Proposal for the Restoration of Loch Flemington using Controlled Application of a Lanthanum-Bentonite Clay (Phoslock®)

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1 RATIONALE

Loch Flemington is designated as a Special Protection Area (SPA; 79/409/EEC) due to its recent use as a nesting site for the rare Slavonian Grebe and is situated within the Kildrummie Kames Site of Special Scientific Interest (SSSI). In recent years, the loch has become increasingly eutrophic due to nutrient laden waste entering from the catchment. This has resulted in a build up of phosphorus (P) within the loch, which causes troublesome algal blooms to develop over the summer months each year. These cause serious water quality problems that threaten the conservation status of the loch. The loch is now classified as being in unfavourable condition in relation to all of the current conservation targets (i.e. specifically macrophyte community composition, macrophyte colonisation traits, and habitat quality for the Slavonian Grebe (*Podiceps auritus*)) and is in urgent need of restoration. However, any restoration activities that are undertaken here must not act to the detriment of the conservation attributes of the loch.

An application of lanthanum-bentonite clay (marketed as Phoslock®) has been proposed to reduce the effects of the phosphorus (P) pollution (eutrophication) in Loch Flemington. The clay product strips P from the water-column when first applied and, once settled onto the lake bed, reduces the magnitude of P cycling between the sediments and the water-column. A key aim of the proposed restoration programme is to attempt to force the lake to switch from a turbid, phytoplankton dominated state to a clear-water, macrophyte dominated state that is consistent with the conservation attributes of the site (i.e. characteristics of a naturally eutrophic ecosystem).

This risk assessment considers the proposed clay application to Loch Flemington and highlights any possible low-risk, short-term (< 1 month), negative effects on biota that this is likely to cause. These are generally associated with the temporary increase in suspended sediment that will be associated with the application of the clay. These effects can largely be mitigated by spreading the application over a number of days (potentially weeks), timing the application for the winter period when most species will be least affected and by ensuring that relatively unimpacted refuge areas are maintained during the application. In the longer term (> 1 month), positive effects associated with a general improvement in water quality and, more specifically, with an improvement in conditions that support and encourage the desired macrophyte community and the Slavonian Grebe population, are expected to result in a significant overall improvement in the integrity of the site.

1.1 Introduction to risk assessment

Loch Flemington is a high alkalinity, very-shallow (mean depth 0.75 m; maximum depth 2.35 m) eutrophic loch of glacial origin. The loch lies above an impermeable iron pan and is surrounded by an area of gravel above an impermeable till and sandstone layer (British Geological Survey (BGS), *pers. comm.*). Significant hydrological modifications were made to the loch during the 19th century. This involved blocking the natural surface-water outflow and significantly increasing the surface area and depth of the loch (May et al., 2001).

The loch has a long and relatively well documented history of cultural eutrophication problems, including regular summer blooms of potentially toxin producing cyanobacteria (1990 – 2004; May et al., 2001; Bennion et al,. 2008). As a result, nutrient budgets were constructed for the loch and its catchment, which resulted in both the identification and subsequent reduction of significant point sources of P (e.g. upgrading of Croy waste water treatment works). A recent assessment of total P (TP) loads to Loch Flemington indicated that diffuse sources (e.g. agricultural sources) were the dominant external TP source (~ 80% external TP load) with septic tanks representing ~ 18% of the external TP load (May et al., 2001). However, the same study suggested that the internal, sediment-driven load to the water-column (680 kg TP yr^{-1}) was far greater than the load from the catchment (120 kg TP yr^{-1}).

May et al. (2001) also assessed the functioning of Loch Flemington and found that high particulate P and chlorophyll *a* concentrations within the water-column were usually coupled with low dissolved P concentrations. This suggested that any biologically available (dissolved) P was quickly and efficiently converted into particulate-organic P (i.e. algae). Also, after the hydrological alterations described above, there was no longer any surface-water outflow through which particulate P could leave the loch, as only dissolved P could be discharged to groundwater *via* the sand and gravel banks towards the eastern shores. As a result, the majority of the influent P became trapped within the loch and probably resulting in a “stock-piling” of P in the sediments. It is likely that significant improvements in water quality can now only be achieved by the management of internal P loads from the sediment.

Although improvements in water quality have been observed following the significant reductions in both point and diffuse sources within the catchment (Ian Milne, *pers. comm.*), these restoration efforts have not resulted in the desired ecological responses; the characteristics of the macrophyte community, in particular, have lead to the site being classified as being in “unfavourable condition” according to the criteria for a naturally eutrophic loch (SNH Condition Monitoring Report, 2005). This prolonged recovery (commonly > 10 years in moderately flushed lakes; Spears et al., 2007a) is common in many shallow lakes and is caused by internal loading of sediments (predominantly in late summer) following a reduction in the external load (Sas, 1989; Søndergaard, 2007; Spears et al., 2007b). However, estimated recovery rates are based on situations where large amounts of P can be flushed from the outflow. In the case of Loch Flemington, where this is not possible, there is an expectation that the rate of recovery will be very much slower than in lakes with surface water outflows.

This risk assessment considers the likely positive and negative effects of the proposed restoration programme on the loch in relation to its expected short-term (< 1 month) and long-term (> 1 month) effects on site attributes, using recent, i.e. 2005 – present, and long-term, i.e. pre-1850 – present, site assessments as a baseline. These recent assessments were conducted by the Royal Society for the Protection of Birds (RSPB), who provided the results of long-term monitoring of the Slovenian Grebe population and habitat quality at Loch Flemington (Stuart Benn, *pers. comm.*), Scottish Natural Heritage (SNH) who provided a Site Condition Monitoring Report from 19th September 2005 (SNH, 2005), and University College London who carried out a palaeoecological assessment of the sediment cores (Bennion et al., 2008).

1.2 Details of proposed clay application

Phoslock® is a lanthanum (La) modified bentonite clay with a very high binding capacity for dissolved P (100g Phoslock® binds 1 g of P). La^{3+} ions that are strongly bound within the clay matrix react with dissolved P to form the mineral Rhabdophane

($LaPO_4$). $LaPO_4$ is very stable in the environment and is unlikely to release P even under conditions of anoxia or at extreme pH levels (i.e. outwith pH range 4 – 9; Ross et al., 2008). Additionally, both the clay substance and lanthanum are common inorganic constituents of lake sediments, with natural lanthanum concentrations in the sediments of 10 European lakes being found to range from 10 mg kg^{-1} dw to 45 mg kg^{-1} dw (Spears; unpublished data).

As a restoration measure, lanthanum modified clay is designed to enhance the capacity of natural lake sediments to adsorb dissolved (i.e. bio-available) P and significantly reduce its subsequent release. As such, it may provide an effective treatment for lakes where sediments represent the dominant source of P to the water column, especially if the external load has been reduced (Robb, et al., 2003; Hupfer et al., 2008). Phoslock® has been used to successfully control sediment P release and reduce water-column P concentration in a number of lakes across the world (http://www.phoslock.com.au/technical.php).

The proposed application of clay will be conducted by Phoslock® Water Solutions Ltd. Europe in February 2010. The exact timing of this application will be agreed by SNH, SEPA, CEH and other interested parties if this CAR application is successful. The clay application process has been designed to control the mass of phosphorus in the lake water and sediments that may fuel algal growth over the summer period. As such, this will involve the addition of ~ 25 tonnes of Phoslock® to control a maximum of ~ 22 kg TP in the water column (i.e. ~ 180 mg P m^3 x 122,000 m^3 lake volume) and ~ 217 kg TP in the active layer (i.e. upper 3 cm) of the surface sediments (see Appendix 2). As a general rule, 100 g of Phoslock® binds 1 g of phosphorus.

The Phoslock® will first be mixed with lake water to produce slurry that will be applied directly to the water surface from a floating pontoon (Figure 1). The dosage level has been calculated to ensure that the release sensitive phosphorus pools in the sediments and water-column (estimated to be ~ 240 kg in total) are controlled and this will result in a maximum increase in the load of clay to the water-column of < 204 mg L^{-1}. Although water clarity will reduce at first, as a result of the increase in clay particles in the water, this effect will decrease over time. For example, the time taken for water clarity to increase from a post-application Secchi disk transparency of

~ 75 cm to a Secchi disk transparency that was similar to the pre-application level of ~ 1.75 m in Clatto Reservoir (a lake of similar depth and size to Loch Flemington) was about 4 weeks. The proposed application will result in a final concentration of < 16 mg clay cm^{-2} over the bed of the loch after about 4 weeks, once the clay particles have settled.

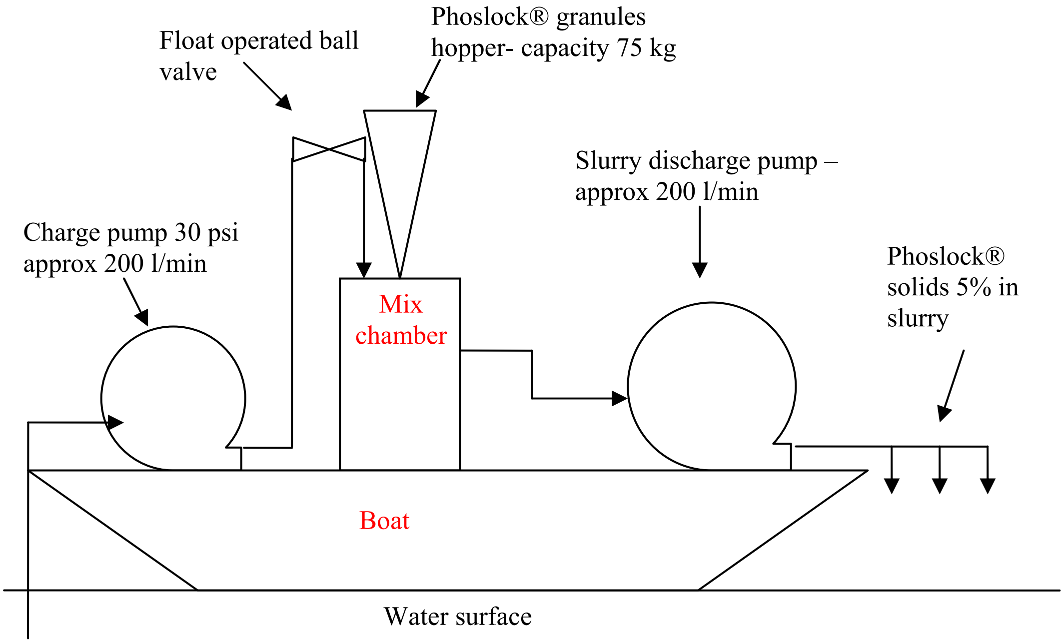

Figure 1. Schematic diagram of the application pontoon that will be used at Loch Flemington.

