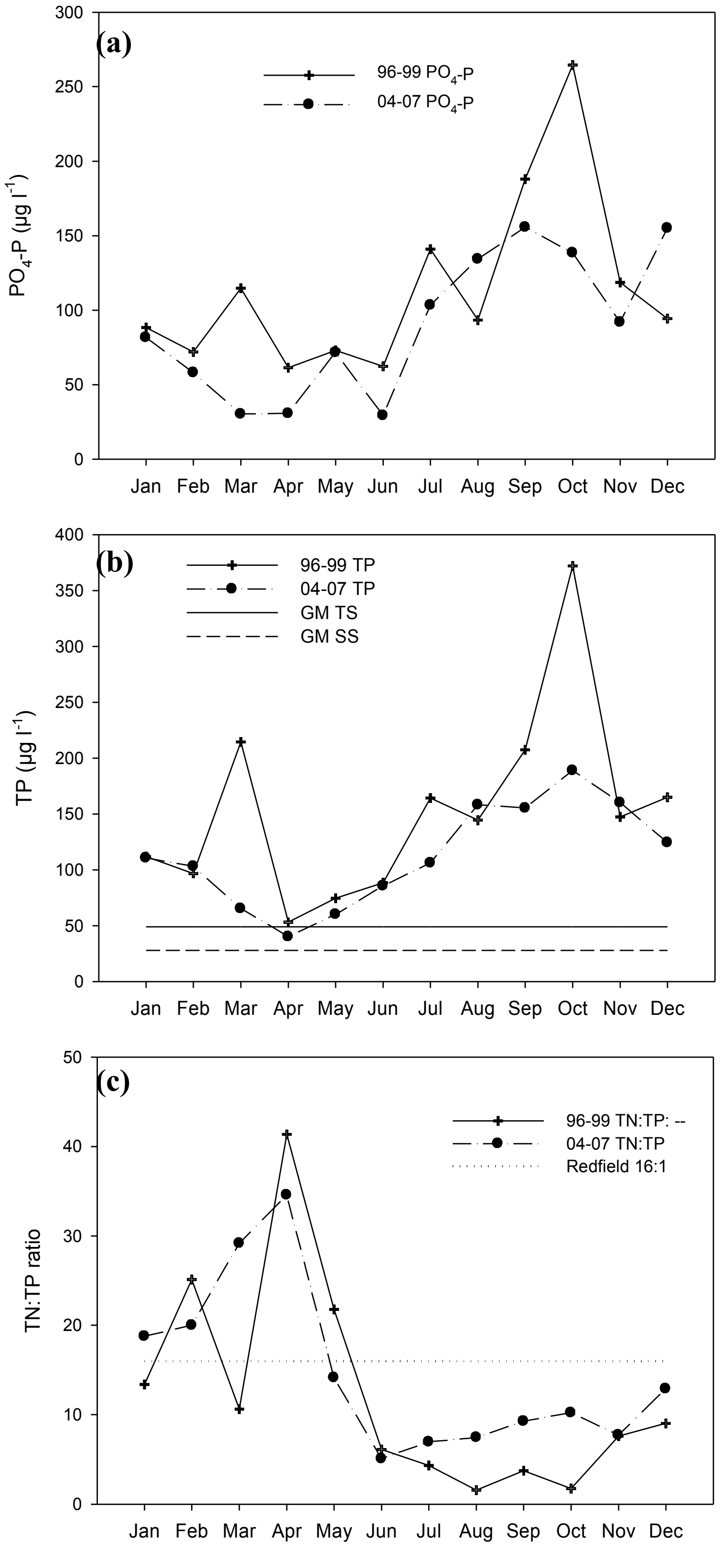

Figure 5.27 Variation in monthly (a) PO_4-P concentrations, (b) TP concentrations and (c) TN:TP ratio at the outflow in 1996-1999 compared to 2004-2007. Values were estimated from data provided by the EA. The horizontal dashed line in (b) represents the type specific good/moderate boundary (GM TS) and the full horizontal line represents the site specific good/moderate boundary (GM SS) for Llangorse Lake (Carvalho *et al.,* 2006). The dashed line in (c) represents the 16N:1P Redfield ratio (Redfield *et al.,* 1963); anything below this line indicates N limitation and anything above this line indicates P limitation.

The pattern of change in TN:TP ratio shown by the long-term data from the outflow (Figure 5.27c) highlights the need for a seasonal assessment of nutrient dynamics when considering lake management activities. Llangorse Lake appears to switch between P-limitation (January-May) and N-limitation (May-December) over the year. This switch highlights the role of shallow lakes in "scrubbing" nitrogen from the system through denitrification, a process that is most efficient during anoxic events (i.e. in summer, see Figure 5.28a) and corresponds to the same conditions that drive P release from the sediment to the water column. Figure 2.7c also suggests that N-limitation has become less prominent in summer in recent years, suggesting alterations of in-lake processes. Such alterations might result, for example, from higher DO concentrations in summer. This would result in reduced water column PO_4-P (due to reduced internal loading) and higher NO_3-N concentrations (due to reduced denitrification). Such elevated DO concentrations in summer may result from improvements in water clarity, as this encourages higher primary productivity (i.e. algal/macrophytic photosynthetic production of dissolved oxygen) at the sediment surface. The expected result of this process would be the increased retention of PO_4-P in the sediment and reduced NO_3-N removal from the system (Spears *et al.,* 2008). However, it is difficult to differentiate between the effects of external and internal processes on P and N concentrations in the lake using the available data. The signal presented in Figures 5.27 and 5.28 will represent the combined effects of variations in both external and internal processes. These have resulted in an overall decrease in lake PO_4-P and NO_3-N concentrations coupled with a decrease in external loading of both. It is important to note, however, that the data presented may not accurately reflect "in-lake" conditions and should be validated.

The chlorophyll-a concentrations shown in Figure 5.28b do not correspond with those observed in most P-limited shallow lakes. Unfortunately, due to a lack of data, no comparison can be made between the periods 1996-1999 and 2004-2007. Instead, all data were combined to produce an average seasonal variation across all years. In P-limited lakes, where N is in sufficient quantity, biomass peaks usually occur in spring and late summer, the latter event corresponding well to internal P-loading events. However, in Llangorse Lake, chlorophyll-a concentrations remain low despite a significant increase in water column P concentration in summer/autumn. This reflects the switch between P and N-limitation, such that phytoplankton biomass is controlled by N availability in the summer, when P concentrations are high, and P availability in the winter, when N concentrations are high. As a result, any management strategy must consider the regulation of both N and P loads to the lake.

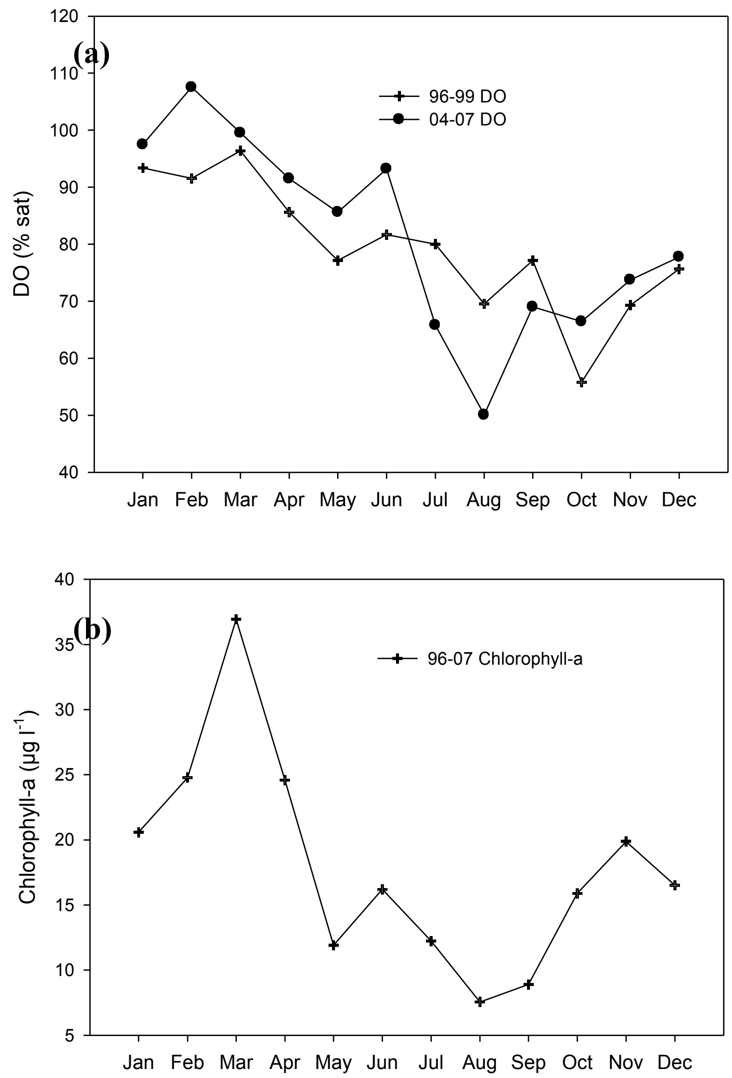

Figure 5.28 Variation in monthly (a) DO (1996-1999 and 2004-2007) and (b) chlorophyll-a (1996-2007) concentrations in the outflow.

6DISCUSSION

The nutrient load to Llangorse Lake from its catchment is very high in comparison with the indicative loadings for a shallow eutrophic lake given by Vollenweider (1968). Vollenweider (1968) suggests that lakes with a mean depth of up to 5 m will become increasingly eutrophic at loadings above an areal loading of 0.13 g P m^{-2} y^{-1} and 2 g N m^{-2} y^{-1}. The values for Llangorse Lake during 2006/2007 were found to be approximately 1.5 g P m^{-2} y^{-1} and 53 g N m^{-2} y^{-1}. These are approximately 10 and 25 times greater, respectively, than these indicative loadings.

