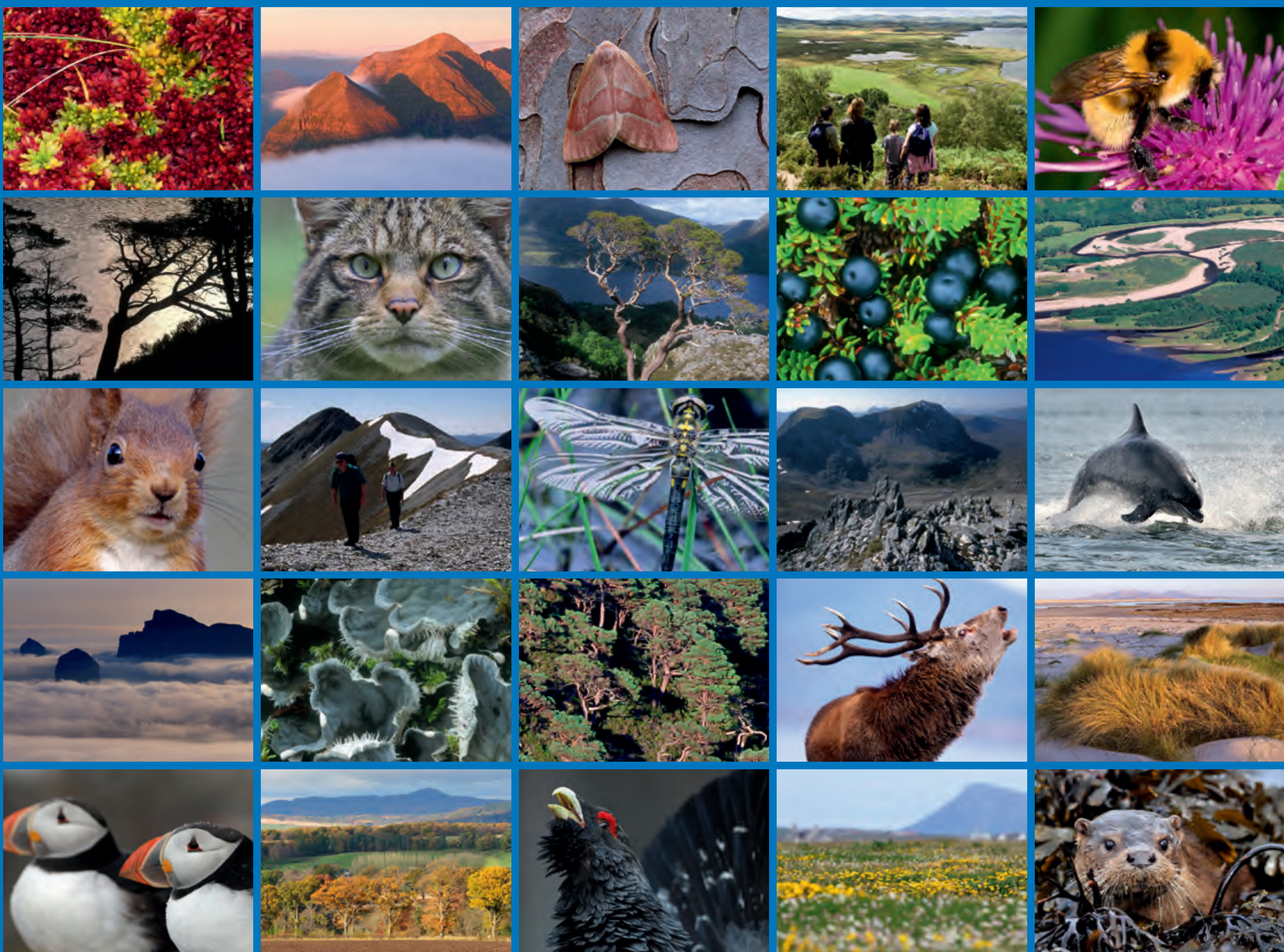
Scottish Natural Heritage
Commissioned Report No. 443

Recommendations on the management of standing water features in unfavourable condition due to nutrient enrichment



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COMMISSIONED REPORT

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For further information on this report please contact:

Mary Hennessy
Scottish Natural Heritage
Strathallan House
Castle Business Park
STIRLING
FK9 4TZ
Telephone: 01786 435358
E-mail: mary.hennessy@snh.gov.uk

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COMMISSIONED REPORT

Summary

Recommendations on the management of standing water features in unfavourable condition due to nutrient enrichment

Commissioned Report No. 443
Project No: 10585
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Keywords

Chlorophyll; loch; management; nutrient; phosphorus; SSSI; unfavourable condition.

Background

Water quality and diffuse nutrient sources were investigated within the catchment areas of eight inland lochs that are interest features of SSSIs. All of the lochs were in unfavourable condition and the aim of this project was to identify management recommendations that could help to restore the lochs to favourable condition.

A nutrient budgeting exercise was carried out, comparing predicted export rates based on export coefficients and those based on measured inflow phosphorus (P) concentrations. This enabled problem areas for export of diffuse nutrient pollution to be identified. The responses of each loch to nutrient inputs were also evaluated through assessment of nutrient - chlorophyll relationships and food web structure.

Main findings

- Seven of the target lochs showed strong evidence of increased nutrient concentrations. Further monitoring was recommended for the eighth loch, as the degree to which anthropogenic enrichment was taking place was less clear than for the other lochs.
- Four of the eight lochs showed chlorophyll concentrations similar to those modelled from total P concentrations, indicating a bottom-up control of the phytoplankton.
- Only one loch had measured water column total P concentrations similar to those predicted using the Vollenweider P model. Six had total P concentrations greatly elevated above predicted concentrations, suggesting changes in land management and increased nutrient export.
- Four lochs had substantial P inputs arising from their bird populations which were protected under the conservation designations at the sites. However, the majority of lochs require focus on chronic increases in nutrient export, and nutrient and slurry management planning for improved grassland used for grazing.