1.3 Project costs

Comprehensive pre- and post-application monitoring will be planned and conducted by CEH in collaboration with SEPA and SNH. CEH staff time, Phoslock®, application costs and sample analysis costs will be covered by CEH in the form of a fully funded PhD project (~ £100k over 3 years). Pre-application monitoring began in May 2009 and consists of monthly sampling visits. Daily sampling will be conducted for three days prior to and 7 days following the application, and sample frequency will increase to weekly intervals for the following two months and monthly for a further 10 months post application (i.e. over a 12 month post-application monitoring period). Samples will be collected for the determination of chemical and biological conditions in the water-column and sediments.

2 ASSESSMENT OF RISK TO SITE ATTRIBUTES

A risk assessment was conducted in consultation with SNH to identify (1) the site attributes with which Loch Flemington is designated, (2) the current status of these attributes in line with relevant targets and (3) the expected positive or negative effects of the proposed application of Phoslock® on each of the site attributes and whether action may be taken to reduce any potential negative effects.

2.1 Habitat extent (SNH 2005; *target met*)

The size and physical structure of Loch Flemington was assessed in 2005. It was concluded that these attributes had remained unaltered in recent years, with no loss in the extent of standing water. However, the reported notes that the level of confidence in the data available to make this assessment was low.

2.1.1 Positive/negative effects of proposed clay application

No positive or negative effects on the extent of open water at Loch Flemington are expected as a result of the proposed clay application.

2.2 Composition of macrophyte community (SNH 2005; *target failed*)

In 2005 (SCM, 2005), seven submerged macrophyte species were recorded in Loch Flemington using fixed point sector/transect sampling methods (Gunn et al., 2004). These species were *Littorela uniflora, Myriophyllum spicatum, Potamogeton species* (*gramineus or x nitens*), *P. natans, P. obtusifolius* and *Elodea canadensis*. The characteristic species *Hydrocotyle vulgaris* and *Ranunculus aquatilis* were not recorded in 2005. The exposed littoral zone was characterised by extensive fringing beds of *Persicaria amphibium*. The percentage frequency recorded for species typical of a eutrophic lake was 45% for Loch Flemington, which is below the 60% level required for eutrophic lakes. As a result, Loch Flemington failed to meet the target for this attribute because characteristic species were absent and the percentage frequency observation of characteristic species was too low.

Paeleolimnological analyses of sediment cores (Bennion et al., 2008) indicated that there have been three major time zones during which there have been significant shifts in the macrophyte community. These were:

Zone 1. *Pre-1850, 60 and 52 cm (mesotrophic conditions)*
Sparse plant macrofossils with *Nitella* oospores present at 52 cm. Species present included *Myriophyllum alterniflorum*, *Callitriche* spp., *Rannunculus* spp., *Potamogeton* cf *praelongus* and *P. obtusifolius*. These species are characteristic of mesotrophic – eutrophic conditions.

Zone 2. *About 1850 to post-1850, 40-16 cm (meso-eutrophic conditions)*
Species diversity increased relative to zone 1. Species included *Chara* spp., *Rannunculus* spp., several *Potamogeton* spp., *Isoetes lacustris*, *Myriophyllum alterniflorum* and *Najas flexilis* (spines recorded - 35 cm, seeds first recorded– 21 cm; i.e. post 1850). Evidence of cyanobacterial occurrence in the water-column was observed within this zone in the form of *Gloeotrichia spp.* This tended to increase with decreasing depth.

Zone 3. *Post-1850, 10-1 cm (eutrophic conditions)*
Species diversity decreased relative to zone 2. *Potamogeton* leaf fragments evident but seeds not recorded. *Nymphaeaceae trychosclereids* remains observed at 9 cm. *Najas flexilis* spines observed throughout peaking at 5 cm. *Gloeotrichia* spp. occurrence was significantly higher in this zone and was highest at around 10 cm, decreasing towards the sediment surface.

Bennion et al. (2008) suggested that the macrophyte community in the loch had undergone a “complete turnover” in comparison to reference conditions (i.e. pre-1850). This change was characterised by dominance of Charophytes pre-1850, a species phase change and increased biodiversity shortly after 1850, and a loss of biodiversity and change to more eutrophic species in recent years. Evidence of these changes was also observed in zooplankton remains in the sediments, with

Simocephalus (a macrophyte obligate taxon) being observed to decrease with decreasing macrophyte community diversity and abundance. The observed step-change in the macrophyte community composition (~1850) occurred around the time that the surface-water outflow was blocked at Loch Flemington. A comparison of historical and contemporary maps of the area suggests a significant increase in loch surface area before and after this event. Although *Nijas flexilis* has not been reported in any recent macrophyte surveys at Loch Flemington, remains of this species have been found in sediments deposited over the last 100 years, including in 2004. The fact that no observations of *Nijas flexilis* were reported in the recent loch surveys (e.g. SCM, 2005) indicates that the species is scarce and suggests that a higher sampling effort may be necessary to record this species during macrophyte surveys of this loch in future (Spears et al., 2009).

2.2.1 Positive/negative effects of proposed clay application

The effects of the clay application on macrophyte growth are expected to be negative in the short-term (i.e. within 4 weeks of the application) due to increased turbidity and greater light attenuation caused by clay particles in the water-column. These short-term negative effects can be minimised by conducting the application during late winter; i.e. before the start of the macrophyte growing season which spans May to October. Observations from similar studies suggest that, once settled, the clay does not inhibit the establishment of macrophytes (Spears, *pers. obs*.), although it is possible that lower P availability in the surface sediments could result in some P-limitation of macrophyte growth rates, initially.

Sporadic disturbance and settling of surface sediments in exposed shallow lakes that are subject to wind disturbance, such as Loch Flemington, will result in the clay layer becoming dispersed vertically over the top 2-3 cm of the sediments in shallow areas (Cyr, 1998). This will (1) reduce the absolute concentration of Phoslock® per unit volume of sediment and (2) result in a supply of available P for macrophyte uptake. At current sedimentation rates (i.e. ~ 2.6 cm yr^{-1}; Bennion et al., 2008) layering processes will result in the clay zone exceeding the zone of macrophyte root extension (greater than about 15 cm sediment depth) within about 10 years. However, it should be noted that macrophytes can alter their root penetration characteristics in response to changes in environmental conditions (Idestam-Almquist & Kautsy, 1995).

Following the initial short-term increase in light-attenuation, significant positive long-term (i.e. > 4 months) effects are expected. These effects will be associated with an increase in light conditions at the sediment surface as a result of reductions in water-column P concentrations and phytoplankton biomass. An improved light climate will favour an increase in macrophyte biodiversity (Scheffer, 2001) and it is expected that these conditions will favour re-establishment of characteristic species that are currently absent (e.g. *Najas flexilis*, *Hydrocotyle vulgaris* and *Ranunculus aquatilis*). Similar community shifts associated with recovery from eutrophication, after management intervention, have been observed in Loch Leven over a 100 year period (Dudley et al., in prep.). It is, however, unlikely that clay addition, alone, will reduce the abundance of the invasive species *Elodea canadensis* and additional measures may be necessary to remove this species from dense macrophyte beds. Although an increase in overall biodiversity is expected to favour the re-emergence of characteristic species, the dominance of *Elodea canadensis* may have to be controlled (Van Dijk & Van Donk, 1991) to allow the less competitive, desirable, species to gain a foothold within the canopy (as outlined in Appendix 1).

Owing to its importance as a protected species, the specific habitat requirements of *Najas flexilis*, and the expected effects of the proposed clay application on its habitat quality, are reviewed separately (Appendix 1). In general, the expected reduction in P concentration and associated increase in light availability at the sediment surface will improve the habitat quality for this species. Additionally, previous studies have indicated that the clay application will have little impact on water-column pH conditions. So, the existing pH conditions in Loch Flemington, which are already within the required range for *Najas flexilis*, are expected to remain unchanged.

2.3 Macrophyte community structure (SNH 2005; *target failed*)

The specific targets (e.g. maximum colonisation depths, maintenance of present structure, estimates of the extent of characteristic zones) of this attribute were not quantified in the recent SCM report. However, it was noted that the percentage frequency occurrence of the uncharacteristic *Elodea canadensis* (i.e. > 50% occurrence) would result in failure of this attribute.

2.3.1 Positive/negative effects of proposed clay application

The expected long-term improvement in light availability will result in a deepening of the overall colonisation depth of macrophytes in the loch. This relationship has been well documented in the literature (Scheffer, 2001; Spears et al., 2009). Assuming that no other management practices are conducted, the increased aerial coverage of macrophytes resulting from this will cause an overall increase in the macrophyte P buffering capacity (i.e. trans-locating P *via* the sediment-macrophyte-sediment pathway as opposed to the sediment-phytoplankton-sediment pathway; Scheffer, 2001); this will effect a switch from a phytoplankton dominated turbid lake to a clear water macrophyte dominated lake.

2.4 Water quality (SNH 2005; *target failed*)

Few historical water quality data exist for this site (i.e. for previous decades), so long term changes in water quality are difficult to quantify. However, there is some evidence that Loch Flemington has suffered from elevated TP concentrations and periodic cyanobacterial blooms for several decades (May et al., 2001). If Loch Flemington had fallen within the size range considered by the WFD, it would have been classified as a high alkalinity, very shallow site. As such, the loch would have been assigned a good/moderate annual mean TP boundary value of about 36 $\mu g\ L^{-1}$ and a high/good boundary value of about 26 $\mu g\ L^{-1}$ (UK-TAG, 2007). This would equate to chlorophyll *a* concentration targets of 8.6 $\mu g\ L^{-1}$ and 16.5 $\mu g\ L^{-1}$ for the high/good and good/moderate boundaries, respectively (Carvalho et al., 2008). Current water quality conditions at this site for 2009 are discussed in Appendix 2 and summarised below.