Most of the P and N loads were found to be entering the lake in the streams draining to monitoring Site 2 (Nant Cui) and Site 6 (Afon Llynfi). Together, these inflows accounted for 85 per cent of the annual TP load and 82 per cent of the annual load of NO_3-N to the lake. Any attempts to significantly reduce the loads of these nutrients will need to be targeted at sources that contribute to these streams. This, however, will be difficult to determine given what appears to be a significant contribution from sub-surface flow of unknown origin (see below).

The hydrology of the Llangorse catchment appears to be very complex and strongly affected by sub-surface flow. This is best demonstrated at Site 6, where the surface water catchment upstream of the site accounts for only 36 per cent of the area of the lake catchment but contributes 67 per cent of annual surface flow to the lake. This, and the fact that the flow at Site 6 is almost double that which can be accounted for simply by rainfall, suggests that there is considerable sub-surface flow in this area. There is also evidence of sub-surface flow in many of the smaller streams around the catchment. Many of these have low, seasonal or intermittent flows that suggest that they are spring fed (Jones and Benson-Evans, 1974). If this is the case, the streams that flow into the lake may have significant input from sub-surface flow in terms of their hydrology and chemistry, and this sub-surface flow may enter the drainage system from an area beyond the boundary of the surface water catchment. This could have serious implications for catchment management planning aimed at reducing the nutrient loads to the lake. It is possible, for example, that some of the nutrient load from Bwlch sewage treatment works (STW), which was diverted away from the surface water catchment, may still be making its way into the lake *via* a sub-surface flow route.

Some of the inflow streams showed evidence of occasional point source pollution. This was especially true of Site 2 which, during the heavy storms of July 2007, carried more than 7 kg of P to the lake in a single day compared to its more usual 1 - 2 kg. This was thought to have been linked to storm overflow from the Llangorse STW. However, there was also some evidence of point source pollution occurring in some of the smaller streams during wet conditions, especially at Site 3 (Hoel Ddu). The causes of these pollution events are unclear but, given the land use within the catchment, it is likely that these are associated with rainfall driven discharges from slurry tanks, farm ponds or septic tanks. This indicates a need, at least in some places, to control point sources of pollution that occasionally leak or overflow during heavy rainfall events.

Most nutrient transport within the catchment seems to be associated with diffuse sources, such as agriculture, and with widely distributed site-based sewage treatment facilities such as septic tanks. This is true even of the increased P loading ‘event’ that was triggered by heavy rainfall in early December 2006. Although this brought more than 20 kg of P into to the lake in a single day, the event was not confined to a single subcatchment. This sudden increase in P load occurred in several streams across the catchment, i.e. Sites 2, 3 and 6, at the same time. It is interesting to note, however, that this sudden increase in P transport across the catchment was not associated with an increase in nitrate loads in all of these streams. At Sites 2 and 6, both P and nitrate loads increased but, at Site 3, only P loads increased. As nitrate is mainly associated with surface runoff from land, and the increased P load at this site comprised mainly (84%) soluble reactive P (SRP), this tends to indicate a sewage-related source.

The published literature concerning the eutrophication and recovery of Llangorse Lake focuses on P, with very little attention being paid to the role of nitrogen in the eutrophication or lake recovery process. This is probably for historical reasons, because it was (and in many cases still is) widely believed that P is the key limiting nutrient in shallow eutrophic lakes and that water quality can be improved by limiting the availability of this nutrient. As a result, the P-laden effluent from two local sewage treatment works was diverted away from the lake in 1981 and 1992, respectively. Although this reduced the TP load to the lake by an estimated 0.6 tonnes y^{-1} (approximately 30%) and led to a small reduction in in-lake TP concentrations, the results were generally disappointing. This study has shown that one of the reasons for this is that, for most of the summer, algal productivity in Llangorse Lake is actually N-limited rather than P-limited. This restricts algal growth and allows P, especially SRP, to accumulate in the water column from late spring until late autumn. This accumulation of P puts the lake at great risk of algal blooms developing in late autumn/early winter if there is an influx of N from the catchment or a significant release from the sediments at this time. The main message from this part of the study is that water quality in Llangorse Lake is, clearly, determined by a delicate balance between P and N availability throughout the year and, especially, in summer. So, it is important to consider both of these nutrients in the developing a catchment management plan.

Figure 6.1 Animal waste along a dry riverbed close to Llangorse Lake during a period of low flow in 2006.

One final consideration in developing a management plan for this catchment is the possible impact of occasional flooding of the surrounding meadows in terms of the transport of nutrients in the form of animal waste from land to water. There are a large number of livestock in the fields adjacent to the lake and their waste can be seen clearly both in the fields and along dry riverbeds during periods of low flow (Figure 6.1). In the 1700s, engineering works were undertaken so that "water, especially during floods, was conducted onto the meadows by every means at the farmer's disposal …In this manner, plant food was carried to the pastures, both in solution and in very finely divided particles, and there deposited for future absorption to rich verdure of a number of the best meadows" (Griffiths, 1939). In these days of intensive agriculture, the surrounding farmland is probably more nutrient rich than the lake water. If so, the system will now work in reverse, fertilising the lake from the catchment.

7IMPLICATIONS FOR CATCHMENT MANAGEMENT

Lakes are at topographic low points in the landscape where they tend to become the focus of pressures associated with increased anthropogenic activity within their catchment (EPBRS, 2008). These pressures cause water quality problems, such as algal blooms and the degradation of macrophyte communities. Managing these problems to improve water quality requires a catchment-based approach that focuses on the source of the problem. This is usually delivered through a catchment management plan.

A useful approach to this is the Total Maximum Daily Load (TMDL) approach, which is the basis upon which strategies to improve and protect water quality have been developed within the United States (US). The TMDL of a waterbody is the amount of pollutant that it can receive and still meet water quality standards.

Once the TMDL of a particular pollutant has been calculated for a given waterbody, allowable loads from contributing sources within the catchment are determined. Once established, responsibilities for reducing pollution among point and diffuse sources are then assigned following the underlying principle that responsibility lies with everyone who lives, works or undertakes recreational activities within the catchment.

An essential part of the TMDL process is to determine the water quality target for the pollutant of concern. In Europe, water quality targets are being set on the basis of a range of ecological objectives. One of the main drivers for setting these ecological water quality targets is the EU Water Framework Directive (WFD) (Council of the European Communities, 2000). Another is the EU Habitats Directive (Council of the European Communities, 1992).

The main steps in the development of a TMDL for a given pollutant and a given waterbody are:

- Identify the problem
- Develop numerical targets
- Assess the sources
- Link targets to sources
- Reducing loads
- Develop a monitoring evaluation/plan

Although it is not possible to develop a full TMDL for Llangorse Lake on the basis of the information that is available from this study, the main steps outlined above provide a useful approach to catchment management planning and have been used to structure this chapter of the report.

7.1Identifying the problem

This study has confirmed that Llangorse Lake still has a eutrophication problem, even though steps have been taken to reduce nutrient loads in recent years. Mean annual TP concentrations are still high, i.e. 130 µg l^{-1}, and the annual nutrient load to the lake from its catchment is about 2 tonnes y^{-1} of P and 74 tonnes y^{-1} of nitrate. This is 10 and 25 times greater, respectively, than the indicative loadings for shallow eutrophic lakes given by Vollenweider (1968).

In addition to high in-lake P concentrations and high nutrient loads from the catchment, there is evidence of ecological damage at this site due to eutrophication. Macrophyte communities have been badly affected and, although there has been a recovery in macrophyte diversity since the diversion of treated sewage effluent away from the lake in 1981 and 1992, they still remain in relatively poor condition.

Algal blooms are a common nuisance in most lakes that are very eutrophic. These are particularly troublesome at locations that are used for watersports, because some of these produce toxins that are a danger to human health. On the basis of P concentrations alone, this situation would be expected to occur in Llangorse Lake on a regular basis. However, historical data suggest that significant algal blooms rarely occur here, with in-lake chlorophyll-a concentrations remaining at 10-20 µg l^{-1} for most of the summer. This unusual situation has developed because algal productivity in Llangorse Lake is N-limited rather than P-limited for most of the summer months. As a result, algae growth remains low and high levels of P accumulate in the open water due to inputs from the catchment sources and release from the sediments. This accumulation of P puts the lake at great risk of algal blooms developing in late autumn/early winter if there is an influx of N from the catchment or a significant release from the sediments at this time. So, water quality in Llangorse Lake is, clearly, determined by a delicate and seasonally changing balance between P and N availability and it is important to consider both of these nutrients in the developing a catchment management plan.

7.2Developing numerical targets

7.2.1Water quality targets for the lake

Water quality targets for Llangorse Lake are set under the EU Water Framework Directive (WFD) (Council of the European Communities, 2000) and the EU Habitats Directive (Council of the European Communities, 1992). Both of these Directives place an emphasis on the ecology of the lake, rather than the chemistry, in setting these targets. However, within the UK, supplementary P standards for water quality assessment are also being implemented (UKTAG, 2007). At present, there are no corresponding N standards because analysis of the relative importance of N and P in determining growing season (April to September) chlorophyll-a levels, conducted as part of the EU funded 'REBECCA' project, concluded that there was little evidence of chlorophyll-a levels being more closely related to N availability than P availability in lakes across Europe (Carvalho, *pers. comm.*). This general conclusion appears to be in contrast to the site-specific case for Llangorse Lake.