For further information on this project contact:
Mary Hennessy, Scottish Natural Heritage, Strathallan House, Castle Business Park, Stirling, FK9 4TZ.
Tel: 01786 435358 or mary.hennessy@snh.gov.uk
For further information on the SNH Research & Technical Support Programme contact:
Knowledge & Information Unit, Scottish Natural Heritage, Great Glen House, Inverness, IV3 8NW.
Tel: 01463 725000 or research@snh.gov.uk

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The manuscript was improved as a result of comments from Mary Hennessy. We would like to offer our sincere thanks for her valuable contribution to this report.

1. INTRODUCTION

Scottish Natural Heritage (SNH) appointed Royal Haskoning (RH) to carry out limnological studies of eight freshwater lochs. All of the lochs are included as interest features of designated Sites of Special Scientific Interest (SSSIs), which are considered to be in unfavourable condition, based on the results of Site Condition Monitoring (SCM). They have therefore been identified by SNH as requiring rehabilitation. In all cases, failure to meet targets for favourable condition was linked with elevated nutrient loadings to the water bodies. The aims of the present study were therefore to assess the water quality and nutrient status of the lochs, produce nutrient budgets to help identify nutrient sources and problem areas within the catchments, and develop recommendations for restoration that may be used to return each loch to favourable condition, through appropriate management interventions.

The present report contains details of all methods and field work undertaken (winter, spring, summer and late summer surveys), and documents water chemistry results, nutrient budgeting, phosphorus modelling and mapping exercises. Based on this information, management measures have been recommended. The large amount of data generated by the project including the management recommendations are summarised in a set of Loch Summary Sheets set out in Appendix 1.

1.1 Background to the target lochs

In 2004, SCM was carried out on all standing water features of interest of designated sites. The monitoring programme included lochs in SSSIs as well as those in Special Areas of Conservation (SACs). Assessment of the condition of each water body surveyed was then undertaken with reference to targets documented in the *Common Standards Monitoring Guidance for Standing Waters* (JNCC, 2005). From the features of interest identified as requiring restoration to favourable condition, SNH produced a shortlist of eight lochs for immediate action. These lochs are as follows:

- Mochrum Loch
- Milton Loch
- Woodhall Loch
- White Loch
- Loch Spynie
- Loch of Aboyne
- Dun's Dish
- Kilconquhar Loch.

The lochs were chosen using the following criteria:

- they are within SSSIs with standing water listed as an interest feature
- they are in unfavourable condition
- they have problems with water quality and/or algal blooms
- unfavourable condition appeared likely to be linked to nutrient pollution
- no measures or actions were in place or planned to improve their status.

A map of the locations of the eight lochs is shown in Figure 1. For ease of reference, the lochs can be divided along geographic lines into two groups of four that will be referred to as the southern and northern lochs. The southern lochs are all located south of the central belt. They are White Loch, Mochrum Loch, Milton Loch and Woodhall Loch. The northern lochs are located north of the central belt and are Kilconquhar Loch, Dun's Dish, Loch of Aboyne and Loch Spynie. Note that there is also a longitudinal divide, with the northern lochs being concentrated on the east coast and the southern lochs on the west. Both geographic divides have implications for climatic factors affecting the lochs.

A brief introduction to the eight lochs is provided Table 1. This includes grid references, trophic status, loch surface area, altitude, catchment area and character. Trophic status refers to the names of the notified features of interest within the designated sites. Loch surface and catchment areas are those determined using the digital terrain model (DTM) in the present project. Altitude was taken from the UK Lakes website, which was accessed on 12 September, 2010. At the time of publishing, the UK Lakes data are being moved. The initial assessment of catchment character, which is outlined in Table 1, used Google Earth aerial photography. More detailed assessments of catchment character and land use, based on direct field observation and LCM2000 data, are also included in the present report.