Data were provided by SEPA detailing water column TP concentrations from 5th July 2000 to 13th May 2009. However, the quality of these data is under review (Ian Milne, pers. com.; SEPA) at present and will, therefore, not be discussed in relation to this application. CEH data collected during 2009 show a significant positive correlation phytoplankton biomass (chlorophyll *a* concentration) and phosphorus concentration over this period, suggesting that phytoplankton productivity is being regulated by phosphorus availability at this site (Appendix 2; section 4.3).

Chlorophyll *a* concentrations measured by SEPA were also provided for the period 23rd February 2005 – 13th May 2009). Mean average chlorophyll *a* concentrations for the existing values were as follows; 51.2 µg l^{-1} in 2005 (all months except January included); 37.6 µg l^{-1} in 2006 (all months included); no data for 2007; 37.3 µg l^{-1} in 2008 (May-September only); and 58.09 µg l^{-1} in 2009 (SEPA data January, April and May; CEH data May-August). These average concentrations are in excess of the WFD guidelines for a lake of this type and suggest very high concentrations of TP in line with those reported in other studies (May et al., 2001: 37.8 – 110.3 µg TP l^{-1} in 1989 and 1990, and 167.6 – 270.1 µg TP l^{-1} in 2000; Appendix 2: 178 µg TP l^{-1} in 2009). Peak concentrations of chlorophyll *a* occur commonly in summer in Loch Flemington and for the years in which data are available have been observed to reach 300 µg l^{-1} in 2000 (CEH data; May et al., 2001); 169 µg l^{-1} in 2005; 48 µg l^{-1} in 2006; 105 µg l^{-1} in 2008; and 167 µg l^{-1} in 2009 (CEH data; Appendix 2).

Paeleolimnological analyses of sediment cores suggest that (diatom inferred) TP concentrations in the water-column have been between 72 and 95 µg TP l^{-1} since the 1880s.

2.4.1 Positive/negative effects of proposed clay application

The application of lanthanum-clay to Loch Flemington will act to (1) reduce soluble reactive phosphorus (SRP) concentrations in the water column; (2) enhance the settling of phytoplankton to the lake bed; and (3) cap P release from the sediments, which are a major source of P to the water column in the loch (Appendix 2; May et al., 2001). Laboratory tests have indicated that Phoslock® is capable of reducing SRP concentrations in the water column to around 10 µg SRP l^{-1} (Sebastian Meis, unpublished data). The effect of this drop in available phosphorus will be to lower the overall productivity of the phytoplankton in the water column. Thus, an overall reduction in water column TP and chlorophyll *a* concentrations is expected.

2.5 Hydrology (SNH 2005; *target met*)

The hydrological regime of Loch Flemington was altered by the construction of an earth bank on the eastern shore in the mid 19th century. This blocked the surface water outflow and resulted in the loch discharging to groundwater *via* sand and gravel beds. This modification pre-dated any conservation designations and the hydrological regime appears to have changed little since designation.

2.5.1 Positive/negative effects of proposed clay application

No positive or negative effects of clay addition on the hydrological regime of Loch Flemington are expected.

2.6 Lake substrate (SNH 2005; *target met*)

The majority of the bed in Loch Flemington is covered by fine mud and silts, with sand and gravel beds being the dominant substratum near the eastern shore. Open water surface sediments are composed of organic material (e.g. algal detritus from the water-column) and inorganic material (e.g. clays and other minerals from the catchment) (Bennion et al., 2008). The organic content of the surface sediments in the open water is about 40%, indicating a significant input of both organic and inorganic matter to the lake bed. However, the organic content of the cores in the littoral zone was higher (~55%) suggesting a higher load of organic matter in these areas (Bennion et al., 2008). This is likely due to higher annual loads of organic material in the form of macrophyte biomass contributing to the sediments in these well illuminated littoral zones. Sedimentation rates for 1998-2004 ranged from 0.05 to 0.06 g cm^2 yr^{-1} and from 0.67 to 0.83 cm yr^{-1}. Similar estimates for 1880 were in the range 0.01 g cm^2 yr^{-1} to 0.06 cm yr^{-1} (Bennion et al., 2008).

2.6.1 Positive/negative effects of proposed clay application

Initially, for the first month, the proposed clay application will be expected to result in a short-term, approximately 400 per cent, increase in the inorganic content of the lake sediments. The ratio of inorganic to organic matter in the sediments will then re-equilibrate to a lower level reflecting the reduction in water-column phytoplankton biomass, which has been assumed to be the key source of organic material to the loch bed. Additionally, wave mixing will relocate any clay that settles within rocky/sandy littoral zones to zones of sediment accumulation (Hilton, 1985).

The effects of the Phoslock® application on sensitive organisms within lakes have been assessed experimentally and used to construct a range of threshold dose concentrations in relation to ecological sensitivity. These include tests on micro-organisms (EC50 = 37 mg dissolved La^{3+} L^{-1} (ISO 11348-3); Institut Dr. Nowak pers. comm.), macroinvertebrates (*Chironomus zealandicus*; LC50 > 400 mg Phoslock® L^{-1} (Clearwater, 2004); *Macrobrachium sp*. EC50 = > 800 mg Phoslock® L^{-1}; Ecotox report (2006)), zooplankton (*Daphnia magna* EC50 = 103 mg dissolved La^{3+} L^{-1} (DIN 38412-L30); Institut Dr. Nowak, pers. comm.) and fish (fish eggs EC50 = 150 mg dissolved La^{3+} L^{-1} (DIN 38515); Institut Dr. Nowak, pers. comm.; fish fry LC50 = 4350 mg Phoslock® L^{-1}; Martin and Hickey, 2004). It should be noted that most of these toxicological assessments considered concentrations of bio-available, dissolved La^{3+}. However, the majority of the La^{3+} in the form that it will be applied to the loch is expected to remain bound within the particulate bentonite-La matrix and will not, therefore, contribute to the bio-available pool. Dissolved La^{3+} concentrations measured following a Phoslock® application in Bärensee Lake (Bruchköbel City, Germany; 11.5 MT added to a 156,000 m^3 water-column volume lake) did not exceed 20 µg L^{-1} (Institut Dr. Nowak, pers. comm.).

Bioaccumulation of lanthanum is also a potential concern in natural ecosystems. However, studies assessing the risk of lanthanum bioaccumulation in common eel tissues (total La accumulation in skin, muscle and liver tested using DIN 38406-E29:1999-05; Institut Dr. Nowak, pers. comm.) after a Phoslock® application reported no significant bioaccumulation. This is in agreement with the findings of medical research, where the high phosphate binding capacity and low bioaccumulation rate of lanthanum (i.e. it does not accumulate in human tissue) have led to its use in treating phosphate accumulation in patients suffering from renal failure (Finn et al., 2004; Swainston-Harrison and Scott, 2004).

2.7 Sediment load (SNH; *target met*)

The load of inorganic sediments to the loch bed in 2004 was 58.3 mg cm^{-2} yr^{-1}. The sediment load to the loch bed increased between 1880 and 1968 (9.3 – 31.7 mg cm^{-2} yr^{-1}), remained fairly constant between 1974 and 1995 (45.2 – 48.5 mg cm^{-2} yr^{-1}) and increased to 2004 (50.0 – 58.3 mg cm^{-2} yr^{-1}). These results suggest a significant increase in sedimentation rate in recent years and indicate that Loch Flemington would fail with respect to this attribute.

2.7.1 Positive/negative effects of proposed clay application

The proposed clay application would have short-term negative effects in relation to sedimentation rates of inorganic matter. The proposed treatment dosage (i.e. ~ 30 tonnes) would result in an increase of about 19 mg cm^{-2} (i.e. 30 tonnes over 157,000 m^2) over a period of about 1 month, depending on local wind conditions. One concern is the effect that this increase in sediment concentration may have on the fish community. The estimated maximum water-column concentrations of suspended clay immediately after application would be < 204 mg L^{-1} (i.e. 25 tonnes in 122,126,000 L of water). This will result in a maximum total lanthanum concentration of ~ 11 mg L^{-1}.

In accordance with a review of the effects of suspended sediment concentrations in lakes and rivers on fish health, this maximum increase in sediment concentration would represent a "moderate risk" to the fish population present (Birtwell, 1999). However, it should be noted that this level of risk does not represent a lethal concentration. Instead, "moderate risk" refers generally to sub-lethal effects that include avoidance and displacement, cover and risk of predation, feeding and growth, and fish health, all of which may be affected negatively by prolonged periods of high sediment load (e.g. > 100 mg L^{-1} for weeks to months). Laboratory estimates of the concentrations of natural river bed sediments required to kill 50% of a freshwater fish population (i.e. 96hr-LC50) range from 7,000 mg L^{-1} (juvenile Coho salmon) to 31,000 mg L^{-1} (Chinook salmon) with onset of death occurring between 2,000 mg L^{-1} and 3,000 mg L^{-1} (juvenile Coho salmon). These potential negative effects may be mitigated by administering a lower daily rate of clay application over a number of days during a period of low temperature (winter). It should also be noted that the sediment concentrations will decrease following application.

Scientific information regarding the fish population in Loch Flemington is limited. However, the RSPB have conducted routine monitoring of the stickleback population in the loch and have reported no significant change in fish numbers in recent years (Benn, *pers. comm.*). However, the health of the fish population has been relatively poor with parasites being commonly reported and fungal infections being apparent. This is probably due to the eutrophic nature of the loch and the high organic matter content of the water-column. If so, an overall improvement in fish population health would be expected once the clay has settled. This would result from three key factors, (1) decreased organic matter (i.e. phytoplankton biomass) in the water-column and, consequently, decreased likelihood of algal toxin production, anoxia following algal decomposition, and occurrence of parasites and infections; (2) increased transparency, which aids prey detection, and (3) enhanced macrophyte canopy cover (i.e. habitat quality and quantity), which will improve refuge-habitat for juvenile/small fish.

2.8 Indicators of local distinctiveness (SNH 2005; *target failed*)

2.8.1 Slavonian Grebe

An assessment of the effects of water quality on loch selection and breeding success of the Slavonian Grebe suggested that these birds tended to choose lochs that provided more suitable nesting habitat, a better food supply (preferentially sticklebacks, but also macroinvertebrates) and clearer waters (Summers et al., 1994). Water clarity was highlighted as being of particular importance, because Slavonian Grebes pursue their prey underwater.