The current P concentration target set for Llangorse Lake under the Habitats Directive is 35 $\mu g\ P\ l^{-1}$ (JNCC, 2005). This value was chosen to correspond to the WFD target that was being proposed at that time. Although WFD water quality targets are now being revised (UKTAG, 2007), and it seems likely that the type-specific 'high-good' and 'good-moderate' boundaries for P concentrations for this type of lake (i.e. high alkalinity, very shallow) will be set at 31 $\mu g\ l^{-1}$ and 46 $\mu g\ l^{-1}$, respectively (Carvalho *et al*., 2006), for the purposes of this study the water quality target has been assumed to be that of the existing target, i.e. 35 $\mu g\ P\ l^{-1}$ (JNCC, 2005). This is because, in general, when water quality targets for lakes set under the WFD do not agree with those set under the EU Habitats Directive (SAC, 2005), the latter take priority. It should be noted that these boundary values relate to the annual geometric mean of the measured P concentrations, which may differ a little from the arithmetic mean value that is usually referred to as an annual mean. Values for 1995 to 2007 have been calculated from the outflow monitoring data provided by the EA and are compared to the site specific boundaries for this lake in Figure 7.1.

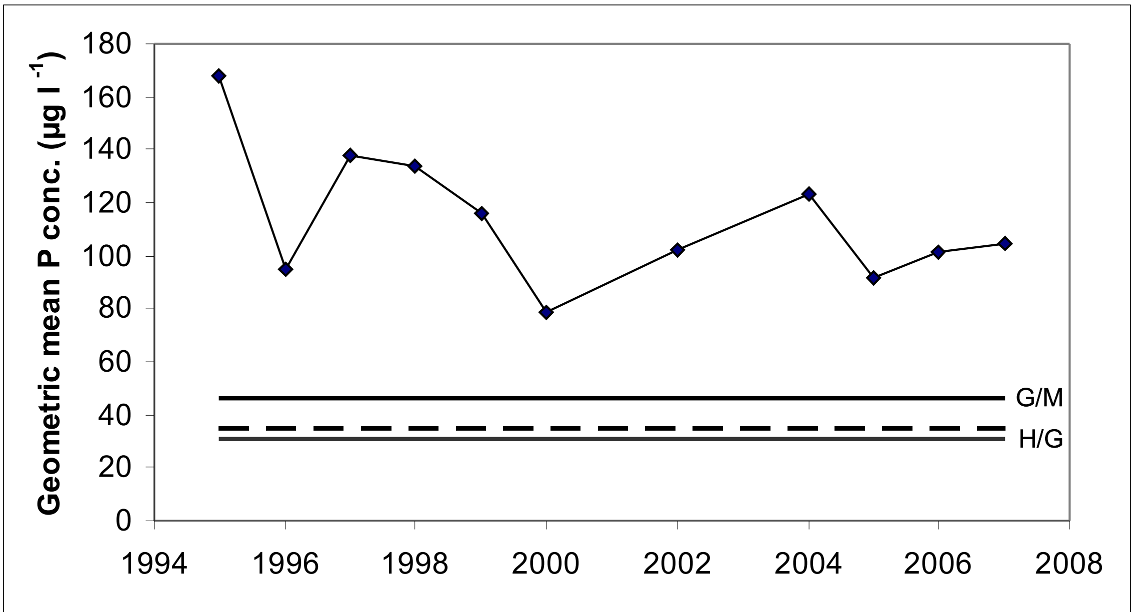

Figure 7.1 Variation in annual geometric mean of in-lake P concentrations in Llangorse Lake in relation to the proposed WFD status class boundaries for high alkalinity, very shallow waterbodies (see text for details). Data are based on EA monitoring data from the lake outflow. WFD water quality class boundaries are: H/G = high/good; G/M = good/moderate. The dotted line shows the existing water quality target used in this report.

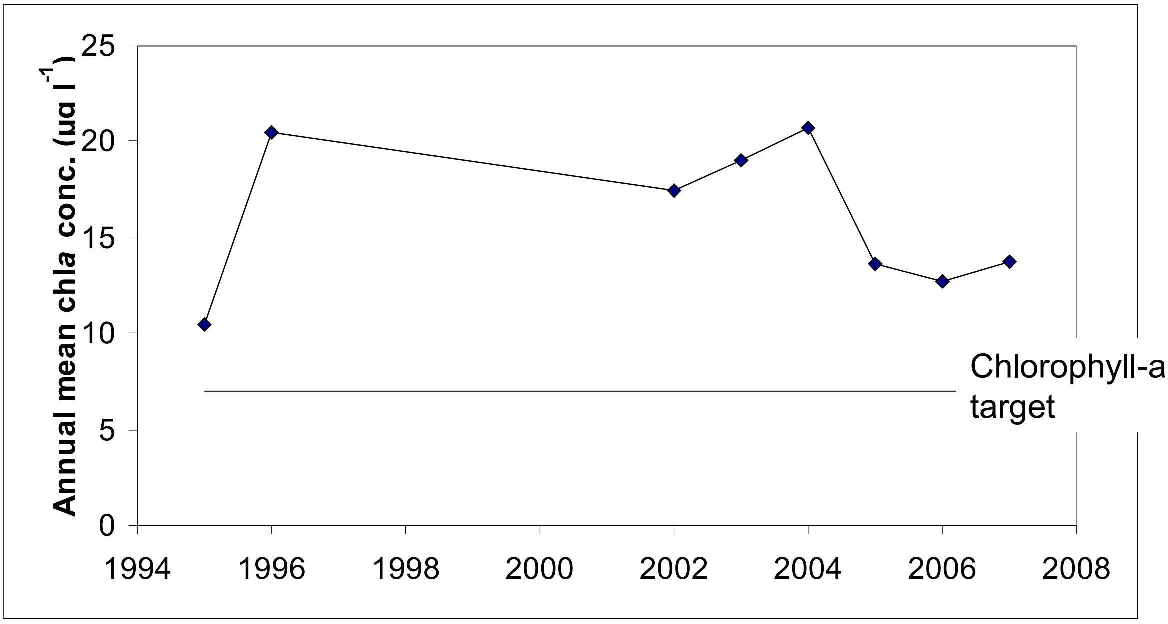

Figure 7.2 Variation in annual mean in-lake chlorophyll-a concentration in relation to the target calculated from the existing WFD high/good boundary for P concentrations in Llangorse Lake (see text for details). Data are based on EA monitoring data from the lake outflow.

There are currently no agreed targets for NO_3-N concentrations or biological elements, apart from chlorophyll-a concentrations (Carvalho *et al*., 2006) and macrophytes (Willby *et al*., 2006). However, it is possible to calculate an annual mean chlorophyll-a concentration for the lake from the P target value of 35 µg l^{-1}, using the relevant equations for high alkalinity, very shallow lakes given by Carvalho *et al*. (2006). These calculations give a corresponding mean annual chlorophyll-a concentration of about 7 µg l^{-1}. Annual mean chlorophyll-a concentrations for the lake, calculated from the outflow monitoring data provided by the EA for 1995 to 2007, are compared to the mean annual chlorophyll-a value given above in Figure 7.2.

7.2.2Water quality targets for the catchment

A target for P delivery from the catchment corresponding to the in-lake water quality target for P outlined above can be derived from the equations of Kirchner & Dillon (1975) and Dillon & Rigler (1974). These calculations suggest that an annual load of no greater than 1.7 tonne P would enable the lake to meet WFD targets once recovery had been achieved. However, in the interim period between P load reduction and recovery, high P loads from the sediments would be expected to maintain high P concentrations in the water column.

The causal relationship between NO_3-N loads from the catchment and in-lake NO_3-N concentrations is less well known than that for P because this aspect of lake water quality has received little attention. However, given that N-limitation in the lake seems key to controlling potential algal blooms in summer while P levels remain high, the current load should not be allowed to increase and any decrease in load that can be achieved over the recovery period can only benefit ecological water quality. The most critical issue for nitrate delivery from the catchment is controlling the amount of nitrate that enters the lake in autumn when levels of P are high. A sudden increase in nitrate availability at this time of year puts the lake at high risk of developing algal blooms and failing water quality targets.

7.3Assessing the sources of N and P

The annual P load to the lake has been estimated to be about 2 tonnes. The main sources of P within this rural catchment are likely to be agricultural runoff, animal excreta and domestic waste. It is difficult to locate and quantify these sources, exactly, because this requires a detailed catchment-wide survey of the quality of both surface and sub-surface water, which was outside the scope of this project. It is also difficult, here, because there are significant sub-surface flow issues in this area and some significant sources of P may lie outside the topographically defined surface water catchment of the lake. There is certainly evidence that nutrient pollution in some streams may not originate from the surface water catchment upstream of the sampling point, alone. However, some general estimates of P sources can be made at the catchment scale on the basis of the information that has been gathered.

In terms of sewage-related P sources, most of the treated effluent from the Llangorse and Bwlch STWs has been diverted away from the lake. However, on occasion, storm water overflow from the Llangorse STW still appears to flow into the lake. A single storm overflow event at the end of July 2007 increased the instantaneous P load to the lake by about 5 kg d^{-1}. With fortnightly sampling, it is impossible to estimate exactly how long this event lasted, but it has been assumed to last for about 3 days. As such, the P load from this source due to storm overflow events has been estimated to be about 15 kg y^{-1}. In addition, about 1000 people within the catchment seem to depend on septic tanks or similar on-site waste water treatment systems for the treatment and disposal of domestic waste. The P export from these systems, calculated on a *per capita* basis following the method recommended by Carvalho *et al*. (2005), is likely to be about 400 kg y^{-1} (Table 7.1). The P from the suspected storm overflow at the STW was equivalent to an extra 15 days worth of P exported from all septic tanks across the catchment, but still accounted for only 1% of the annual P load to the lake.