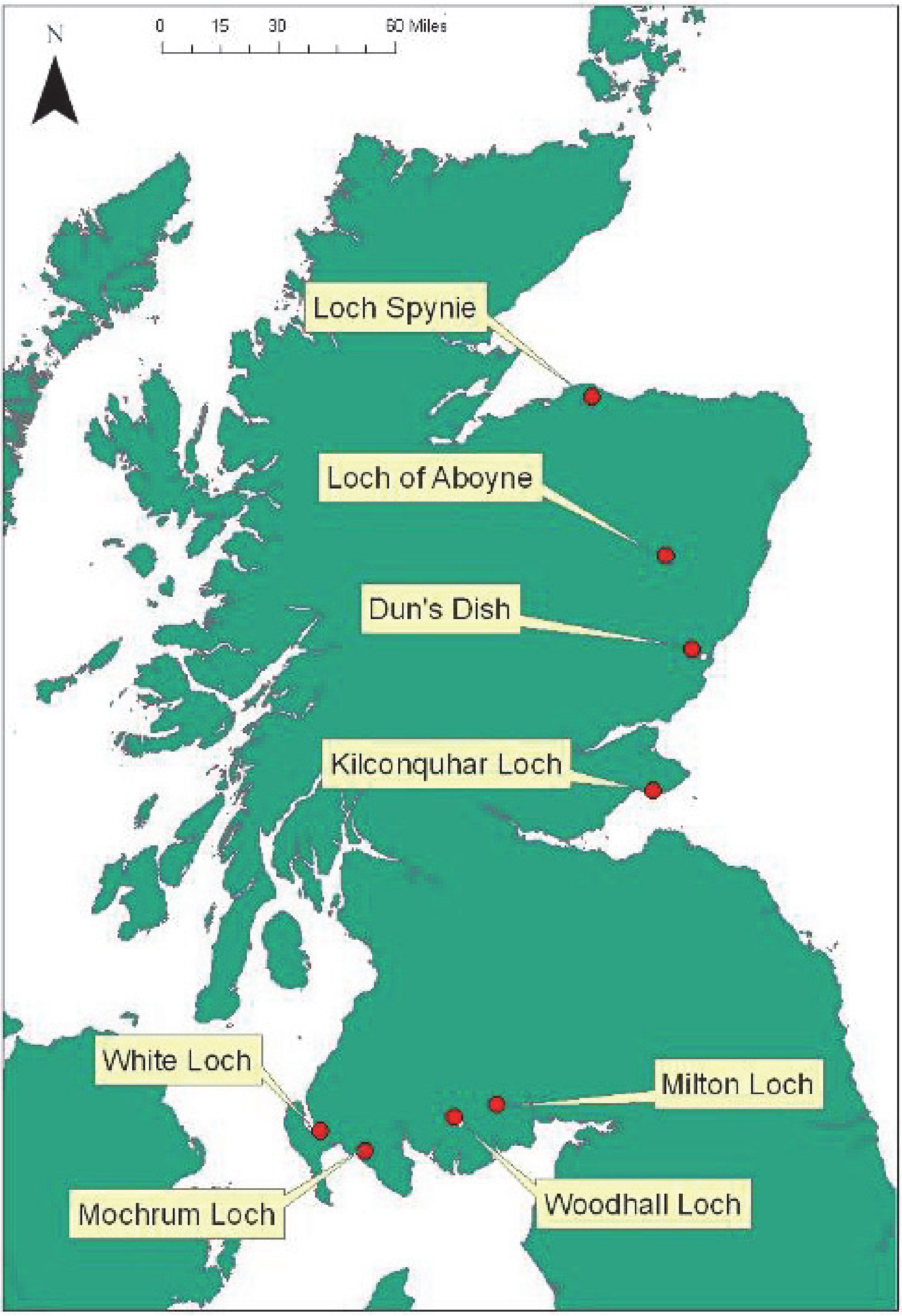


Figure 1. Locations of target lochs

Table 1. Summaries of information on the eight target lochs, including trophic status and catchment statistics

Loch	Trophic status	Size (ha)	Altitude (m)	Catchment area (ha)	Catchment character
White Loch (Loch Inch)	Eutrophic	56.5	18	192	Managed estate; improved parkland and deciduous/mixed mature woodland; small catchment; several buildings
Mochrum Loch	Oligotrophic	178.1	75	1053	Some forest plantation including several different ages and some recently felled trees; few dwellings; large areas of rough, unimproved grassland and heathland; low intensity sheep grazing
Woodhall Loch	Oligotrophic	87.9	54	2584	Conifer plantation with large felled areas; some rough, some improved pasture; few dwellings
Milton Loch	Eutrophic	47.6	128	365	Improved pasture; lush fields for cattle grazing; few dwellings
Kilconquhar Loch	Eutrophic	19.3	17	128	Improved agricultural land with ploughed fields; mature woodland and wet woodland; village on north shore and scattered farm buildings
Dun’s Dish	Eutrophic	10.4	75	113	Woodland and wet woodland; reedbeds; tilled land with ploughed fields; improved grassland; farmyard; few other dwellings
Loch of Aboyne	Mesotrophic	14.4	136	268	Forest plantation with felled areas; some agricultural and some unimproved land; several dwellings; small catchment
Loch Spynie	Eutrophic	17.3	3	669	Forest plantation; wetland and wet woodland; extensive reedbeds; very large catchment; intensive agriculture; Loch Spynie Canal cuts off catchment to the north. Area of 668.8 ha refers to the functional catchment area.

1.2 Designations

Each of the eight lochs has at least one type of protected feature. All of them are designated SSSIs, and several are also included in SAC, SPA (Special Protection Area) and Ramsar designations. Information about the designations at each site was taken from Sitelink, on SNH's internet site (http://www.snh.gov.uk/). The citation, site condition and site management statement (SMS) were consulted and a digest of information relevant to the present project produced for each loch, including water features of interest, condition of each loch and the role of bird assemblages in the designations, as birds can have a considerable impact on nutrient loadings to standing waters (Table 2).

1.2.1 White Loch

White Loch (Figure 3) is a designated SSSI with two interest features. These fall in the general categories of standing open water and canals and aggregations of non-breeding birds. More specifically, the interest features are described as the eutrophic loch and greylag goose (*Anser anser*).

The citation covers only the Loch itself and describes it as a shallow, base-rich and nutrient-rich Loch, formed in glacial gravels. The site is important for large numbers of over-wintering wildfowl, supporting up to 2% of the Icelandic greylag geese overwintering in the UK, as well as internationally important numbers of Greenland white-fronted geese (*A. albifrons flavirostris*). The Loch is rich in organic and mineral nutrients and therefore supports a rich invertebrate and plant life, including the uncommon six-stamened waterwort (*Elatine hexandra*).

Following SCM in 2004, the condition of the site was described as 'unfavourable – no change'. The unfavourable status was linked to the eutrophic loch interest feature, and was attributed to poor water quality, evident due to the occurrence of surface blooms of cyanobacteria (blue-green algae). Such blooms are often a consequence of excessive phosphorus (P) levels in the water columns of lakes, though nitrogen is also important.

The SSSI overlaps with Loch of Inch and Torrs Warren SPA, which is designated for non-breeding Greenland white-fronted geese and hen harriers (*Circus cyaneus*), and was considered to be in favourable maintained condition for each species at the time of the most recent monitoring (1999 and 2006 respectively).

As part of the Castle Kennedy (Loch Inch) Estate, the land surrounding the Loch has long been managed as parkland, and this helps to maintain a stable environment for the designated bird species. Public access to the site is managed to minimise disturbance to the birdlife, and no shooting is carried out in the immediate vicinity for the same reason. The stated management aims at the site are to maintain the internationally important numbers of geese, and to control nutrient losses to the Loch, to avoid excessive nutrient enrichment and the loss of sensitive plant species.