Since that study was completed, the number of breeding pairs of Slavonian Grebe at Flemington Loch has fallen, with no breeding pairs of birds recorded here since 2001 and no birds at all since 2005 (Benn, *pers. comm.*). There are two possible reasons for this. The first is that their numbers may be following a general decline in breeding pairs of this grebe at the national scale, a trend that has affected many sites across Scotland. Since, at the same time, numbers have increased in Iceland, it seems likely that this has been driven more by national scale climatic variability (e.g. caused by variations in the North Atlantic Oscillation) than by any local, site specific changes in water quality. The second is site specific deterioration in water quality. There is some anecdotal evidence that this may have adversely affected food quality at this site, where the main prey species is believed to be sticklebacks. Regular surveys by the RSPB have found that stickleback numbers are falling, with many individual fish showing signs of infections and parasites. These problems are believed to be linked to stress effects (Pottinger, *pers. comm.*), probably associated with eutrophication.

2.8.1.1 Potential positive/negative effects on the Slavonian Grebe

As Slavonian Grebes are no longer resident at Loch Flemington, it is unlikely that there will be any short-term negative or positive effects on this bird of the addition of lanthanum modified clay to this water body. However, even if there were still Slavonian Grebes at the site, any short-term effects (i.e. < 1 month) could be mitigated by conducting the clay application during the winter, i.e. before the birds arrive in April (Summers & Mavor, 1995). Concerns about lanthanum bio-accumulation have been addressed in Section 2.6.1., above, and it is assumed that the risk of this occurring is very low

In the longer-term (i.e. > 1 month), positive effects of the clay treatment are expected, including overall improvements in water clarity (see Section 2.4.1), prey quality and quantity (see Section 2.7.1), and the extent of nesting habitat (see Sections 2.2.1 and 2.2.2).

2.8.2 Great Crested Newt

A Great Crested Newt (GCN) was reported at Loch Flemington by SNH in July 2009. GCNs typically over winter on land and lay their eggs on submerged macrophyte leaves from mid-April to mid-June (Langton *et al*., 2001).

2.8.2.1 Potential positive/negative effects on the Great Crested Newt

An overall improvement in the extent of macrophyte colonisation should improve habitat for the GCN by increasing available egg laying sites and increasing levels of protection from predators.

The risk of a negative impact on GCNs would be highest during the period in which they are in the water, especially during egg laying periods. As GCNs over winter on land, it follows that the proposed application in February will result in the lowest risk of negative impacts on the community. Additionally, we expect the clay to have settled within a 1 month period during which macrophytes will be sparse. Any potential short term effects of clay application on important Newt habitat and reproduction will therefore be minimised.

3 POTENTIAL SOCIO-ECONOMIC IMPACTS

The socio-economic impacts of the proposed project are expected to be very positive, with application of Phoslock® to Loch Flemington improving water quality and decreasing the severity of potentially toxic algal blooms over the summer months. This will improve the amenity value of the loch by providing better habitat for aquatic biota, helping conservation targets to be met, and increasing the overall aesthetic value of the loch for both local residents and visitors. This is expected to increase the number of visitors to the area, including birdwatchers and anglers, which will generate income for the local community.

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5 REFERENCES

Bennion H., G. Clarke, T. Davidson, D. Morley, N. Rose, S. Turner and H. Yang. 2008. Palaeoecological study of seven mesotrophic lochs. Report to the Scottish Environment Protection Agency and Scottish Natural Heritage. Research Report Number: 121. ISSN: 1366-7300.

Birtwell, I.K. 1999. The effects of sediment on fish and their habitat. Canadian Stock Assessment Secretariat, Fisheries and Oceans Canada, Research Document: 99/139: ISSN 1480-4883.

Clearwater, S.J. 2004. Chronic exposure of midge larvae to Phoslock. NIWA Client Report. Reporth Number: NAU04927.

Cyr, H. 1998. How does the vertical distribution of chlorophyll vary in littoral sediments of small lakes? Freshwater Biology. 39: 25-40.

Dudley, B. I.D.M. Gunn, L. Carvalho, I. Proctor, M.T. O'Hare, K.J. Murphy and A. Milligan. *In prep*. Changes in aquatic macrophyte communities in Loch Leven – evidence of recovery from eutrophication? Submission as part of the proceedings of the Loch Leven: 40 years of scientific research symposium. Eds. May,L. and B. M. Spears.

Ecotox Services Australia. 2006. Toxicity assessment of Phoslock to the freshwater shrimp *Macrobrachium sp.* Test report to Phoslock Water Solutions Ltd. Test Report Number: TR0224/2.

Finn, W.F., M.S. Joy, G. Hladik. 2004. Efficacy and safety of lanthanum carbonate for reduction of serum phosphorus in patients with chronic renal failure receiving hemodialysis. Clinical Nephrology. 62:193-201

Gunn, I.D.M., L. Carvalho, A.M. Darwell, D.B. Roy, P. Rothery, P.M. Wade, N. Stewart, M.M. Dent, A. Kirika, J.B. James, P.M. Hodgson, and D.V. Abel. 2004. Site Condition Monitoring of Standing Waters Phase 1, Report 1: Aquatic Macrophyte Method Development. Report to Scottish Natural Heritage.

Hilton, J., 1985. A conceptual framework for predicting the occurrence of sediment focussing and sediment redistribution in small lakes. Limnology and Oceanography 30: 1131-1143.

Hupfer, M. and S. Hilt. 2008. Lake Restoration. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief). Ecological Engineering. Vol. [3] of Encyclopaedia of Ecology, 5 vols. pp. [2080-2093] Oxford: Elsevier.

Idestam-Almquist, J and L. Kautsy. 1995. Plastic responses in morphology of Potamogeton pectinatus L. to sediment and above-sediment conditions at two sites in the northern Baltic proper. Aquatic Botany. 52: 205-216.

Langton, T.E.S., Beckett, C.L., and Foster, J.P. 2001. Great Crested Newt Conservation Handbook, Froglife, Halesworth.

Martin M.L. and C.W. Hickey. 2004. Determination of HSNO ecotoxic thresholds for granular Phoslock (Eureka Formulation) Phase 1: acute toxicity. NIWA Client Report. Report Number: HAM2004-137.

May, L., I. Gunn, and A. Kirika. 2001. Phosphorus study at Loch Flemington. Report to Scottish Natural Heritage. SNH contract no.: HT/LE08/00/01/35

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

Ross, G., F. Haghseresht and T.E. Cloete. 2008. The effects of pH and anoxia on the performance of Phoslock®, a phosphorus binding clay. Harmful Algae 7: 545-550.

Sas, H., 1989. Lake Restoration by Reduction of Nutrient Loading. Academic Verlag Richarz.

Scheffer, M., 2001. Ecology of shallow lakes. Kluwer Academic Press. London, UK.

SNH. 2005. Condition Monitoring Report for Loch Flemington. Form Identification Number: 379.

Søndergaard, M., 2007. Nutrient dynamics in lakes – with emphasis on phosphorus, sediment and lake restorations. Doctor's dissertation (DSc). National Environmental Research Institute, University of Aarhus, Denmark. 276 pp.

Spears, B.M., L. Carvalho, & D.M. Paterson, 2007a. Phosphorus partitioning in a shallow lake: implications for water quality management. Water and Environment Journal. 21: 47-53.

Spears, B.M., L. Carvalho, R. Perkins, A. Kirika & D.M. Paterson, 2007b. Sediment P cycling in a large shallow lake: spatio-temporal variation in P pools and release. Hydrobiologia 584: 37-48.

Spears, B.M., I.D.M. Gunn, L. Carvalho, I.J. Winfield, B. Dudley, K. Murphy, L. May. 2009. An evaluation of methods for sampling macrophyte maximum colonisation depth in Loch Leven, Scotland. Aquatic Botany, doi:10.1016/j.aquabot.2009.02.007

Swainston-Harrison, T. and L.J. Scott. 2004. Lanthanum Carbonate. Drugs. 64: 985-996.

UKTAG (2007) UK Environmental Standards and Conditions, Phase 2, SR-1, June 2007

Van Dijk, G.M. and E. Van Donk. 1991. Perspectives for submerged macrophytes in shallow lake restoration projects in the Netherlands. Aquatic Ecology. 24: 125-131.

Appendix 1

Habitat requirements of the rare aquatic macrophyte *Najas flexilis*

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Background information and threats

Ecology of Najas flexilis

Najas flexilis (Willd.) Rostk. & Schmidt is a rare European macrophyte that is protected by national and international legislations (e.g. Natura 2000, EC Habitats Directive, Wildlife and Countryside Act, UK Biodiversity Action Plan). The legislation calls for the safeguarding of remaining populations and the creation of suitable habitats for its survival (UK Biodiversity Action Plan). *N. flexilis* is an annual species that reproduces predominantly *via* seeds (Willby et al., 2000; Wingfield et al., 2004). In the climatic conditions of Scotland, the life cycle of this species generally encompasses germination of seeds in June followed by plant growth throughout July and August resulting in seed production around September (Wingfield et al., 2004). Due to its annual life cycle and its late germination in June, this species is reported to require microhabitats that are sparsely covered with other macrophytes to successfully germinate and grow (van de Weyer, 2005). Furthermore, *N. flexilis* is an obligate user of carbon dioxide (CO_2) for carbon fixation during the process of photosynthesis and, unlike other species, cannot utilise bicarbonate (HCO_3^-) (Hough and Wetzel, 1978; Hough and Fornwall, 1988).

Habitat requirements and threats

Nutrient concentrations and pH/alkalinity conditions are reported to set limits on possible habitats for this species (Wingfield et al., 2004). In terms of nutrient concentrations, *N. flexilis* was found to be more abundant in oligo- to meso-trophic lakes (van de Weyer, 2005), with total phosphorus concentrations of around 15 µg L^{-1} (range 1-26 µg L^{-1}; Wingfield et al., 2005). Beyond the mesotrophic boundary (i.e. for shallow lakes, approximately beyond 50 µg L^{-1}) abundances are reported to decline (Willby et al., 2000; Wingfield et al., 2005). A study by Wingfield et al. (2005) found that *N. flexilis* became less abundant as total phosphorus levels increased to an average of approximately 80 µg L^{-1}. In terms of favourable pH conditions, the species showed higher occurrence in lakes with pH values in the range of 6.5 to 8.8, while abundances started to decline in lakes where the pH reached or exceeded values of 9 (Wingfield et al., 2004). Table 1 summarises the habitat preferences of *N. flexilis* and compares them to prevailing conditions at Loch Flemington, based on values obtained from the literature.