Phosphorus losses from livestock waste to water are also a problem in this catchment. These were calculated on a *per capita* basis from data published for the Slapton Ley catchments in England given by Burt *et al*. (1996). Although Slapton Ley is at lower altitude, it is also in western Britain, has a very similar type of catchment to that of Llangorse Lake (rural, sheep & cattle farming, steep slopes) and so could be expected to have similar levels of nutrient loss from the different sources. The P export coefficients derived from these values were 0.22 kg P $capita^{-1}$ yr^{-1} for cattle and 0.03 kg P $capita^{-1}$ yr^{-1} for sheep. If it is assumed that there are about 1,000 cattle and 9,000 sheep grazing within the catchment (Dickinson & Teeuw, 1999), then the total P load from this source is estimated to be about 490 kg P y^{-1} (Table 7.1).

Phosphorus losses from landcover sources within the catchment were calculated from the area covered by each broad land cover type shown in Table 7.1, using area-based P export coefficients derived from Burt *et al.* (1996) and Haygarth *et al.* (2003). These areas were calculated from LCM2000 land cover data for Great Britain and Northern Ireland which was provided under licence by CEH. The total load to the lake of P from land cover sources was estimated to be about 450 kg y^{-1} (Table 7.1).

In terms of nitrogen transport, and assuming that the event lasted about 3 days as suggested above for P from this source, the measured data suggest that the storm overflow event involving the Llangorse STW in late July 2007 probably contributed about 30 kg N to the lake. In addition, the estimated N load from septic tanks was approximately 2,240 kg N y^{-1}. This gave an overall figure for N from sewage related sources of 2,270 kg N y^{-1} (Table 7.2). The N from the suspected storm overflow at the STW was equivalent to an extra 5 days worth of N exported from all septic tanks across the catchment, but still accounted for only 0.08% of the annual N load to the lake.

Table 7.1 Predicted P export to Llangorse Lake from all known sources within the catchment

Source of waste	Number of items	P export to lake (kg capita^{-1} y^{-1})	P export to lake (kg y^{-1})
Septic tanks	1000	0.4	400
STW overflow	1 event	n/a	15
Cattle	1000	0.22	220
Sheep	9000	0.03	270
Subtotal			905

Land cover	Area of catchment	P export to lake (kg ha^{-1} y^{-1})	P export to lake (kg y^{-1})
Arable land	11%	0.68	165
Improved grazing	47%	0.26	269
Moorland/heath	27%	0.02	12
Woodland/scrub	14%	0.02	6
Subtotal			451
Total			**1,356**

Nitrogen losses from livestock to water were derived in a similar way to that described for P, above. The corresponding NO_3-N export coefficient values were 11.6 kg NO_3-N *capita*$^{-1}$ yr^{-1} for cattle and 1.2 kg NO_3-N *capita*$^{-1}$ yr^{-1} for sheep. The nitrogen loads to the lake from these sources were calculated from these values on the basis of the livestock numbers outlined above. The estimated N load from this source was estimated to be about 21,500 kg NO_3-N y^{-1} (Table 7.2).

Nitrogen losses from landcover sources within the catchment were calculated from the area covered by each broad land cover type shown in Table 7.2 (values derived from LCM2000 lancover data, see above) using areal NO_3-N export coefficients derived from Haygarth *et al.* (2003). The total load to the lake of NO_3-N from this source was estimated to be about 3,498 kg (Table 7.2).

The overall loss of NO_3-N to the lake from catchment sources on the basis of land cover, livestock numbers and human population was predicted to be about 27.3 tonnes y^{-1} (Table 7.2).

Table 7.2 Predicted N export to Llangorse Lake from all known sources within the catchment

Source of waste	Number of items	N export to lake (kg capita^{-1} y^{-1})	N export to lake (kg y^{-1})
Septic tanks	1000	2.24	2,240
STW overflow	1 event	n/a	30
Cattle	1000	11.6	11,600
Sheep	9000	1.1	9,900
Subtotal			23,770

Land cover	Area of catchment	N export to lake (kg ha^{-1} y^{-1})	N export to lake (kg y^{-1})
Arable land	11%	3.52	852
Improved grazing	47%	1.38	1427
Moorland/heath	27%	2	1188
Woodland/scrub	14%	0.1	31
Subtotal			3,498
Total			**27,268**

The total predicted annual P and NO_3-N loss from land to water based on land cover, livestock numbers and human population in the topographically defined surface water catchment was about 1.4 tonnes of P and 27.3 tonnes of NO_3-N. This is 30 per cent lower than the measured value of about 2 tonnes for P and about 63 per cent lower than the measured value for NO_3-N. This discrepancy will, in part, reflect uncertainties within the data used to estimate these values. For example, livestock numbers may have changed significantly since 1993 but more recent data were not available within the timescale of this project. However, there are two other possible reasons for this. The first is the amount of livestock that are kept close to the water's edge. Burt *et al*. (1996) estimate that nutrient losses to water from animal waste can double if animals are grazed within 50 m of a receiving waterbody. Keeping livestock close to water does appear to be a problem in this catchment, as evidence of animal waste near to and even along stream beds was clearly seen in areas close to the lake during a site visit carried out as part of this project. The second possible reason for the under prediction of nutrient loads from the catchment is that nutrients transported to the lake from areas outside the surface water catchment by sub-surface flow are not accounted for in these calculations.

When the predicted contributions from each nutrient source within the surface water catchment are compared, the main sources of P are clearly livestock waste (36%), runoff from improved grazing (20%), treated sewage effluent (31%) (Figure 7.3). The corresponding values for NO_3-N are livestock waste (80%), and runoff from arable land (3%) (Figure 7.3). It should be noted that the values for N are based mainly on nitrate and that other sources of N, such as NH_4-N are only partially accounted for. Although the predicted absolute loads are much lower than the measured values, any additional load from the catchment that contributes to sub-surface flow is likely to have the same proportional contributions from the different sources. This is because there are no major land use changes or large centres of population within the immediate area surrounding the surface water catchment on which the calculations were based.

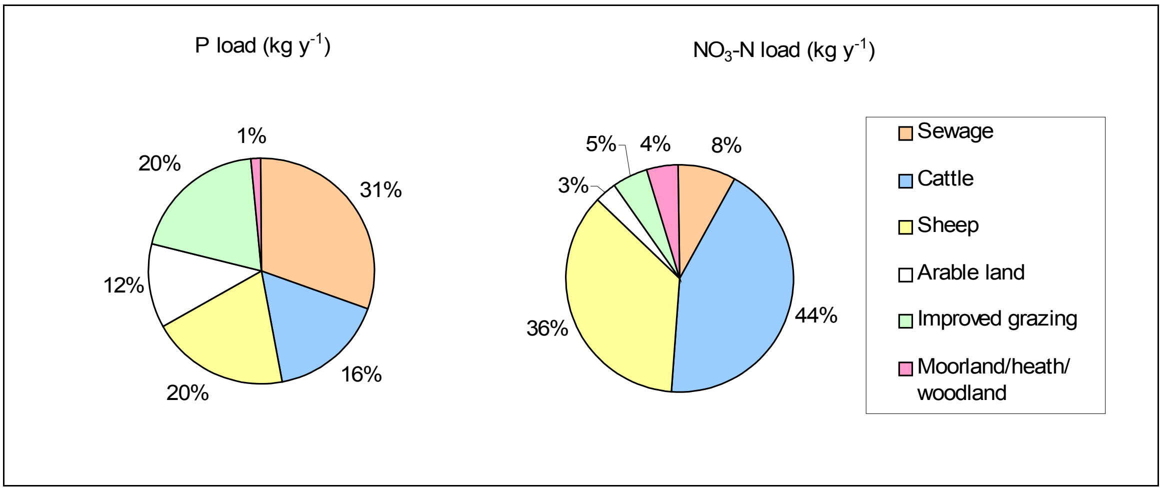

Figure 7.3 Estimated relative importance of sources of P and NO_3-N in the catchment of Llangorse Lake in relation to loads to the lake.

7.4 Linking targets to sources

In the case of Llangorse Lake, sources of both N and P are widely dispersed across the catchment and it is not possible to identify any particular source for control. Nutrient load reduction must address both N and P, and must be introduced at the catchment scale. Initially, that catchment will, out of necessity, need to be defined as the surface water catchment. However, there is evidence that some of the nutrient load to the lake may originate from outside of this area and be transported to the lake and its feeder streams by sub-surface flow. So, catchment management initiatives should, ideally, include the catchment area that contributes to this sub-surface flow too. At present the extent of that area is unknown.

7.5Reducing loads

As nutrient loads to Llangorse Lake come from widespread and mainly diffuse sources, it is not possible to allocate loading targets to particular sources. Control must be implemented at the catchment level and focus on the reduction of both P and N loads to the lake. A number of approaches can be used to achieve this. These include catchment sensitive farming initiatives, the establishment of nitrate vulnerable zones, the development of sustainable tourism and the better management of domestic waste disposal systems. It is important to remember that, in the case of Llangorse Lake, any nutrient management initiatives such as these may also need to be applied to areas beyond the surface water catchment to account for nutrient transport in sub-surface flow.

7.5.1Catchment sensitive farming

Catchment sensitive farming helps farmers to manage their land in ways that safeguard the local water environment. This is achieved by:

- maximising the retention of nutrients within the field to which they are applied
- matching nutrient applications to crop requirements
- improving the management of livestock waste
- preventing soil erosion by changing land management practices or land use

One benefit of such a scheme could be free soil nutrient testing, which would enable farmers to target fertilizer applications more cost-effectively and reduce nutrient loss to the environment.