1.2.2 Mochrum Loch

Mochrum Loch is part of Mochrum Lochs SSSI. The designation also includes Castle Loch to the west and Black Loch to the north of Mochrum Loch, as well as the land in between, which has an area of 456 ha. Both Castle Loch and Black Loch flow into the northwest end of Mochrum Loch via Inflow 1 (see Figure 4).

Mochrum Lochs SSSI incorporates three interest features. These are blanket bog (unfavourable condition, SCM 2006), breeding cormorants (*Phalacrocorax carbo*) (favourable condition, SCM 2000) and oligotrophic loch (unfavourable condition, SCM 2004, 2009). The blanket bog consists of a mosaic of wet and dry areas, which are habitats of the following species. Wet habitat supports cranberry (*Vaccinium oxycoccus*), purple moor grass (*Molinia caerulea*), cross leaved heath (*Erica tetralix*), heather (*Calluna vulgaris*), hare's tail cotton grass (*Eriophorum vaginatum*), *Sphagnum rubellum*. Dry habitat is colonised by bog rosemary (*Andromeda polifolia*), white beak-sedge (*Rhynchospora alba*), various *Sphagnum* species, deergrass (*Trichophorum cespitosum*) and bog myrtle (*Myrica gale*). The cormorant breeding colony is the third largest inland population in the UK. In addition, the Loch and its surrounding habitats provide for a very rich breeding bird assemblage, including great-crested grebe (*Podiceps cristatus*), little grebe (*Tachybaptus ruficollis*), redshank (*Tringa totanus*) and lapwing (*Vanellus vanellus*).

The Mochrum Lochs site has also been designated a SAC for depressions on peat substrate (unfavourable, no change). The SAC lies between Mochrum and Castle Lochs, but does not include these water bodies, only the area of blanket bog that lies in between them.

Management of the site includes low levels of fishing, sheep grazing, low level cattle grazing and muirburning. Part of the area is under an SNH management agreement supporting an agreed management regime. During the past 30-40 years, land to the south and west has been commercially planted with conifers, some of which have now been permanently removed. The Loch was described following SCM in 2004 as being in unfavourable, declining condition, due to deteriorating water quality and the presence of the invasive water plant, New Zealand pygmyweed (*Crassula helmsii*). This species may threaten biodiversity by causing light limitation, oxygen depletion and pH changes, and forms very dense monospecific stands on damp ground, and in water up to 3 m in depth. During SCM of the Loch in July 2004, a significant cyanobacterial bloom was present. In addition, two macrophyte species, which may be indicative of nutrient levels that have been increased anthropogenically, were recorded – curled pondweed (*Potamogeton crispus*) and common duckweed (*Lemna minor*). SCM results from 2009 indicated that condition remained unfavourable, because of failure to meet water quality targets and the continued presence of *C. helmsii*.

Management aims are to maintain the extent and condition of the blanket bog and the wetness and water quality of the bog habitats. The abundance of cormorants, diversity of breeding birds, and the quality of the standing water are also to be maintained according to the SMS accompanying the designation.

1.2.3 Woodhall Loch

Woodhall Loch is designated as a SSSI with a number of features of interest: an unusually diverse aquatic water beetle community; the caddis fly *Phacopteryx brevipennis*; lowland acid grassland; lowland neutral grassland; oligotrophic loch; fen meadow and open water transition fen. The transition fen and fen meadow and are in favourable condition (SCM 2010 and 2011, respectively), though the fen meadow has been judged to be declining. The invertebrate interest features, beetles and caddis fly, have been monitored and described as favourable maintained (SCM 2010 and 2013, respectively). However, in 2004 and 2009, the condition of the standing water interest feature was judged to be unfavourable. The Loch failed to meet targets for water quality and the macrophyte community. The designation covers the Loch itself, as well as a short section of the outflow and its banks. The total area of the SSSI is 130 ha.

Woodhall Loch represents a transitional water body, with peaty upland and wooded lowland influences. It is surrounded by fen, mire and species-rich grassland. Base enrichment in localised areas promotes the growth of sedges, with white, pale and tawny sedge present (*Carex canescens, C. pallescens and C. hostiana*, respectively). The management statement for the site aims to ensure that nutrient enrichment of the Loch does not take place. Partly, this is to be achieved through careful management of surrounding land uses and the use of mitigation, such as buffer strips near watercourses. Land use includes a commercial conifer plantation on the western shore, while the eastern shore has improved pasture with drainage, wetlands and broadleaved woodland. Angling, shooting, pest control and boating all take place at the Loch.

1.2.4 Milton Loch

Milton Loch SSSI is designated for its aquatic beetle assemblage and eutrophic water body. The area covered by the designation includes the Loch itself which is shallow and nutrient-rich, and a small area (13 ha) of the catchment to the north containing wetland areas with globeflower (*Trollius europaeus*) and willow carr. The diverse invertebrate assemblage includes declining northern species of water beetles as well as surviving remnants of southern populations typical of the Solway region e.g. *Hygrotus quinquelineatus*, *Ilybius fenestratus*, *Oulimnius troglodytes* and *Gyrinus aerates*. Several species are classed as 'nationally scarce'. The site is important for migratory and breeding wildfowl including tufted duck (*Aythya fuligula*) and mute swan (*Cygnus olor*).