Table 1 Habitat preferences of the rare aquatic macrophyte *Najas flexilis* and prevailing conditions at Loch Flemington (Inverness, Scotland).

Parameter	**Conditions at Loch Flemington**	**Conditions allowing growth of *Najas flexilis***	**References**
Nutrient concentration	eutrophic (mean total phosphorus 40 – 239 μg L^{-1}; 2009)	oligo-mesotrophic (upper limit of total phosphorus 50 μg L^{-1})	(Wingfield et al., 2004; van de Weyer, 2005; Figure 1, Appendix 2)
pH	7.5 – 9.5 (2001 – 2002)	6.0 – 9.0	(Roberts et al., 1985; Jackson and Charles, 1998; Wingfield et al., 2004; Wallace, 2005)
Habitat availability	< 1.5 m maximum colonisation depth (reported dominance of *Elodea* spp. suggests limited extent of suitable habitats)	sparsely covered microhabitats to germinate and grow	(Carvalho and Kirika, 2003; Carvalho and Dale 2004; van de Weyer, 2005; Appendix 2)

Considering the factors discussed above, suitable habitat availability for *N. flexilis* is threatened on the one hand by factors that affect the nutrient status of lakes (i.e. eutrophication) and on the other hand by factors influencing the pH of lakes (i.e. acidification) (Wingfield, 2002; Wingfield et al., 2005). So, two possible scenarios could be responsible for the absence of this species from any given lake: i) extinction or reduced growth due to nutrient enrichment beyond the mesotrophic boundary and ii) extinction or reduced growth due to acidification at oligo-mesotrophic sites.

The detrimental effects of nutrient enrichment and acidification on *N. flexilis* seem to be caused by different underlying mechanisms. Eutrophication is likely to involve two mechanisms that act together and reduce the survival of *N. flexilis*. Firstly, increased nutrient loading causes enhanced photosynthetic activity of macrophytes and algae, which causes a decline in carbon dioxide (CO_2) concentration in the water column at least during daytime. This limits carbon fixation by *N. flexilis*, which cannot utilise bicarbonate (HCO_3^-). Limited carbon fixation ultimately causes reduced growth rate and seed production, which causes a decline in the abundance of *N. flexilis* in the long -term (Wingfield et al., 2004). Secondly, enhanced nutrient levels sustain more prolific growth of other macrophyte species, which limits the availability of the sparsely vegetated habitat patches that this annual plant species seems to require for survival (van de Weyer, 2005). As species like *Elodea* spp. or *Ceratophyllum* spp., which grow well under eutrophic conditions, are also evergreen species (Willby et al., 2000), they can rapidly out compete *N. flexilis* by colonising formerly available habitats and retaining their dominance there throughout the year. I extreme cases of eutrophication, phytoplankton production will be favoured resulting in turbid conditions and light limitation of *N. flexilis.* Acidification, on the other hand, is reported to act negatively on reproductive capacity (i.e. seed germination; Titus and Hoover, 1991; Titus and Hoover, 1993; Wingfield et al., 2004). This process would therefore, from an inter-annual perspective, lead to declining abundances of plants which, in turn, would lead to the production of fewer new seeds for the following year; a process that can lead to extinction in the long -term.

Conditions in Loch Flemington and potential impact of a Phoslock® application

Site monitoring indicated that nutrient enrichment is the main problem affecting water quality at Loch Flemington. Total phosphorus values for spot measurements increased from around 70 µg L^{-1} during 1981 and 1990 (May et al., 2001) towards peaks exceeding 170 µg L^{-1} during 2000 and 2004 (Carvalho and Dale, 2004). Measured phosphorus levels in these years are indicative of eutrophic conditions and internal loading (i.e. nutrients released from sediments) is the most likely source of much of these nutrients (May et al., 2001; Appendix 2). It was shown that internal nutrient loading (i.e. nutrients released from sediments) can delay lake recovery for periods of many years to decades after external sources have been reduced (Phillips et al., 2005).

As the growth of *N. flexilis* was reported to be improved by lower nutrient concentrations (around 20 to 30 μg L^{-1}; Willby et al. 2000; Wingfield et al., 2005), a reduction in phosphorus concentration is a key requirement for sustaining or re-creating suitable habitat for *N. flexilis*. In recent laboratory studies, it was shown that a lanthanum based clay product (Phoslock; Phoslock Water Solutions Ltd) can effectively reduce the amount of available phosphorus over a pH range of 5 to 10 as well as under anoxic conditions (Douglas et al., 1999; Robb et al., 2003). The specific properties of Loch Flemington hamper the employment of certain commonly used management techniques; firstly, the loch has no surface outflow so it is not possible to reduce phosphorus concentrations by controlled lake flushing at times of high phosphorus concentrations in the water. Secondly, the close proximity of the site to the sea and its relatively high salinity prevent the application of ferric based phosphorus binding agents. In such situations sulphur would be bound to the iron binding sites instead of phosphorus. In recent laboratory studies, it was shown that a lanthanum based clay product (Phoslock™; Phoslock Water Solutions Ltd) can effectively reduce the amount of available phosphorus over a pH range of 5 to 10 as well as under anoxic conditions (Douglas et al., 1999; Robb et al., 2003). It might, therefore, be suggested that Phoslock™ wcould be a suitable tool to reduce phosphorus concentrations at this site.

Although information about pH conditions at the site is sparse, a study conducted between 2001 and 2002 indicated that pH values generally range between 7.5 to 8.25, with peaks in July up to pH 9.5 (Wallace, 2005). Although peak pH values exceed the reported favoured range of *N. flexilis*, it seems likely that the prevailing pH conditions would sustain the growth of this species. With respect to a potential application of Phoslock®, weekly monitoring conducted by CEH at Clatto Reservoir (Dundee), where Phoslock® was applied in March 2009, revealed no significant change in pH following applicatoin (pH 7.7 ± 0.1; between February and April 2009).

In terms of macrophyte community composition, *N. flexilis* was not found during the most recent plant survey in 2003 (Carvalho and Kirika, 2003; Carvalho and Dale, 2004). The macrophyte community during this year was dominated by *Elodea canadensis* (Carvalho and Kirika, 2003; Carvalho and Dale, 2004), which is characteristic of eutrophic conditions (Willby et al., 2000). At the moment it is unknown whether a reduction in water-column nutrient concentration will decrease the dominance of *E. canadensis* at this site, as this species can also grow in meso-eutrophic conditions. It might therefore be necessary, in addition to lowering the phosphorus concentration, to clear some habitat patches from of extensive *E. canadensis* growth to allow the growth of *N. flexilis* seeds to germinate and establish. However, this undertaking would only be sensible if the nutrient concentrations and pH values were within the preferential range of *N. flexilis* in the first place. This practice has been discussed with SNH and may be trialled in combination with a Phoslock® addition.

References

CARVALHO, L. & DALE, K. (2004) Condition monitoring form. Edinburgh, Centre for Ecology and Hydrology.

CARVALHO, L. & KIRIKA, A. (2003) Site condition monitoring - Loch Flemington. Edinburgh, Centre for Ecology and Hydrology.

DOUGLAS, G. B., ADENEY, J. A. & ROBB, M. S. (1999) A novel technique for reducing bioavailable phosphorus in water and sediments. *International Association Water Quality Conference on Diffuse Pollution*

HOUGH, R. A. & FORNWALL, M. D. (1988) Interactions of inorganic carbon and light availability as controlling factors in aquatic macrophyte distribution and productivity. *Limnology and Oceanography,* 33**,** 1202-1208.

HOUGH, R. A. & WETZEL, R. G. (1978) Photorespiration and CO_2 compensation point in *Najas flexilis*. *Limnology and Oceanography,* 23**,** 719-724.

JACKSON, S. T. & CHARLES, D. F. (1998) Aquatic macrophytes in Adirondack (New York) lakes: patterns of species composition in relation to environment. *Canadian Journal of Botany,* 66**,** 1449-1460.

MAY, L., GUNN, I. & KIRIKA, A. (2001) Phosphorus study at Loch Flemington - Report to Scottish Natural Heritage. Edinburgh, Centre for Ecology and Hydrology.

Phillips, G., Kelly, A., Pitt, J.-A., Sanderson, R. & Taylor, E. (2005) The recovery of a very shallow eutrophic lake, 20 years after the control of effluent derived phosphorus. *Freshwater Biology,* 50**,** 1628-1638.

ROBB, M. S., GREENOP, B., GOSS, Z., DOUGLAS, G. & ADENEY, J. (2003) Application of Phoslock, an innovative phosphorus binding clay, to two western Australian waterways: preliminary findings. *Hydrobiologia,* 494**,** 237-243.

ROBERTS, D. A., SINGER, R. & BOYLEN, C. W. (1985) The submersed macrophyte communities of Adirondack Lakes (New York, U.S.A.) of varying degrees of acidity. *Aquatic Botany,* 21**,** 219-235.

TITUS, J. E. & HOOVER, D. T. (1991) Toward predicting reproductive success in submersed freshwater angiosperms. *Aquatic Botany,* 41**,** 111-136.

TITUS, J. E. & HOOVER, D. T. (1993) Reproduction in two submersed macrophytes declines progressively at low pH. *Freshwater Biology,* 30**,** 63-72.

VAN DE WEYER, K. (2005) Re-establishment plan for the Natura 2000 species *Najas flexilis* in Poland. Nettetal, Lanaplan Report for Ministry of Environment Poland.

WALLACE, G. (2005) Chapter 4: Potamogeton rutilus - Water/sediment chemistry and light conditions. Glasgow, Glasgow University.

WILLBY, N. J., ABERNETHY, V. & DEMARS, B. O. L. (2000) Attribute-based classificiation of European hydrophytes and its relationship to habitat utilization. *Freshwater Biology,* 43**,** 43-74.

WINGFIELD, R. A. (2002) The functional ecology of *Najas flexilis*. University of Glasgow.

WINGFIELD, R. A., MURPHY, K. & GAYWOOD, M. (2005) Lake habitat suitability for the rare European macrophyte *Najas flexilis* (Willd.) Rostk. & Schmidt. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 15**,** 227-241.

WINGFIELD, R. A., MURPHY, K. J., HOLLINGSWORTH, P. & GAYWOOD, M. J. (2004) The ecology of *Najas flexilis*. Edinburgh, Scottish Natural Heritage Commissioned Report No. 017 (ROAME No. F98PA02).