Catchment sensitive farming within the catchment of Llangorse Lake would be expected to reduce loads of both N and P from agricultural sources, as steep gradients in the catchment make it particularly sensitive to poor nutrient management practices.

7.5.2Nitrate vulnerable zone

Declaring the area a nitrate vulnerable zone (NVZ) would encourage farmers to reduce the transfer of nitrates from land to the lake by:

- matching inorganic nitrogen fertiliser application to crop requirements
- limiting organic manure applications according to nitrogen content
- only applying slurry, poultry manures or liquid digested sludge to farmland on sandy or shallow soils outside the autumn ‘closed’ period
- keeping adequate farm records of cropping, livestock numbers and the use of organic manures and nitrogen fertilizers

Treating the catchment of Llangorse Lake as a NVZ would reduce loads of N from agricultural sources, especially during the critical autumn period when algal blooms are more likely to occur due to a build up of P in the lake water over the summer months.

7.5.3Sustainable tourism

Large numbers of tourists are attracted to Llangorse Lake each year and it is important that they do not inadvertently damage the environment that they have come to visit. Of particular concern in relation to nutrient management and eutrophication is the increased waste water and sewage that these visitors generate. Consideration needs to be given to the impact of this on the lake during the planning and approval process when the development of holiday properties, activity centres and other tourist attractions in the area are considered. For example, in some areas of Scotland, planning applications are only approved if developers can show that they will offset 125% of the P-pollution that their development creates by reducing P discharges elsewhere in the catchment. Examples include the catchment of Loch Leven, where there are similar problems to those found at Llangorse Lake. The use of phosphate free detergents in the area should also be considered. The Llangorse Lake Advisory Group could have an important role to play, here, in promoting sustainable tourism in this area.

7.5.4Better management of domestic waste

In rural areas such as around Llangorse Lake, the local population and visitors often rely on septic tanks for the management of their waste water and sewage. The data suggest that the waste from about 1000 people may be managed in this way in the Llangorse catchment. Studies from elsewhere have shown that many of these systems, especially the older ones, may be faulty or badly managed. In many cases, owners are unaware of the need to empty them on a regular basis and many are overflowing. This creates high levels of nutrient discharge into the waters that drain the catchment. Simply making sure that septic tanks are working correctly and are being emptied regularly could make an enormous difference to the amount of nutrients from these sources that is finding its way into the lake. This could be addressed through a local leafleting campaign to raise public awareness of the problem and dispel the widely held belief that, if a septic tank is working properly, it doesn't need emptying. However, care should be taken in implementing long-term 'solutions' to this problem that have not been properly researched, such as the installation of mains sewerage systems. Many of these perform partial P removal before discharging effluent directly into watercourses, which may make the situation worse (Dudley & May, 2007; White & Hammond, 2006).

7.6Developing a monitoring evaluation/plan

Once a catchment management plan has been developed, it is important to monitor its impact on the target waterbody - in this case, Llangorse Lake. This study has shown that most of the nutrients entering the lake do so in the streams draining to Sites 2 and 6. So, these should be monitored for any reduction in nutrient loads resulting from catchment management activities such as those outlined above. In addition, water quality should be monitored in the lake itself to assess any changes in water quality, there. Although the outflow is more accessible, it is not possible to be sure that nutrient and chlorophyll-a values in the outflow accurately reflect those of the lake, especially during low flows. Monitoring should focus on all P and N fractions.

8POSSIBLE IN-LAKE RESTORATION MEASURES TO ACCELERATE RECOVERY PROCESSES

Although most restoration measures need to focus on the main sources of nutrients within the catchment, even when these are reduced many lakes can maintain their eutrophic state for several years through the internal recycling of P from the sediments. The evidence suggests that this would be true of Llangorse Lake, once nutrient inputs were reduced to a suitable level to promote recovery. At present, the external nutrient load is still too high for this to occur (see Section 6). In such cases, alternative approaches to remediation can be used to accelerate recovery. Some of these methods are reviewed below in relation to their potential applicability to Llangorse Lake. However, it should be noted that once external loads are reduced sufficiently, internal re-cycling will probably be, at most, a medium term problem at this site (*c*. 5-10 years) and it may be more cost effective to let the lake recover naturally rather than attempt a 'quick fix' that could be environmentally damaging in other ways.

8.1Vertical Mixing

Vertical mixing of the water-column can be used to control algal blooms in lakes that do not stratify. The mixing forces individual algae to spend more time in low light conditions than they would naturally. This reduces their capacity to grow by changing the main growth limiting factor from nutrient availability to light availability. However, this technique does not work well in lakes that are less than 5m deep. This technique is unlikely to work well in Llangorse Lake for several reasons. Firstly, the main problem is not algal blooms but an accumulation of dissolved P in the water column. Secondly, Llangorse Lake is a relatively exposed shallow lake that is used for water sports, so it is probably already subject to considerable mixing due to wind and power boat activity (Dickinson & Teeuw, 1999). Finally, artificial mixing may cause damage to aquatic plants due to the redistribution and settling of suspended sediments.

8.2Flushing

The control of eutrophication by manipulating flushing rates works on the principle that inflowing water containing little or no algae or nutrients displaces impounded water that contains large amounts of algae and nutrients at a rate that exceeds the replacement rate within the lake. This reduces in-lake nutrient concentrations and associated algal blooms. Even if this is successful, it is necessary to maintain the high flushing rate to prevent the algal populations re-establishing themselves. This approach has been applied successfully to Green Lake, USA, resulting in a reduction in TP concentration from 60µg l^{-1} to 20µg l^{-1} and in chlorophyll-a concentration from 50µg l^{-1} to 10µg l^{-1}, within 3 years (Oglesby, 1969). A similar improvement was also recorded in Moses Lake, USA (Welch & Patmont, 1980) when it was flushed, periodically, by water from the nearby Columbia River. However, the success of this method is dependent upon a readily-accessible source of low-nutrient water being available in sufficient quantities. There is no obvious source of such a water supply close to Llangorse Lake.

8.3Bio-manipulation

It is sometimes possible to manage lake eutrophication problems by transferring the excess nutrient capacity into a more aesthetically pleasing higher trophic level, such as crustacean zooplankton or fish. This management technique has worked well in some small or shallow water bodies, although there is evidence that it is less successful in larger lakes where zooplankton populations tend to 'boom and bust' in line with the phytoplankton. Without further information on the species composition and abundance of plant and animal communities in Llangorse Lake, especially within the plankton, it is impossible to determine how this technique might be used here. Duigan *et al*. (1999) note that removal of zooplanktivorous fish or addition of piscivores can switch a lake from phytoplankton to plant dominated, encouraging clearer water. However, the authors advise that any such activity would need to be assessed and monitored as part of an overall management plan if applied to Llangorse Lake. They also recommend that any fishery management in the lake is carried out in a sensitive manner, because changing the fish community can increase predation on the main algal grazer, *Daphnia*, which in turn would lead to an increase in algal abundance (Duigan *et al*., 1999). In general, this method is controversial and the unpredictability of the outcome could compromise the conservation status of the lake.

8.4Sediment removal

Sediment removal is an expensive technique for reducing the internal P load to lakes. It has usually been used only as a last resort when other methods have failed. In Lake Trummen, Sweden, for example, effluent diversion in 1958 failed to achieve the expected improvement in water quality. So, in 1970-71, suction dredging was used to remove the upper half metre of the sediments. Almost immediately, this resulted in a 50% reduction in P concentration and algal biomass (Bengtsson & Gelin 1975). However, the cost (about £1.25M at present day prices) for treating this waterbody was high. More recent estimates for sediment removal from lakes in Cumbria are similarly high, ranging from £4M to £10M per lake (Hall *et al.*, 2000). Based on the information given by these authors, the estimated cost for sediment removal in Llangorse Lake could be as high as £5M. As Peterson (1979) suggests, cost and sediment disposal problems are likely to be the main factors limiting the use of this technique in Llangorse Lake although application of this physical and very destructive method of sediment removal could also seriously damage the conservation status of the lake.

8.5Nutrient inactivation by precipitation or bottom sealing

Iron, aluminium or similar salts have been added to some lakes to enhance recovery by precipitating nutrients. Most studies have reported success in the short-term followed by a return to pre-treatment levels of P release within a few years (e.g. Foy 1985). There are also concerns that such techniques may have adverse effects, such as toxicity, increased turbidity and oxygen depletion, on lake ecosystems (Randall *et al.*, 1999). The technique precipitates available phosphates from the water-column to the sediments and prevents aerobic internal loading from the sediments. The P bound within the formed complexes is sensitive to release under conditions of anoxia and associated pH shifts.

The addition of lanthanum based clay as a P binding agent has recently been conducted in Australia (Robb *et al.*, 2003). This approach assumes an irreversible scrubbing of P from the water column before the clay-P matrix settles to the sediment surface. Sufficient product is added to act as a barrier to P efflux from the sediment (i.e. internal loading) to the water column. Initial results indicate this approach to be successful in reducing SRP concentrations in the water column. However, no long term monitoring studies (i.e. >5 years) have been conducted.

The general ecological effects of all potential P-binding agents require further investigation, especially for application in environmentally sensitive waterbodies and those with a high conservation status.

8.6Biomass harvesting

Removal of biomass, and the nutrients that it contains, is another technique that can be used to accelerate lake recovery once external nutrient loads have been reduced. This approach is generally thought to be practical only in relation to the removal of large aquatic plants or fish (Harper, 1992).