Following SCM in 2004, the condition of the eutrophic loch feature was categorised as unfavourable no change. The beetle assemblage was regarded as favourable maintained, but SCM in 2010 indicated that the latter feature was now in unfavourable condition. The water level can be controlled by a sluice on the Milton Burn, which has been *in situ* for around 100 years. Coarse fishing, shooting, pest control, drainage, cattle and sheep grazing, and fertilizing are all activities carried out in the Loch or surrounding land. A main objective of the management statement is to maintain the Loch's nutrient status, by careful agricultural management in the catchment area. Support of the water beetle assemblage and maintenance of the wetland plant interest are also management aims. It is an important aim of the SMS that the breeding and wintering wildfowl are maintained and disturbance to them does not increase. Conditions such as high winter water levels, stable water levels during nesting and drying out of some pools in summer are required to help maintain biodiversity at the site.

1.2.5 Kilconquhar Loch

Kilconquhar Loch SSSI is designated for its breeding bird assemblage (unfavourable condition, SCM 2008), eutrophic loch (unfavourable condition, SCM 2004), transition fen (favourable condition (declining), SCM 2013), the presence of pochard (*Aythya farina*) (unfavourable condition, SCM 2008), tufted duck (unfavourable condition, SCM 2008) and wet woodland (unfavourable condition, 2009). The designation includes the Loch itself and approximately 10 ha of the surrounding swamp and wet woodland. The total area of the designated site is 47 ha.

The site is composed of a large, eutrophic kettle hole, surrounded by an extensive fringe of transition mire and wet woodland. The mire is dominated by common reed (*Phalaris arundinacea*), with localised reed sweet grass (*Glyceria maxima*), bottle sedge (*C. rostrata*) and reedmace (*Typha latifolia*). Swamp and willow carr occur in association with the mire. The breeding bird assemblage is diverse at the site, and includes the nationally rare black-necked grebe (*Podiceps nigricollis*).

The Loch was considered to be in unfavourable condition (SCM 2004), because of its impoverished plant assemblage, the causes of which are not fully understood. Although the transition fen is in favourable condition it was judged to be declining following SCM in 2013. The wet woodland is not considered to have met its regeneration potential and hence is in unfavourable condition. The bird features are in unfavourable condition due to declining abundance and diversity, and these changes may be associated with the decline in the quality of the standing water habitat.

The site is part of a lowland estate with a mainly recreational use, and is adjacent to agricultural land and private gardens. The Loch is primarily fed by underground springs, and the outflow is controlled by a weir. The high levels of nutrients in the Loch give rise to occasional algal blooms. Diffuse pollution and inputs from the bird assemblage may contribute to enrichment. Boating is rare on the Loch, and shooting of wildfowl appears low-key. Control of rhododendron and sycamore in the wet woodland has been carried out in the past. The control of diffuse pollution sources is a stated management aim at the site, along with the enhancement of mire, wet woodland and bird populations.

1.2.6 Dun's Dish

The designation for Dun's Dish SSSI includes the open water of the loch itself, plus 15 ha of the surrounding carr and swamp habitat. The total designated area is 31 ha. There are three interest features notified under the designation. These are breeding bird assemblage, eutrophic loch and open water transition fen. According to the citation, the transition fen with swamp and carr communities is species-rich, including marsh marigold (*Caltha palustris*), bottle sedge and marsh willow-herb (*Epilobium palustre*), as well as some species with a very localised distribution in Angus e.g. lesser tussock-sedge (*Carex diandra*), marsh ragwort (*Senecio aquaticus*) and blue water-speedwell (*Veronica anagallis-aquatica*). Extensive reedbeds are dominated by common reed and reed canary-grass. However, the open water transition fen in unfavourable condition (SCM 2010).

The bird assemblage is diverse, thriving in the wetland habitats, with a large colony of common terns (*Sterna hirundo*) present. The SSSI lies within the Montrose basin SPA, which is designated for dunlin (*Calidris alpina*), eider (*Somateria mollissima*), grey-lag goose, knot (*Calidris canutus*), oystercatcher (*Haematopus ostralegus*), pink-footed goose (*Anser brachyrrynchus*), redshank, shelduck (*Tadorna tadorna*) and wigeon (*Anas penelope*). The breeding bird assemblage is in favourable condition (SCM 2002).

The eutrophic loch component of the designation was found to be in unfavourable condition (SCM 2004), due to poor water quality, with evidence of high phosphate enrichment through catchment run-off. The macrophyte complement was also found to be deficient, with previously present *Potamogeton* species found to be absent. Fen habitat was observed to be expanding, possibly due to silt build-up. The water levels are thought to be increasing, and monitoring of this characteristic of the site is required. Physical and chemical changes may contribute to declines in the success of breeding birds.

The site is used for wildfowling and for agriculture. A series of field drains conducts run-off from the fields into the loch and these could be contributing to enrichment. A primary management objective is to improve the poor water quality and reduce nutrient inputs from the surrounding catchment.

1.2.7 Loch of Aboyne

Loch of Aboyne SSSI is designated for the features of the water body and grasswrack pondweed (*Potamogeton compressus*). The designation covers the Loch and 2 ha of the surrounding catchment area. The designation was created because of the rich flora and fauna in Loch of Aboyne, along with associated reedbed and fen vegetation. The sheltered and shallow eastern arm of the Loch has not been disturbed by power craft, and has an exceptional diversity of invertebrates. The reedbeds also provide shelter for modest numbers of passage and wintering birds.

The Loch is considered to be mesotrophic and at the time of designation, it was noted as being unusually free from the adverse effects of enrichment from fertiliser run-off and sewage effluent. According to the citation, the macrophyte flora recorded in the Loch is diverse, including eight species of *Potamogeton*, in addition to locally uncommon species, such as spiny-spored quillwort (*Isoetes echinospora*), short-leaved water crowfoot (*Ranunculus trichophyllus*) and grass-wrack pondweed (*P. compressus*). However, the Loch is in unfavourable condition (SCM 2004).