Appendix 2

An assessment of water and sediment conditions in Loch Flemington (May-August 2009)

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1 Executive summary

This paper reports on a recent (May-August 2009) assessment of water quality attributes in Loch Flemington. The general findings are that:

1. Surface water-column total phosphorus (TP) concentrations increased to 178 µg L^{-1} in August 2009.
2. Bottom water TP concentrations were consistently higher than water-column TP concentrations indicating that sediment is a major source of P to the water-column.
3. About 0.21 tonnes of the P contained within the upper 3 cm of sediment was release sensitive.
4. Water-column chlorophyll *a* concentration increased to 167 µg L^{-1} (Secchi depth less than 50 cm) in August and was composed mainly of cyanobacteria.
5. The macrophyte community was dominated by the non-native species *Elodea Canadensis*, while only two of the six characteristic species for this lake type were present. The invasive species *Crassula helmsii* was observed for the first time.

2 Introduction

Spears and May (2009) considered the potential effects of a lanthanum-modified clay (Phoslock®) application on the site attributes of Loch Flemington. The risk assessment was based on recent site assessments and available literature (e.g. Bennion *et al*., 2008; May *et al*., 2001; SNH, 2005). In combination with this risk assessment, and to fill gaps in available data important for understanding site-specific lake restoration requirements, a comprehensive field assessment of important water and sediment conditions was conducted. This included ecological and chemical assessments as outlined below. This section summarises the results of this field assessment and outlines the current ecological status of the loch in relation to conservation targets and restoration requirements.

3 Methods

Field surveys were conducted at monthly intervals between May and August 2009. All field assessments were conducted from a boat following access guidance from Scottish Natural Heritage (SNH). Water and sediment samples were collected from 5 open water sites.

3.1 Assessment of the phytoplankton community and water clarity

The phytoplankton community was assessed *in situ* at 5 open water sites using a fluoroprobe (BBE fluoroprobe, EnviTech Ltd). This allowed the biomass of algal groups (diatoms, cyanobacteria, green algae, cryptophytes, total algae) to be quantified in terms of chlorophyll *a* concentration. The Secchi depth transparency was recorded at each of the 5 open water stations on each sample date.

3.2 Assessment of water and sediment chemistry

Water samples were collected from the surface and bottom (1 cm above sediment) of the water-column at each site. The water samples were either filtered (Whatman® GF/C) for analysis of soluble reactive phosphorus (SRP) concentration or not filtered for the analysis of TP. All phosphorus analyses were conducted according to the methods of Wetzel and Likens (2000).

A sediment core was collected on 28th May 2009 using a HTH Gravity Corer (Pylonex Ltd, Sweden). The core was sectioned to produce five 2 cm subsamples between 0 and 10 cm sediment depth, 1 subsample from 18 - 20 cm and 1 subsample from 28 – 30 cm sediment depth. The sections were homogenised and subjected to a modified phosphorus (P) sequential extraction procedure as described by Farmer *et al*. (1994). The extraction scheme allows quantification of release sensitive sediment P pools important for determining the sediment P release potential (Spears et al., 2007a).

3.3 Assessment of the macrophyte community

The macrophyte community was assessed each month by conducting a 2 hour boat survey using a double headed rake and a bathyscope (Spears et al,. 2009). The abundances of observed species were estimated according to the DAFOR scale and used to construct a species list. In addition, a survey using "Common Standards Monitoring Guidance for Standing Waters" ('SCM survey'; JNCC, 2005) was conducted in August. The method involves strandline, wader and boat surveys of fixed transects using a double headed rake and a bathyscope.

The typical macrophyte community of a natural eutrophic loch, such as Loch Flemington, would consist of *Magnopotamion* or *Hydrocharition*-type vegetation (JNCC, 2009). The former vegetation type includes predominantly *Potamogeton* spp. and associates such as *Chara* spp. and *Callitriche* spp., while species like *Stratiotes aloides*, *Lemna* sp., *Hydrocharis morsus-ranae*, *Riccia fluitans*, *Utricularia* spp. and *Spirodela polyrhiza* are characteristic for the latter vegetation type.

4 Results & Discussion

4.1 Total phosphorus (TP) and soluble reactive phosphorus (SRP) concentrations

Surface and bottom water TP concentrations between May and August are shown in Figure 1. The TP concentrations in both surface and bottom water increased from May to August reaching 178 ± 22μg l^{-1} and 239 ± 20 μg l^{-1}, respectively. TP concentrations in the bottom water were consistently higher than the surface waters, indicating that P was being released from the sediments to the water-column throughout the monitoring period. This is in agreement with studies in other shallow lakes where sediments are a major source of P to the water column and shows the strong concentration gradients that are responsible for sediment-P release throughout the study period (Spears et al., 2007a).

SRP concentrations over the same period did not exceed 10 μg l^{-1} in the surface water samples. Taken together with the high surface water TP concentrations it is apparent that most SRP was readily taken up by phytoplankton in Loch Flemington. The high TP concentrations and low SRP concentrations in the loch are in agreement with an earlier study (May *et al*., 2001).

The good/moderate boundary for Loch Flemington under the Water Framework Directive guidelines would be an annual mean TP concentration of 32 µg l^{-1} (category: high alkalinity, very shallow lake; UKTAG, 2008). However, it should be noted that Loch Flemington is too small to be considered under the WFD.

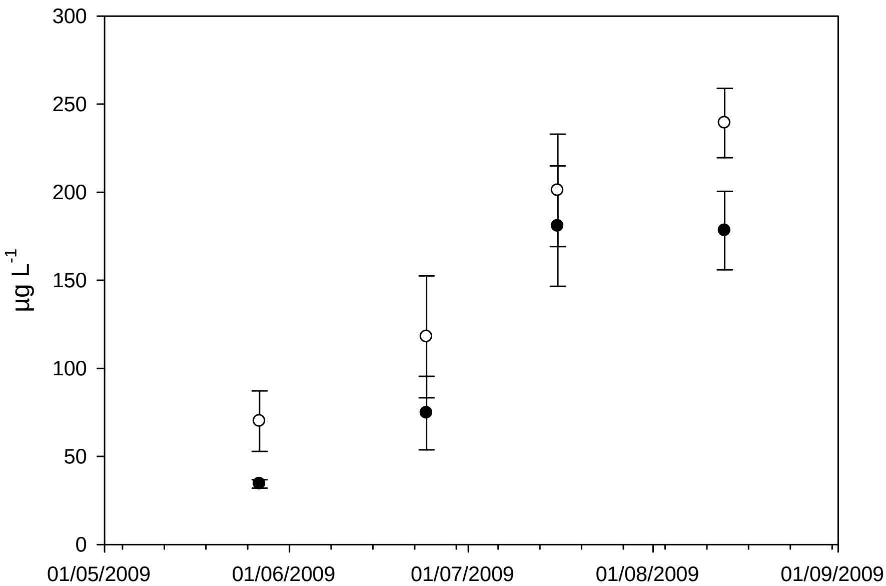


Figure 1 Surface (●) and bottom (○) water total phosphorus concentrations in Loch Flemington between May and August 2009. Error bars indicate standard deviation between the 5 sample points in Loch Flemington.

4.2 Sediment P fractions

Sediment depth profiles of the P fractions are shown in Figure 2. A summary of the sediment TP concentrations across a range of lakes is also shown (Figure 3). Sediment P concentrations generally decreased with sediment depth, with release sensitive P fractions making up a significant proportion of the TP concentration throughout the core. The dominant fraction was organic P, which is most probably made up of algal detritus. All fractions generally increased towards the sediment surface. This is common in many shallow lakes where P turnover processes are concentrated at the interface between the water column and the sediment as a result of settling of organic material (e.g. phytoplankton) from the water column to the sediment, aeration of the sediment surface (reductant-soluble P), and elevated pH conditions (apatite P) (Spears *et al*., 2007a). In eutrophic shallow lakes, P is cycled between the sediment and the water column through these pools. Algae settle onto the sediment surface as organic P; microbes remineralise organic P which is stored as reductant-soluble P in aerobic conditions; reductant-soluble P is released to labile P under anoxic conditions; labile P is leached to the water column and enters the phytoplankton (Spears et al., 2007b). The key aim of any effort to control sediment P release is to interrupt this cycle by intercepting the P and containing it in a form that is not sensitive to release. Phoslock® is an example of an inactivation tool. However, benthic algae and submerged plants can also act to intercept sediment P and to inactivate P at the sediment surface (Spears et al., 2008).

The reductant-soluble and labile fractions of P are "release-sensitive", with labile P being continually released across chemical gradients (i.e. as indicated by high bottom water concentrations) and with reductant-soluble P being released under conditions of anoxia. The concentration of both of these fractions is highest in the shallowest sediment layers. In Loch Flemington, this represents approximately 0.14 tonnes of P in the upper 2 cm of sediment and 0.21 in the upper 3 cm, across the loch (assuming 100% sediment cover of loch basin).