Nutrient control by the removal of macrophytes is unlikely to be effective unless there is dense plant growth (Burton *et al.*, 1979). Also, as macrophyte stands in Llangorse Lake are already a cause for concern from a conservation point of view, further damage through the application of this technique to aid lake recovery is unlikely to be seen as a viable solution to eutrophication problems here. The principal aim of any management activity, here, would be to shift the biomass in Llangorse towards aquatic plants rather than away from them.

The benefits of harvesting fish to remove nutrients are thought to be too small for this technique to be practical (Bull & Mackay, 1976). However, it should be noted that fish removal could have some beneficial effects in terms of altering the nutrient balance of the lake by removing large benthivorous species, such as bream, which disturb nutrient-laden sediments while searching for food (Duigan *et al*., 1999).

9CONCLUSIONS

Although P limitation has always been considered to be the main factor limiting phytoplankton productivity in Llangorse Lake, this study has suggested that the lake is actually N-limited for most of the summer months. For this reason, catchment management activities aimed at improving water quality in the lake need to focus on both N and P delivery to the lake, rather than P alone. It should be noted, however, that these findings are based on water chemistry data from the outflow, just downstream of the lake. Ideally, in-lake data for water chemistry and, especially, chlorophyll-a concentration, are needed to validate the findings. This is because outflow data may not always reflect in-lake conditions, especially under low flow conditions. Information on in-lake zooplankton communities and the role of the sediments in nutrient cycling would also be useful.

The conclusions of this report are based, mainly, on nitrate measurements, only. Ideally, there is a need to confirm that NH_4 concentrations are also low to be absolutely sure that N limitation is reducing the likelihood of algal blooms over the summer period. Information on total nitrogen and dissolved inorganic nitrogen would also be useful to ensure that no other sources of N are being missed.

Levels of SRP within the lake still seem to be very high in spite of reductions in catchment sources. High levels in summer are probably related to recycling from the sediments, but very high levels in winter also suggest that more P control from external sources is possible. Further P control would help reduce chlorophyll-a levels within the system, which are still above recommended water quality standards.

Other important findings from this study are:

- Phosphorus loads to the lake need to be reduced by about 15 per cent, and nitrate loads need to be maintained at or below the current level, for the lake to achieve good water quality
- More than 80 per cent of the nutrients are delivered to the lake by the two main inflow streams
- Sub-surface flow may significantly influence stream flow and nutrient delivery to the lake; if so, the water and nutrients may enter the lake from a catchment area wider than that defined on the basis of surface topography
- The lake appears to have a much shorter retention time than previously calculated
- Nutrient levels in the sediments are not likely to greatly slow the recovery of the lake once appropriate management is in place

10 MANAGEMENT RECOMMENDATIONS

Llangorse Lake is worth investing in as the prospects for recovery seem good if appropriate measures are taken to reduce nutrient delivery from the catchment. There seems to be a strong case for a catchment sensitive farming initiative, here, including provision for nitrate management by establishing a nitrate vulnerable zone (NVZ) in this area.

Residents in the area need to be made aware of the importance of proper maintenance of domestic sewerage systems, although it should not be assumed that replacing properly managed septic tanks with a mains sewerage system would necessarily improve the situation without further investigation. Nevertheless, planning authorities need to take the sensitivity of the lake into account when considering new development proposals.

There is a strong possibility that land close to the lake shore may deliver large amounts of N and P to the lake when the area floods. Conservation bodies should consider strategic land purchase near the lake shore to extend areas of wet woodland and / or reedswamp. This would enable intensive agriculture, especially livestock grazing, to be excluded from areas that are sensitive to flooding, thereby reducing the nutrient load to the lake.

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12REFERENCES

Bengtsson, L. and Gelin, C. (1975). Artificial aeration and suction dredging methods for controlling water quality. In *Effects of Storage on Water Quality*. Water Research Centre, Medmenham, UK.

Bennion, H. and Appleby, P. (1999). An assessment of recent environmental change in Llangorse Lake using palaeolimnology. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**, 361-375.

Bennion, H., Davidson, T., Simpson, G., Solovieva, N., Rose, N., Theophile, S., Yang, H., Anderson, N.J., Brooks, S. and Peglar, S. (2004). *Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Scotland & Northern England) ecotypes.* SNIFFER Report no.: WFD08, 151 pp.

Benson-Evans, K., Antoine, R. and Antoine, S. (1999). Studies of the water quality and algae of Llangorse Lake. *Aquatic Conservation: Marine and Freshwater Ecosystems* **9**, 425-439.

Bull, C.J. and Mackay, W.C. (1976). Nitrogen and phosphorus removal from lakes by fish harvest. *Journal of the Fisheries Research Board of Canada*, **33**, 1374-1376.

Burgess, A., Goldsmith, B. and Hatton-Ellis, T. (2006) *Site Condition Assessments of Welsh SAC and SSSI Standing Water Features*. CCW Contract Science Report No: 705

Burt, T.P., Heathwaite, A.L.and Johnes, P.J. (1996). Stream water quality and nutrient export in the Slapton catchments. *Field Studies*, **8**, 613-627.

Burton, T.M., King, D.L., and Ervin, J.L. (1979). Aquatic plant harvesting as a lake restoration technique. In *Lake Restoration: Proceedings of a National Conference*. Minnesota: United States Environment Protection Agency.

Carvalho, L., Maberly, S., May, L., Reynolds, C., Hughes, M., Brazier, R., Heathwaite, L., Liu, S., Hilton, J., Hornby, D., Bennion, H., Elliott, A., Willby, N., Dils, R., Phillips, G., Pope, L. and Fozzard, I. (2005). *Risk Assessment Methodology for Determining Nutrient Impacts in Surface*

Freshwater Bodies. Environment Agency and Scottish Environment Protection Agency Science Report SC020029/SR, 220 pp.

Carvalho, L., Phillips, G. Maberly, S.C. and Clarke, R.. (2006). *Chorophyll and phosphorus classifications for UK lakes*. SNIFFER report no: WFD38.

Chambers, F.M. (1999). The Quaternary history of Llangorse Lake: implications for conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**, 343-359.

Collins, V.G., Jones, J.G., Hendrie, M.S., Shewan, J.M., Wynn-Williams, D.D. and Rhodes, M.E. (1973). Sampling and estimation of bacterial populations in the aquatic environment. In: *Sampling – microbiological monitoring of the environment*. (eds. R.G. Board and D.W. Lovelock). Soc. Appl. Bact. Tech. Ser, 7, 77-110. London: Academic.

Council of the European Communities (1992) Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. 48 pp.

Council of the European Communities (2000) Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. 72 pp.

Countryside Council for Wales (CCW), *pers. comm*. The environment history of Llangorse Lake, Appendix 1.

Cragg, B.A., Fry, J.C., Bacchus, Z. and Thurley, S.S. (1980). The aquatic vegetation of Llangorse Lake, Wales. *Aquatic Botany*, **8**, 187-96

Cundale, G.C. (1980). Llangorse Lake is dying : fact or fantasy? *Nature in Wales*, **17**, 71-79.

Dickinson, J. and Teeuw, R. (1999). Recent land-use change in the catchment of Llangorse Lake, Brecon Beacons National Park, Wales. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**, 411-423.

Dillon, P.J. and Rigler, F.H. (1974). A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. *Journal of the Fisheries Research Board of Canada*, **31**, 1771-1778.

Dudley, B. and May, L. (2007). *Estimating the phosphorus load to waterbodies from septic tanks.* Report to the Scottish Environment Protection Agency and Scottish Natural Heritage, 45 pp.

Duigan, C.A., Reid, S., Monteith, D.T., Bennion, H., Seda, J.M. and Hutchinson, J. (1999). The past, present and future of Llangorse Lake – a shallow, nutrient-rich lake in the Brecon Beacons National Park, Wales, UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**, 329-341.

Duigan, C., Kovach, W. & Palmer, M. (2006) A Revised Classification of British Lakes. JNCC, Peterborough.

Eisenrich, S.J., Bernasconi, C., Campostrini, P., De Roo, A., George, G., Heiskanen, A-S., Hjorth, J., Hoepffner, N., Jones, K.C., Noges, P., Pirrone, N., Runnalls, N., Somma, F., Stilanakis, N., Umlauf, G., van de Bund, W., Viaroli, P., Vogt, J. and Zaldivar, J-M. (2005) *Climate Change and the European Water Dimension*. Report by the European Commission Joint Research Centre, no. EUR 21553.

EPBRS (2008). Water For Life: Research Priorities For Sustaining Freshwater Biodiversity. Recommendations of the European Platform for Biodiversity Research Strategy, Slovenia, January 2008. http://www.epbrs.org/PDF/EPBRS-SI2008-Freshwater_Final_.pdf

Farmer, J.G., Bailey-Watts, A.E. Kirika, A. and Scott, C. (1994). Phosphorus fractionation and mobility in Loch Leven sediments. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **4**, 45-56.

Foy, R.H. (1985). Phosphorus inactivation in a eutrophic lake by the direct addition of ferric aluminium sulphate: impact on iron and phosphorus. *Freshwater Biology*, **15**, 613-629.

Griffiths, B.M. (1939). Early references to waterblooms in British Lakes. *Proceedings of the Linnaean Society (London)*, **151**, 14-19.

Hall, G.H., Maberly, S.C., Reynolds, C.S., Winfield, I.J., James, J.B., Parker, J.E., Dent, M.M., Fletcher, J.M., Simon, B.M. and Smith, E. (2000). *Feasibility study on the restoration of three Cumbrian Lakes.* Final Report to English Nature.

Harper, D. (1992). *Eutrophication of freshwaters: principles, problems and restoration*. Chapman and Hall, London, 327 pp.