Loch of Aboyne is artificial, created in Victorian times by the construction of a dam. There is a stone-faced dam at the western edge of the water body, incorporating a spillway which drains into a burn flowing through the adjacent golf course. A water-ski club uses Loch of Aboyne and has built landing stages and a ramp in the Loch. The golf club on the western shore (Aboyne Golf Club) has abstracted water since 1983 to water the greens. The caravan site adjacent to the standing water is connected to the public sewerage system, so is not believed to discharge sewage into the Loch.

Water levels in the Loch of Aboyne need to be maintained, primarily through the survey and repair of the dam and spillway. Excessive water abstraction may also be damaging to the Loch. There are concerns over the impact from nutrient enrichment and sewage. The impacts of physical disturbance due to recreational use could include the disturbance and breaking-up of submerged vegetation by wakes and propellers, and bank erosion and emergent vegetation could be affected by wave action and trampling. The aims of management are to maintain the aquatic flora, particularly the *Potamogeton* species, to maintain water level and quality, and to avoid bank erosion and loss of emergent vegetation.

1.2.8 Loch Spynie

Loch Spynie is designated as a SSSI, SPA and Ramsar site. The notified features of the SSSI, which include the Loch itself and 68 ha of the surrounding catchment area, are fen meadow (unfavourable condition, SCM 2012), breeding bird assemblage (favourable condition, SCM 2002), eutrophic loch (unfavourable condition, SCM 2004 and 2009), greylag goose (unfavourable condition, SCM 2008), open water transition fen (favourable condition, SCM 2001) and wet woodland (favourable condition, SCM 2002). The SPA designation is based on one feature, an internationally important roosting population of greylag goose (up to 7% of the world population), whilst the Ramsar designation includes the eutrophic loch and transition fen features in addition to the geese.

Naturally eutrophic lochs are rare in northern Scotland. Loch Spynie SSSI is documented as supporting a rich aquatic and terrestrial fauna and flora, including nine *Potamogeton* species and several southern species that are rare in Scotland, e.g. water violet (*Hottonia palustris*), great spearwort (*Ranunculus lingua*), hemlock water-dropwort (*Oenanthe crocata*) and narrow leaved water parsnip (*Berula erecta*). There is good representation of the successional stages between open water, through transitional fen and swamp, to alder woodland. The fen and swamp habitat is of national importance, with nine communities present, the most extensive of which is common reed.

Loch Spynie is very shallow (~1 m deep) and is fed by one stream and groundwater seepage. The outlet drains to the Spynie Canal. Until the 16th century, the Loch was part of the sea, which is reflected in its unusual water chemistry and plant assemblage. Currently, the water body is maintained by artificial banks which allow a constant water level to be maintained. It was once part of a much more extensive wetland system, but this has been reduced by successive drainage and flood management schemes.

Management for wildfowling has taken place in the past, including reed cutting and fen burning, but these activities stopped in 1981. There is now a management agreement between SNH and the owner of the site that relates to positive habitat and visitor management. Annual mowing of fen and grassland, scrub control and the installation of bird breeding platforms are carried out and funded by SNH. Loch Spynie Advisory Committee, a group of local naturalists, advises on management of the site and has carried out some habitat management. The site is now important for bird watching, and there is a hide on the eastern shore.

Loch Spynie's naturally eutrophic characteristics make it vulnerable to phosphate enrichment from the surrounding intensively farmed agricultural land. Further urban development within the catchment could also adversely affect water quality. New Zealand pygmyweed has been recorded at a nearby site, giving cause for concern. Management objectives for the site include the maintenance of a large area of open water, unusual water chemistry and aquatic plant community. The fen and wet woodland communities must also be maintained.

Table 2. Summary of site designations and condition

Site	Designation(s)	Standing water feature	SCM condition of water feature	Birds included in designation
White Loch	SSSI	Eutrophic loch	Unfavourable, no change (2004)	Yes
Mochrum Loch	SSSI/SAC	Oligotrophic loch	Unfavourable, declining (2004, 2009)	Yes
Woodhall Loch	SSSI	Oligotrophic loch	Unfavourable, no change (2004); unfavourable declining (2009)	No
Milton Loch	SSSI	Eutrophic loch	Unfavourable, no change (2004)	No
Kilconquhar Loch	SSSI	Eutrophic loch	Unfavourable declining (2004)	Yes
Dun's Dish	SSSI/SPA	Eutrophic loch	Unfavourable declining (2004)	Yes
Loch of Aboyne	SSSI	Mesotrophic loch	Unfavourable declining (2004)	No
Loch Spynie	SSSI/SPA/ Ramsar	Eutrophic loch	Unfavourable declining (2004); unfavourable recovering (2009)	Yes

2. METHODOLOGY

2.1 Stakeholder Consultation

Contact was made with SNH area officers at an early stage in the project via the SNH project manager. This enabled the relevant landowners and stakeholders to be identified. SNH area officers contacted all landowners to inform them of the project and the need for access to their land, determined which landowners required advance notice of field work, and passed the relevant contact details to Royal Haskoning. Landowners who had requested contact were contacted in advance of each survey visit. These stakeholders were also consulted for their background knowledge of the lochs and generally expressed an interest in receiving any analysis produced as a result of this project. Information gained from stakeholders is included in the discussion on the lochs in Section 4.

2.2 Field work

2.2.1 Sampling programme and seasonality

Sampling of the eight lochs was carried out on four occasions during 2010 (winter, spring, early summer and late summer), in order to capture and model the limnological changes associated with seasonality. The methodology required the winter and spring sampling trips to be completed before the end of March, but this was problematic as a result of the extremely cold weather at the beginning of 2010. The winter ice lasted well into February in 2010, especially on the northern lochs and delayed the winter sampling, which would ideally have been carried out in January. Two of the lochs remained frozen throughout February, and so were not sampled in winter. The dates of all the sampling visits to each loch are shown in Table 3.