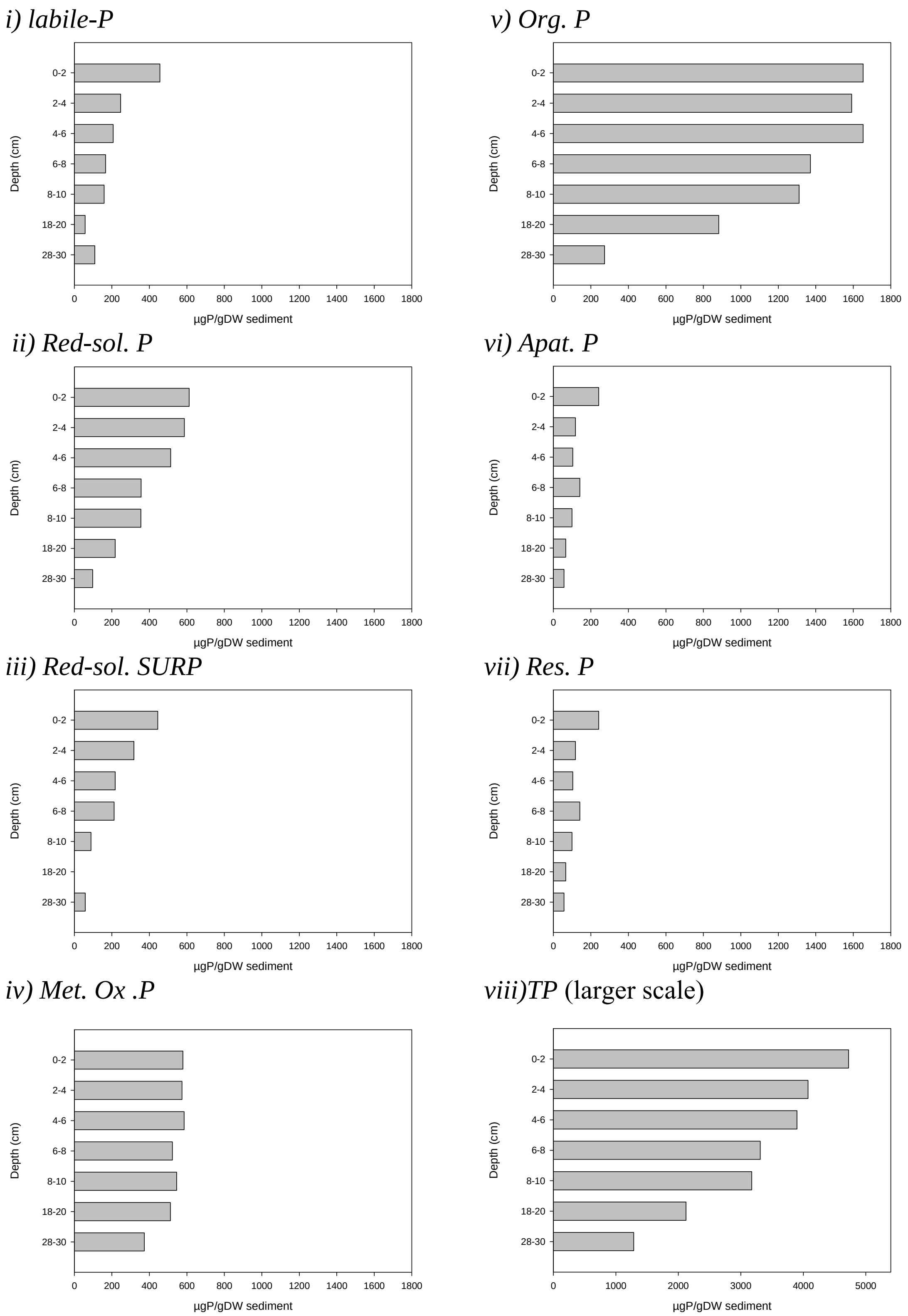


Figure 2 Sediment phosphorus fractions in Loch Flemington. Fractions include i) labile SRP *(labile-P*), ii) reductant-soluble SRP (*Red-sol. P*), iii) reductant-soluble unreactive phosphorus (*Red-sol. SURP*), iv) metal-oxide adsorbed SRP (*Met. Ox .P*), v) organic phosphorus (*Org. P*), vi) apatite-bound phosphorus (*Apat. P*),vii) residual phosphorus (*Res. P*), vii) sum of fractions (*TP*).

The sediment TP concentration in Loch Flemington is relatively high in comparison with other lakes (Figure 3). 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 concentration 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.

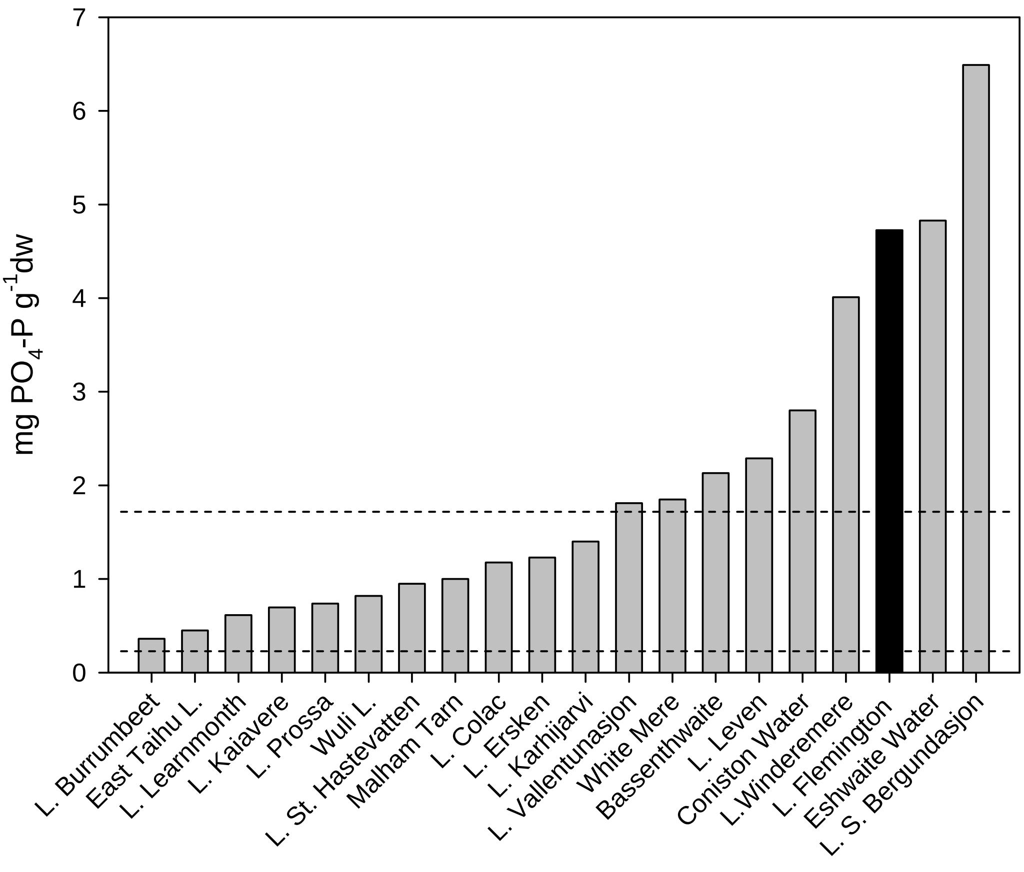


Figure 3 Comparison of sediment total phosphorus concentrations of a variety of lakes. The value used for Loch Flemington (marked black) is an average of all phosphorus fractions from 0-2 cm sediment depth. Thresholds for different recovery patterns are shown as dashed horizontal lines (see text for details).

a)

b)

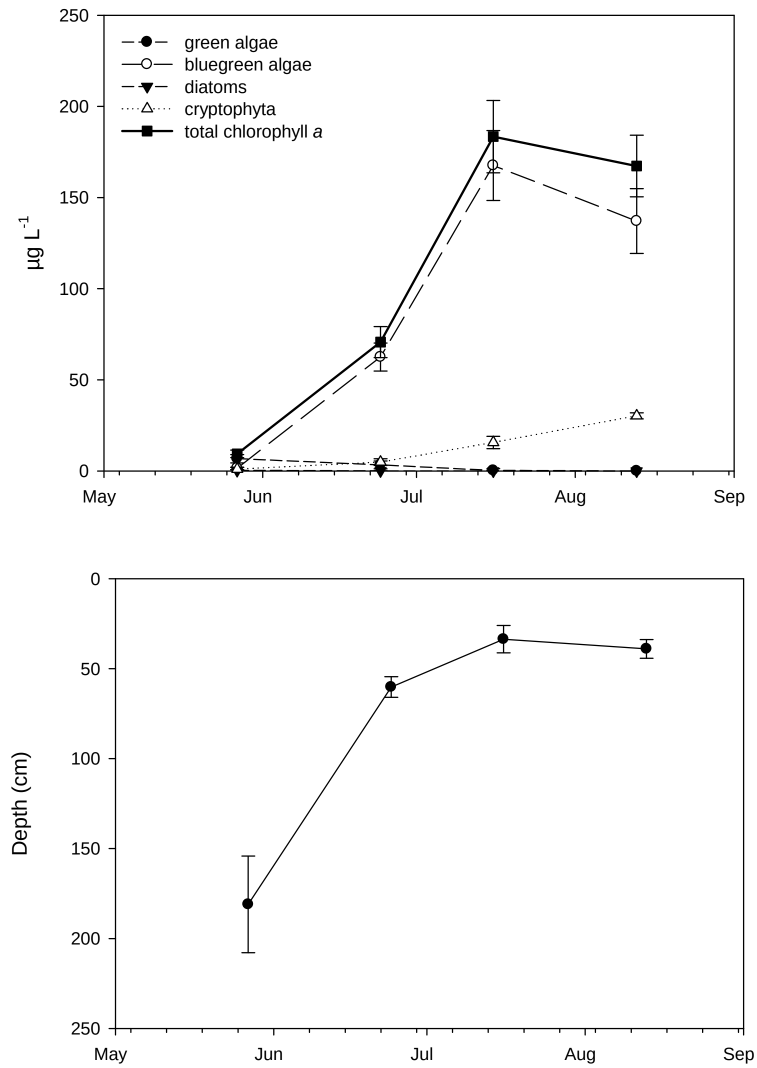


Figure 4 Phytoplankton community composition (a) and Secchi depth (b) in Loch Flemington between May and August 2009. A BBE fluoroprobe was used to measure phytoplankton community composition.

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. In addition, the model by Sas (1989) is based on the assumption that an outflow is present which allows P to be washed out (either as SRP or as particulate phosphorus (PP)).

The current sediment P concentration of Loch Flemington suggests a recovery time of more than 5 years given that external loading has been reduced. As an outflow is absent in Loch Flemington, and as external P input *via* the inflow or *via* surface runoff is still likely even when reduced, significant recovery may never be achieved as there is no means of P relinquishment from the system.

4.3 Phytoplankton and Secchi depth

The phytoplankton community composition and underwater light climate are shown in Figures 4a and 4b. Total chlorophyll *a* concentrations increased significantly from 9.4 ± 2 μg l^{-1} in May to 167 ± 17 μg l^{-1} in August. The phytoplankton community was dominated by cyanobacteria while concentrations of diatoms and green algae were consistently below 10 μg l^{-1}. Algal scum formation occurred in July and was most distinctive in August (Figure 5).

If applicable, the good/moderate boundary for Loch Flemington under the WFD guidelines would be an annual mean chlorophyll *a* concentration of 8.6 μg l^{-1} or a growth season mean (April – September) of 10.8 μg l^{-1} (category: high alkalinity, very shallow lake; Carvalho *et al*., 2006). As mentioned above, it should be noted that Loch Flemington is too small to be considered under the WFD.