Haygarth, P., Johnes, P., Butterfield, D., Foy, R. and Withers, P. (2003). *Land use for achieving 'good ecological status' of waterbodies in England and Wales: a theoretical exploration for nitrogen*. Report to Defra, 30 pp., 11 tables, 28 figures, 3 appendices.

Hydrological Review (2005). http://www.nwl.ac.uk/ih/nrfa/yb/yb2005/

Joint Nature Conservation Committee (JNCC) (2005) *Common Standards Monitoring Guidance for Standing Water*. JNCC, Peterborough. Available at http://www.jncc.gov.uk/page-2232

Jones, R. and Benson-Evans, K. (1974). Nutrient and phytoplankton studies of Llangorse Lake in the Brecon Beacons National park, Wales. *Field Studies*, **4**, 61-75.

Jones, R., Chambers, F.M. and Benson-Evans, K. (1991). Heavy metals (Cu and Zn) in recent sediments of Llangorse Lake, Wales: non-ferrous smelting, Napoleon and the price of wheat – a palaeoecological study. *Hydrobiologia*, **214**, 149-154.

Kirchner, W.B. and Dillon, P.J. (1975). An empirical method of estimating the retention of phosphorus in lakes. *Water Resources Research*, **11**, 182-183.

Macan, T.T. (1970). *Biological studies of the English lakes*. Longman, London.

Mooij, W.M. S. Hülsmann, L.N. De Senerpont Domis, B.A. Nolet, P.L.E. Bodelier, P.C.M. Boers, L.M. Dionisio Pires, H.J. Gons, B.W. Ibelings, R. Noordhuis, R. Portielje, K. Wolfstein & E.H.R.R. Lammens (2005) The impact of climate change on lakes in the Netherlands: a review. *Aquatic Ecology*, **39**, 381-400.

Monteith, D. (ed.) (1996). *Integrated Classification and Assessment of Welsh Lakes: Phase III. Final Report*. CCW Science Report No. 167, CCW, Bangor.

Murphy, J. and Reilly, J.P. (1962). A modified single-solution method for the determination of phosphate in natural waters. *Analyt. Chim. Acta*, **27**, 31-36.

Oglesby, R.T. (1969). Effects of controlled nutrient dilution on the eutrophication of a lake. In *Eutrophication: Causes, Consequences, Correctives* (ed. G.A. Rohlich). Washington: National Academy of Sciences.

Ohnstadt, F.R. and Jones, J.G. (1982). *The Jenkin surface-mud sampler user manual*. Freshwater Biological Association Occasional Publication, No. 15.

Peterson, S.A. (1979). *Dredging and lake restoration. In: Lake Restoration: Proceedings of a national conference.* United States Environment Protection Agency, Washington, USA.

Randall, S., Harper, D. and Brierley, B. (1999). Ecological and ecophysiological impacts of ferric dosing in reservoirs. *Hydrobiologia*, **395/396**, 355-364.

Redfield A.C., Ketchum, B.H. and Richards, F.A. (1963). The influence of organisms on the composition of seawater. In *The Sea 2: The composition of seawater* (ed. Hill, M.N.). Wiley, New York. pp26-77.

Risgaard-Petersen, N., Rysgaard, S., Nielsen, L. P. and Revsbech, N.P. (1994). Diurnal variation of denitrification and nitrification in sediments colonized by benthic macrophytes. *Limnology and Oceanography*, **39**: 573-579.

Robb, M., Greenop, B. Goss, Z. Douglas, G. and Adeney, J. (2003). Application of Phoslock, an innovative phosphorus binding clay, to two western Australian waterways: preliminary findings. *Hydrobiologia*, **494**: 237-243.

Sas, H. (1989). *Lake Restoration by Reduction of Nutrient Loading*. pp. 81-89. Academia Verlag, Richarz.

Spears, B.M., L. Carvalho, R. Perkins, & D.M. Paterson. (2008). The effects of light on sediment nutrient flux and water column nutrient stoichiometry in a shallow lake. *Water Research*, **42**, 977-986.

SAC (2005). *Special Areas of Conservation: Site condition summary report for Llangorse Lake*.

Turner, C., Brooker, M. and Owens, M. (1981). *Llyn Syfaddan-Llangorse Lake. A brief review of scientific and recreational investigations, together with recommendations for future studies*. Welsh water Authority, Directorate of Scientific services.

UKCIP (2002). *Climate Change Scenarios for the United Kingdom: T*

he UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

UKTAG (2007). UK *Environmental Standards And Conditions (Phase 2).* Report of the UK Technical Advisory Group on the Water Framework Directive, no. SR1-2007, 79 pp.

Vollenweider, R.A. (1968). *Water Management Research; Scientific Fundametals of the Eutrophication of Lakes and Flowing Waters, with particular referenece to Nitrogen and Phosphorus as factors in Eutrophication*. OECD, Paris, Technical Report DAS/CSI/68.27

Wade P.M. (1999). The Impact of Human Activity on the Aquatic Macroflora of Llangorse Lake, South Wales. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **9**, 441-60.

Welch, E.B. and Patmont, C.R. (1980). Lake restoration by dilution: Moses Lake, Washington. *Water Research*, **14**, 1317-1325.

Wetzel, R. G. and Likens, G. E. (2000). Inorganic nutrients: nitrogen, phosphorus and other nutrients. In *Limnological Analyses*. Springer-Verlag, New York.

White, P.J. and Hammond, J.P. (2006). *Updating the estimate of the sources of phosphorus in UK waters*. Report to Defra, project number: WT0701CSF; 57 pp.

Willby, N., Hilton, J., Pitt, J.A. and Phillips, G. (2006). *Summary of approach used in LEAFPACS for defining ecological quality of rivers and lakes using macrophyte composition.* Interim Report June 2006. University of Stirling, Stirling.

APPENDIX 1: LLYN SAFADDAN PARISH PROFILE

The Locality

The six churches of Llyn Safaddan serve the communities around Llangorse Lake, Bwlch, Cathedine, Llanfihangel Talyllyn, Llangasty Talyllyn, Llangorse and Llanywern. This is an entirely rural area with a population of 1,200 on the civil electoral roll. It is an area of great natural beauty and historic interest situated in the Brecon Beacons National Park. Llangorse Lake is an important wildlife site with special European environmental status and is the focus of a number of out door activities including sailing, fishing and bird watching.

The local economy is based on farming, tourism and related activities. Several residents commute to work outside the area and there are some retired residents, many of them active in the church and community. The population looks to the nearby market towns of Brecon, Crickhowell and Hay on Wye for facilities not available in small villages, such as shops, hospitals, medical centres, libraries, sporting activities and secondary schools.

The Vicarage is situated on the outskirts of Llangorse Village in a large garden (mostly lawn) and enjoys glorious views over Llangorse Lake to the Brecon Beacons. It is a detached house with 4 bedrooms, built in the first half of the 20th century. It has oil-fired central heating. Renovation work has been undertaken in recent years and further work is planned for the vacancy.

The Community

The separate villages of the parish have lively, distinct and expanding communities with good parish or village halls, which are the focus of a growing variety of social activities and community events. Thriving groups and activities include the Women´s Institute, the Cubs, a young youth club, a photographic society, an art club, junior and senior badminton and ballroom dancing. There is also a monthly older residents lunch club and among annual community events are a pantomime, a summer carnival, a November ball and Christmas and other seasonal celebrations.

Llangors VC Church in Wales School (number on school roll 112) is the one primary school in the parish. It has a settled staff and is popular with local parents. Its excellence is a factor in attracting young families to the area. The parish has strong links with Llangors School and supports it in a number of ways. The incumbent is a member of the school´s governing body and church members serve as foundation governors. From Llangors School pupils go on to high schools at Brecon, Crickhowell or Gwernyfed (near Hay on Wye). Another local educational establishment is Christ College in Brecon, an independent co-educational secondary school.

At the other end of the age range, Brookside residential home in Llangorse houses a number of elderly residents.

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APPENDIX 3: SUMMARY DATA

Date	Site	Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	1	185.08	185.41	0.42	
24/10/06	1	178.95	194.73	1.23	
07/11/06	1	129.10	135.01	0.65	
21/11/06	1	147.90	156.99	0.92	
30/01/07	1	78.38	139.67	1.78	
13/02/07	1	56.58	103.97	3.77	
27/02/07	1	30.02	98.33	3.38	
27/03/07	1	11.54	114.18	1.05	
10/04/07	1	35.68	53.64	0.91	
24/04/07	1	28.17	129.81	0.56	
08/05/07	1	27.54	143.33	0.06	
22/05/07	1	28.87	60.17	0.06	
05/06/07	1	79.49	122.91	0.09	
19/06/07	1	76.09	129.81	0.09	
03/07/07	1	75.88	143.33	0.07	
17/07/07	1	75.88	129.81	0.09	
31/07/07	1	50.04	102.53	0.06	
14/08/07	1	115.61	150.74	0.09	
28/08/07	1	104.51	139.42	0.07	
11/09/07	1	121.89	152.33	0.06	
25/09/07	1	134.67	157.76	0.08	