The four southern lochs thawed, warmed and underwent seasonal changes earlier than the northern lochs, due to climatic differences related to latitude and longitude. Hence, the southern lochs were slightly ahead of the northern lochs in terms of annual cycling, and were sampled before the northern lochs on each sampling occasion.

Table 3. Sampling dates for each loch

	Winter	Spring	Early summer	Late summer
White Loch	17/02/10	23/03/10	16/06/10	24/08/10
Mochrum Loch	17/02/10	23/03/10	16/06/10	24/08/10
Woodhall Loch	15/02/10	22/03/10	22/06/10	25/08/10
Milton Loch	n/a	22/03/10	22/06/10	25/08/10
Kilconquhar Loch	23/02/10	30/03/10	15/06/10	06/09/10
Dun’s Dish	22/02/10	31/03/10	07/07/10	07/09/10
Loch of Aboyne	n/a	30/03/10	07/07/10	06/09/10
Loch Spynie	22/02/10	31/03/10	06/07/10	07/09/10

2.3 Loch water sampling

The deepest part of each loch was located using a Garmin FF160C echosounder and water samples were taken at the location in each loch where the water column was deepest. The boat was anchored in such a way as to allow it to come to rest over the deepest part of the water body. Surface water samples were obtained directly from the surface of all lochs. In addition to surface water samples, composite samples were obtained from the deepest lochs (White Loch and Woodhall Loch), using a weighted, clear plastic tube, 5 m in length. The tube was lowered vertically into the loch and then the lower end was raised in order to expel the composite sample from the upper end. The tube contained approximately 2 L of water, so all of the water from the tube was collected in the composite sample bottle. A 4.2 L

Kemmerer depth sampler was used to obtain samples at 1 m or 5 m increments (or as close to these increments as possible) in the deeper lochs, as appropriate (see Table 4). A YSI probe was used to record temperature and dissolved oxygen concentrations from surface to deep water. Lowering of the probe was stopped approximately 1 m from the substrate to prevent the probe from entering the sediments, where damage could occur and the measurements would be void. A Secchi disc was used to estimate turbidity.

Table 4. Water samples taken from each loch

	Samples obtained				
White Loch	Surface	Composite	5 m	8.5 m	
Mochrum Loch	Surface		3.75 m		
Woodhall Loch	Surface	Composite	5m	8.5 m	
Milton Loch	Surface				
Kilconquhar Loch	Surface		1 m		
Dun's Dish	Surface				
Loch of Aboyne	Surface		1 m	2 m	3 m
Loch Spynie	Surface				

2.4 Inflow water sampling

Inflows and ditches were sampled at points where the water could be seen to be flowing towards the loch, to avoid capture of backwash from the loch itself. A clean decanter bottle was used to fill the sample bottle, as in most cases the inflows were too shallow to allow direct sampling. Great care was taken not to stir up sediments or to allow them to flow into the sample bottle. Often, in the drier months, many of the inflows and ditches were dry. It should be noted that nutrient budgeting involving ditches is difficult unless the network of ditches has specifically been mapped, as they cannot be delineated using a DTM.

2.5 Catchment walkover survey

On the first visit to each loch, a walkover survey of the catchment was carried out. Lochs were circumnavigated on foot or by boat, to record all inflows, characterise the surrounding catchment and assess the major hydraulic characteristics of the waterbody, e.g. artificially managed inflows and outflows or impermeable embankments.

2.6 Alien species – *Crassula helmsii*

Mochrum Loch contains the invasive aquatic weed New Zealand pygmyweed (*C. helmsii*). This species is highly invasive, and can spread vegetatively from small fragments. It was therefore essential to ensure that no fragments were transferred from Mochrum Loch to any of the other target lochs on the equipment used. For this reason, Mochrum Loch was always surveyed last in the day, so the equipment, especially the boat, could be thoroughly power-hosed before being used in the next loch.

2.7 GIS

ESRI software (ArcGIS9) was used to create the shape files and to calculate all land areas.

2.8 Photography

Photographs were taken of the lochs and surroundings in order to illustrate the characteristics of the waterbody and catchment. A set of grid referenced photographs of the lochs and their catchments are included in this report (plates 2-43). Grid references and other metadata can be found in Appendix 2 along with the photographs as JPEG images.

2.9 Laboratory analyses

2.9.1 Parameters measured

The chemical and biological variables measured in the laboratory were as follows:

- alkalinity
- total ammoniacal nitrogen (TAN) and free ammonia (based on temperature and pH)
- total oxidised nitrogen (TON)
- nitrite (NO_2-N)
- total phosphorus (TP)
- total soluble phosphorus (TSP)
- soluble reactive phosphorus (SRP)
- silica
- soluble iron
- manganese
- biochemical oxygen demand (BOD_5) (inflows only)
- suspended solids (SS)
- chlorophyll *a* (Ch*a*) (loch samples only).

For inflow samples, BOD_5 (a measurement of oxygen consumption rate) was used as a surrogate for the quantity of organic matter present (Kalff, 2002). Chlorophyll *a* concentrations were determined as a measure of biological productivity within the water columns of the lochs.

2.9.2 Laboratory methods

The laboratory analyses were undertaken by the Agri-Food and Biosciences Institute in Belfast (AFBI). All water samples were shipped overnight to AFBI in cool boxes. This enabled the preparation of the samples to begin on the day following collection, as is standard practice.

Samples were analysed using standard methods, as listed by Gibson *et al*. (1980). Conductivity, alkalinity and pH were measured in unfiltered samples. Alkalinity was determined by titration to pH 4.5 with strong acids using the Metrohm Titrino autotitrator system. Soluble fractions of nutrients were measured on samples that had been filtered using 0.45 µm membranes made of mixed cellulose acetate and nitrate. SRP was determined by reaction with acid molybdate, whilst TP and TSP were measured after digestion with sulphuric acid/potassium persulphate, using the same analytical method as for SRP. The limit of detection for P fractions was < 5.0 µg P L^{-1}. TAN was determined on filtered samples by reaction with hypochlorite and nitroprusside to give indophenol blue. TON was measured on a Technicon autoanalyser by reduction to nitrite and subsequent colour development using napthyl-ethylenediamine.