Secchi depth decreased significantly following the increase in chlorophyll *a* concentration at the beginning of June (Figure 4b). Total chlorophyll *a* concentrations and water column TP concentrations were highly correlated (P=0.006; R^2=98.2). This highlights the fact that the poor water quality conditions in Loch Flemington are driven by elevated phytoplankton biomass resulting from high concentrations of phosphorus and substantiates the proposed control of phosphorus.

Figure 5 Algal scum around littoral vegetation (left) and close up view (right) in Loch Flemington in August 2009.

Species	May	June	July	August
Crassula helmsii	-	-	-	1
Elodea canadensis	4	4	4	4
Elodea nuttallii	1	-	-	-
Lemna sp.	1	1	-	1
Litorella uniflora	2	2	1	2
Myriophyllum alterniflorum	1	3	3	2
Myriophyllum spicatum	1	1	1	1
Potamogeton crispus	-	1	-	-
Potamogeton gramineus	-	2	3	1
Potamogeton natans	2	3	3	3
Potamogeton obtusifolius	1	1	2	2
Potamogeton perfoliatus	-	1	-	-
Potamogeton x *angustifolius*	-	1	-	-
Maximum growing depth (m)	Not assessed	Not assessed	1.4 ± 0.2	1.5 ± 0.1

Table 1 Abundance estimates of submerse macrophyte vegetation of Loch Flemington between May and August 2009. Abundance estimates are based on the DAFOR scheme (D, dominant – 5; A, abundant – 4; F, frequent – 3; O, occasional – 2; R, rare – 1).

4.4 Macrophyte community

An overview of submerged macrophyte species and abundances is shown in Table 1. Abundance estimates indicated that the submerged vegetation was dominated by *Elodea canadensis*, while characteristic species like *Potamogeton perfoliatus*, *Potamogeton crispus* and *Potamogeton obtusifolius* occurred only in low abundances.

Based on the results from the SCM survey in August 2009, it can be concluded that the macrophyte community of Loch Flemington would fail SCM targets for the following reasons: firstly, only two of the six characteristic species were present in August. Secondly, characteristic species were absent from the majority of sampling spots. Thirdly, there was a high observed frequency of the less invasive and non-native species *Elodea canadensis* and the invasive species *Crassula helmsii* was also reported.

The maximum colonisation depth of macrophytes in Loch Flemington was recorded as < 1.5 m water depth. With respect to sediment P cycling, the natural buffering capacity of macrophytes will be restricted to areas of the loch bed that are less than 1.5 m water depth. This leaves a substantial area of the loch bed in which anaerobic sediment P release and turnover of organic P compounds may continue unchecked. Any restoration project should concentrate on increasing the colonisation depth of macrophytes to cover all depths in the loch. This is a realistic target given the relatively shallow maximum depth (~ 3 m) of Loch Flemington.

5 Conclusions

- Sediments are a major source of phosphorus in Loch Flemington, causing high water column TP and phytoplankton concentrations.

- Recovery from eutrophication using only a reduction in external load is unlikely, due to high P concentrations accumulated in sediments.

- Successful recovery will require treatment of P contained in sediments.

- Elevated phytoplankton biomass is driven by high concentrations of P.

- High phytoplankton biomass causes a reduction in underwater light.

- The macrophyte community is dominated by *Elodea canadensis*, a species not characteristic for this lake type which is less sensitive to eutrophication, while characteristic species occur in low abundances.

- Macrophyte colonisation is restricted to the upper 1.5 m of the loch, leaving a substantial area of the loch bed with no natural buffer to sediment P release.

- Any restoration project should aim to increase the macrophyte colonisation zone to the maximum depth of the loch by improving water clarity and reducing water column total P and chlorophyll *a* concentrations.

6 References

BENNION, H., CLARKE, R., DAVIDSON, T., MORLEY, D., ROSE, N., TURNER, S. & YANG, H. (2008) Palaeoecological study of seven mesotrophic lochs. Report to the Scottish Environment Protectoin Agency and Scottish Natural Heritage. Environmental Change Research Centre.

CARVALHO, L., PHILLIPS, G., MABERLY, S. C. & CLARKE, R. (2006) Chlorophyll and phosphorus classifications for UK lakes. Edinburgh, SNIFFER.

FARMER, J. G., BAILEY-WATTS, A. E., KIRIKA, A. & SCOTT, C. (1994) Phosphorus fractionation and mobility in Loch Leven sediments. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 4**,** 45-56.

JNCC (2005) Common standards monitoring guidance for standing waters. Joint Nature Conservation Committee.

JNCC (2009) Common standards monitoring guidance for standing waters (Draft Version). Joint Nature Conservation Committee.

MAY, L., GUNN, I. & KIRIKA, A. (2001) Phosphorus study at Loch Flemington. Report to Scottish Natural Heritage. Centre for Ecology & Hydrology.

SAS, H. (1989) *Lake restoration by reduction of nutrient loading,* St. Augustin, Academia Verlag Richarz GmbH.

SNH (2005) Condition monitoring report for Loch Flemington. Form Identification Number: 379.

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

SPEARS, B. M., CARVALHO, L., PERKINS, R., KIRIKA, A. & PATERSON, D. M. (2007a) Sediment phosphorus cycling in a large shallow lake: spatio-temporal variation in phosphorus pools and release. *Hydrobiologia,* 584**,** 37-48.

SPEARS, B., L. CARVALHO & D.M. PATERSON. (2007b). Phosphorus partitioning in a shallow lake: implications for water quality management. *The Water and Environment Journal*. 21:47:53.

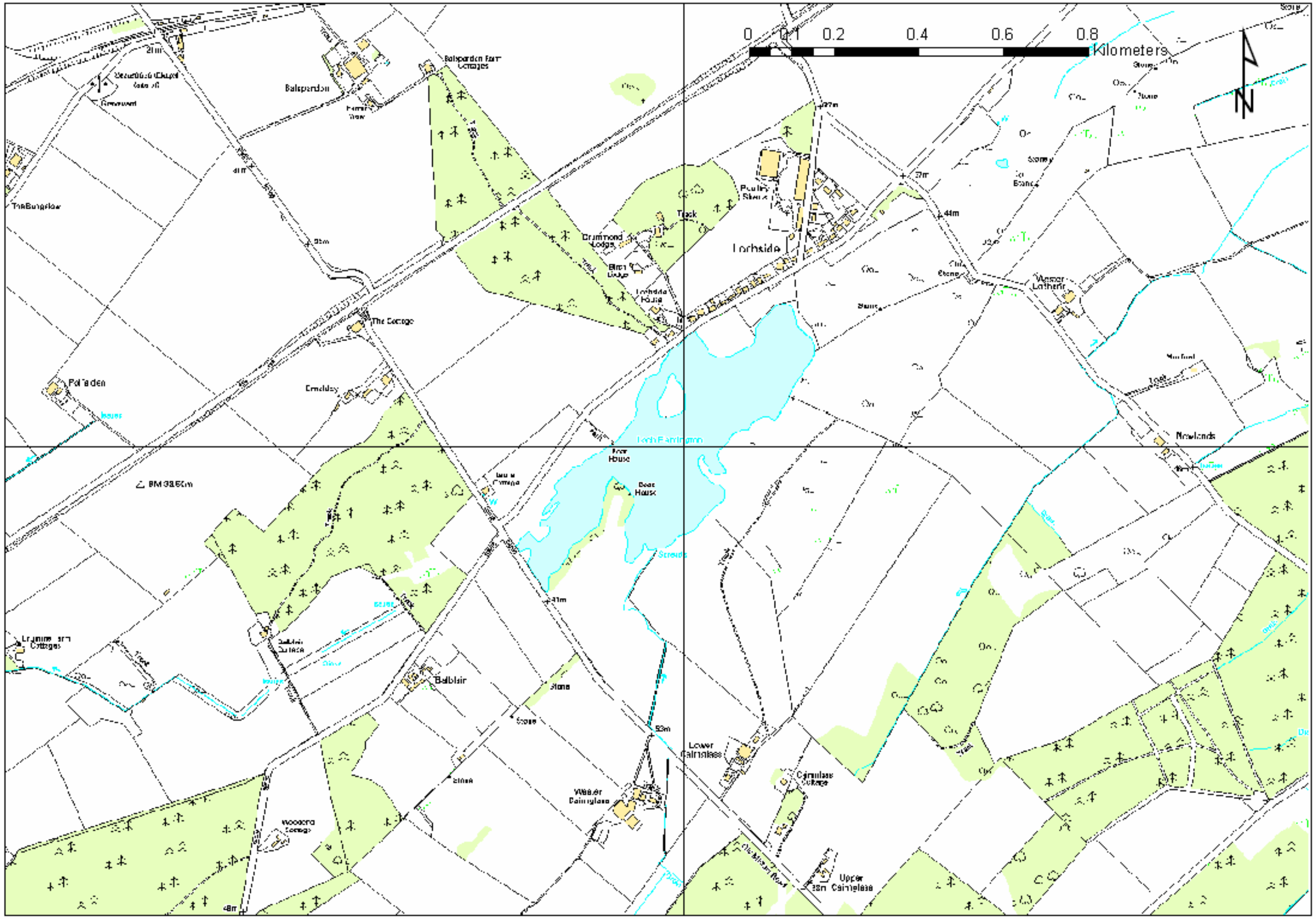
SPEARS, B.M., I. GUNN, L. CARVALHO, I. WINFIELD, B. DUDLEY, K. MURPHY AND L. MAY. 2009. An evaluation of methods for sampling macrophyte maximum growing depth in Loch Leven, Scotland. Aquatic Botany, 91: 75-81.

SPEARS, B. & MAY, L. (2009) Risk assessment for the proposed application of lanthanum-bentonite clay (Phoslock®) for the restoration of Loch Flemington. Edinburgh, Centre for Ecology & Hydrology.

UKTAG (2008) UK environmental standards and conditions (Phase 2, Final). UK Technical Advisory Group on the Water Framework Directive.

WETZEL, R. G. & LIKENS, G. E. (2000) *Limnological analyses,* New York, Spinger Verlag

Appendix 3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Poultry Sheds
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The Cottage
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Balblair
Newlands
Boat House
Lower Cairnglass
Wester Cairnglass
Upper Cairnglass
Cairnglass Cottage
Woodend Cottage
Wester Lothenir
The Bungalow
Track
Stone