Date	Site	Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	2	140.51	152.55	7.90	0.19
24/10/06	2	100.80	129.35	7.09	0.18
07/11/06	2	61.51	39.44	5.70	0.19
21/11/06	2	87.91	85.06	7.87	0.14
05/12/06	2	162.33	271.80	3.17	0.24
19/12/06	2	60.14	59.64	5.39	0.29
02/01/07	2	73.83	105.99	4.26	0.20
16/01/07	2	65.83	75.61	5.59	0.13
30/01/07	2	56.61	94.96	7.37	0.12
13/02/07	2	58.46	87.96	6.77	0.18
27/02/07	2	52.00	105.07	5.93	0.19
13/03/07	2	64.11	75.04	6.00	0.09
27/03/07	2	31.97	110.46	4.25	0.08
10/04/07	2	25.92	39.07	3.38	0.00
24/04/07	2	53.98	171.06	4.19	0.01
08/05/07	2	76.43	137.70	4.34	0.17
22/05/07	2	91.20	105.31	4.38	0.19
05/06/07	2	134.07	153.72	4.00	0.18
19/06/07	2	126.06	171.06	3.36	0.17
03/07/07	2	91.21	137.70	2.91	0.19
17/07/07	2	91.63	171.06	3.07	0.19
31/07/07	2	500.87	492.77	4.65	0.17
14/08/07	2	121.48	154.59	4.91	0.08
28/08/07	2	102.41	86.00	4.71	0.02
11/09/07	2	117.08	118.82	4.19	0.00
25/09/07	2	112.05	104.11	2.67	0.01

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	3	119.39	114.92	7.32	0.06
24/10/06	3	112.42	107.82	7.13	0.04
07/11/06	3	73.34	53.43	4.61	0.21
21/11/06	3	77.99	80.84	4.54	0.08
05/12/06	3	223.59	272.03	2.71	0.12
19/12/06	3	52.76	59.86	5.30	0.02
02/01/07	3	67.72	94.06	3.31	0.25
16/01/07	3	44.55	53.56	4.34	0.08
30/01/07	3	41.33	82.15	8.52	0.02
13/02/07	3	59.71	100.72	7.28	0.06
27/02/07	3	45.72	108.22	6.67	0.06
13/03/07	3	60.29	112.45	4.81	0.04
27/03/07	3	36.56	52.93	5.73	0.01
10/04/07	3	57.32	69.12	3.05	0.00
24/04/07	3	70.35	112.45	3.58	0.00
08/05/07	3	80.00	118.76	4.20	0.10
22/05/07	3	94.54	126.34	4.54	0.10
05/06/07	3	114.83	118.98	5.46	0.06
19/06/07	3	139.92	112.45	4.08	0.02
03/07/07	3	69.37	118.76	3.26	0.06
17/07/07	3	71.05	112.45	3.30	0.23
31/07/07	3	65.33	62.69	4.60	0.12
14/08/07	3	100.53	85.55	5.39	0.06
28/08/07	3	84.60	93.70	5.65	0.01
11/09/07	3	90.68	90.53	4.52	0.01
25/09/07	3	99.48	98.68	3.11	0.00

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	4	33.42	43.10	2.74	0.04
24/10/06	4	19.48	33.89	2.42	0.02
07/11/06	4	28.56	8.36	2.56	0.02
21/11/06	4	17.37	33.45	2.46	0.01
05/12/06	4	24.95	83.49	2.46	0.03
19/12/06	4	15.26	26.57	2.75	0.03
02/01/07	4	14.63	33.99	2.21	0.04
16/01/07	4	10.83	22.52	2.78	0.02
30/01/07	4	13.28	35.20	5.39	0.01
13/02/07	4	16.96	54.55	4.93	0.04
27/02/07	4	8.25	32.05	4.92	0.04
13/03/07	4	12.55	24.04	3.10	0.02
27/03/07	4	15.08	53.16	3.52	0.01
10/04/07	4	12.55	19.94	3.26	0.00
24/04/07	4	16.21	29.72	3.66	0.01
08/05/07	4	15.37	30.40	3.97	0.04
22/05/07	4	16.33	28.35	3.76	0.03
05/06/07	4	35.78	81.48	3.68	0.04
19/06/07	4	34.31	29.72	3.44	0.03
03/07/07	4	13.94	30.40	2.06	0.04
17/07/07	4	15.20	29.72	2.38	0.03
31/07/07	4	18.20	21.03	3.01	0.03
14/08/07	4	20.08	24.43	3.49	0.02
28/08/07	4	17.99	24.66	4.14	0.01
11/09/07	4	19.66	24.20	3.88	0.00
25/09/07	4	19.87	30.54	2.93	0.00

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	5	47.99	36.00	3.44	
24/10/06	5	41.87	31.56	3.99	
07/11/06	5	34.26	7.58	2.96	
21/11/06	5	45.25	23.90	3.09	
05/12/06	5	98.06	145.36	1.77	
19/12/06	5	26.85	33.77	2.87	
02/01/07	5	71.25	29.94	2.81	
16/01/07	5	29.16	34.89	2.04	
30/01/07	5	27.72	54.07	5.93	
13/02/07	5	23.84	57.34	5.40	
27/02/07	5	16.63	48.23	4.11	
13/03/07	5	25.49	32.01	2.53	
27/03/07	5	24.05	74.27	3.30	
10/04/07	5	23.37	32.01	2.84	
24/04/07	5	23.77	46.85	2.20	
08/05/07	5	22.30	45.27	3.18	
22/05/07	5	22.18	31.96	3.78	
05/06/07	5	33.68	51.60	3.92	
19/06/07	5	33.26	46.85	3.70	
03/07/07	5	29.48	45.27	2.17	
17/07/07	5	30.74	46.85	2.22	
31/07/07	5	29.72	34.16	2.61	
14/08/07	5	34.33	50.46	2.96	
28/08/07	5	29.30	33.71	4.17	
11/09/07	5	35.58	45.93	3.75	
25/09/07	5	46.69	108.86	3.17	

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	6	80.10	109.48	2.49	0.69
24/10/06	6	56.44	80.96	2.68	0.66
07/11/06	6	29.83	18.80	2.32	0.68
21/11/06	6	44.82	37.55	2.89	0.52
05/12/06	6	94.43	173.03	1.26	0.83
19/12/06	6	29.37	46.14	2.00	1.00
02/01/07	6	31.48	56.04	1.71	0.71
16/01/07	6	28.32	45.24	1.63	0.49
30/01/07	6	21.65	59.24	4.93	0.44
13/02/07	6	27.80	68.71	4.60	0.63
27/02/07	6	25.63	85.07	3.90	0.68
13/03/07	6	28.89	54.10	2.47	0.35
27/03/07	6	28.43	82.39	1.88	0.33
10/04/07	6	27.40	40.66	2.53	0.07
24/04/07	6	36.57	88.78	2.79	0.08
08/05/07	6	36.99	73.45	2.77	0.61
22/05/07	6	34.94	48.89	2.35	0.68
05/06/07	6	62.55	87.48	2.82	0.66
19/06/07	6	62.02	88.78	1.66	0.61
03/07/07	6	39.77	73.45	1.77	0.69
17/07/07	6	50.69	88.78	1.18	0.69
31/07/07	6	33.49	48.42	1.76	0.60
14/08/07	6	47.73	52.73	1.91	0.32
28/08/07	6	48.57	61.10	2.77	0.13
11/09/07	6	69.73	77.85	2.12	0.04
25/09/07	6	69.47	70.83	2.47	0.08

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	7	106.88	124.91	3.68	0.02
24/10/06	7	120.44	157.99	1.11	0.02
07/11/06	7	41.66	44.99	2.15	0.03
21/11/06	7	86.22	91.39	1.66	0.02
05/12/06	7				0.03
19/12/06	7				0.04
02/01/07	7				0.03
16/01/07	7				0.02
30/01/07	7	55.98	136.52	4.54	0.02
13/02/07	7	43.44	181.69	3.59	0.03
27/02/07	7	46.14	116.98	3.29	0.02
13/03/07	7				0.02
27/03/07	7	33.85	91.44	1.99	0.02
10/04/07	7	32.07	46.35	2.31	0.00
24/04/07	7	34.05	101.85	1.61	0.00
08/05/07	7	33.42	104.56	1.58	0.03
22/05/07	7	39.33	84.93	1.29	0.04
05/06/07	7	50.42	65.81	1.20	0.02
19/06/07	7	63.70	101.85	0.90	0.02
03/07/07	7	61.60	104.56	0.93	0.02
17/07/07	7	65.59	101.85	1.00	0.03
31/07/07	7	59.68	62.46	1.42	0.03
14/08/07	7	56.53	57.03	1.68	0.02
28/08/07	7	33.49	45.93	1.59	0.01
11/09/07	7	53.39	71.51	1.55	0.00
25/09/07	7	49.62	57.71	0.92	0.00

		Nutrient concentrations			
Date	Site	SRP (µg/l)	TP (µg/l)	NO_3-N (mg/l)	Flow (cumecs)
10/10/06	8	47.57	47.32	3.12	
24/10/06	8	46.30	39.11	2.13	
07/11/06	8	24.76	32.23	3.61	
21/11/06	8	45.88	41.88	2.50	
05/12/06	8	92.16	125.79	0.99	
19/12/06	8	28.11	34.67	1.70	
02/01/07	8	39.49	54.01	1.57	
16/01/07	8	23.69	33.09	1.56	
30/01/07	8	16.63	37.44	5.13	
13/02/07	8	26.34	136.91	4.80	
27/02/07	8	22.49	89.57	4.07	
13/03/07	8	21.67	32.46	2.12	
27/03/07	8	18.21	74.97	2.87	
10/04/07	8	18.70	32.46	2.78	
24/04/07	8	25.45	42.57	3.07	
08/05/07	8	32.79	63.31	2.43	
22/05/07	8	42.05	54.76	3.50	
05/06/07	8	67.56	81.84	3.91	
19/06/07	8	51.32	42.57	3.19	
03/07/07	8	37.46	63.31	2.54	
17/07/07	8	30.53	42.57	2.85	
31/07/07	8	21.76	28.05	2.74	
14/08/07	8	22.60	23.52	3.65	
28/08/07	8	21.55	30.77	4.12	
11/09/07	8	22.60	25.79	2.90	
25/09/07	8	21.55	25.56	2.27	