Soluble iron was determined by digestion with acidic hydroxylamine solution and reaction with mildly acidic acetate buffer with 2,4,6-tri (2-pyridyl)-1,3,5-triazine. Silica was determined spectrophotometrically following reaction with acidic molybdate and reduction by ascorbic acid. Mn was determined spectrophotometrically following oxygenation to permanganate by ammonium persulfate. BOD_5 was determined using the Oxitop method. This involved filling airtight 510 ml bottles to overflowing and incubating in the dark at 20 ^{o}C (+/- 0.5 ^{o}C) for five days. Dissolved oxygen (DO) level was measured prior to and after incubation and BOD_5 was calculated from the difference between initial and final DO concentration. Suspended solids levels were measured by filtering 500 ml of sample through a pre-weighed filter paper and drying it for 24 hours at 100 °C. The weight of the dried filter paper plus retained material, minus the weight of the prepared filter paper alone equals the weight of the suspended solids present in 500 ml of sample. Inorganic suspended solids were then determined by flashing (or drying) for a further 24 hours in a kiln at 500 °C to ignite any organic material in the residues. Organic suspended solids concentrations were calculated as the difference between total solids and inorganic solids. Ch*a* was determined using a Unicam UV1 spectrophotometer, following extraction from material retained on a glass-fibre prefilter paper (with a mean pore size ranging from 1 to 5 µm) into hot methanol.

2.10 Phytoplankton and zooplankton

Phytoplankton and zooplankton samples were collected during each sampling trip in order to provide further information about the limnology of each loch through looking at dominance within the plankton.

In the shallower lochs, phytoplankton samples were obtained from surface water, but composite samples were taken from White Loch and Woodhall Loch, where the water columns were deeper. Surface samples were obtained directly from the loch surface by submersion of the sample bottle, whilst composite samples were taken using a 5 m tube which was lowered vertically into the loch. The lower end was raised to decant the tube contents into a sample bottle. A 50 ml sample tube was filled with the water from the mixed surface water sample and approximately 5 ml of Lugol's iodine was added to preserve the phytoplankton.

Phytoplankton were examined using the Utermöhl Lund inverted microscope technique. They were identified to genus, or if possible, to species level, using "The Freshwater Algal Flora of the British Isles" (John *et al*., 2002) and a range of other aids (Lind & Brook, 1980; Barber & Haworth, 1994; Kelly, 2000) at magnifications of X100 and X400. Phytoplankton were also enumerated and measured using a graticule. The dimensions measured and the number of cells of each phytoplankton species were used to calculate results in biovolumes (mm^3 L^{-1}), with the standardized geometric equations of the European Committee for Standardization (CEN, 2003).

Qualitative zooplankton samples were obtained from each survey by dragging the zooplankton net slowly behind the boat for several minutes. The samples were then preserved in Industrial Methylated Spirits (IMS). Subsequently, zooplankton were identified and enumerated in the laboratory using Sedgewick Rafter slides under a light microscope at X10 and X40 magnifications. Freshwater Biological Association keys to Cladocera, Copepoda and Rotifera were used to aid identification (Scourfield and Harding, 1994; Pontin, 1978; Harding and Smith, 1974).

2.11 Hydrometric data

Calculation of a nutrient budget for a loch catchment area, based on measured data, and the response of the loch to a given P loading, require knowledge of the flow regimes in the inflows to the loch. This is because nutrient loadings are the product of flow and nutrient concentration and are normally expressed as tonnes yr^{-1}. None of the inflows or outflows of the target lochs were hydrometrically gauged, so the nearest comparable gauged rivers were used and scaled by catchment size and rainfall differences to derive a surrogate flow record for each target loch.

2.12 Bathymetry

Catchment areas were calculated within GIS and found to correspond to varying degrees with those measured by Murray and Puller (1910). Volumes used are those available from the surveys of Murray and Pullar, which can be obtained online at http://maps.nls.uk/. It was not possible to carry out bathymetric surveys of the target lochs during the present project.

2.13 Nutrient budgeting

2.13.1 Nutrient budgets based on desk-based analysis

An aim of the study was to produce a nutrient budget for each of the eight lochs and estimate water column TP concentrations, based on catchment statistics. The initial budget was produced through a desk-based analysis, relying on the land use characteristics of each catchment and the hydro-geomorphology of each loch. The outputs of these budgets were compared with budgets that were based on monitoring data collected as part of the project.

A series of stages were involved in producing the desk-based budgets as described below.

- The catchment and all sub-catchment areas of each loch were delineated. A DTM was used with spatial analyst in ArcGIS. Catchments were delineated based on the location of the loch's outflow, while sub-catchments were delineated based on the location of the relevant inflow into the loch. Following modelling, each catchment and sub-catchment was checked using 1:50,000 OS maps, to ensure there was no cross-boundary flow.

- Areas of each land use type were calculated in GIS for each land use parcel and summed to provide the percentage of the sub-catchments devoted to each land use type. Land Cover Map data (LCM2000) were used for this purpose. P export coefficients derived from the Phosphorus Land-Use Slope model (PLUS), developed by SEPA and Macaulay Land Use Research Institute (MLURI) (Marsden *et al.*, 1995), were used to calculate the expected rate of P export from each catchment and sub-catchment. This process allowed identification of areas that may be expected to supply large amounts of P to each loch.

- The magnitude of a loading from a sub-catchment is related to its area, so to compare the intensities of nutrient loss between sub-catchments, areal loss rates (loading / unit sub-catchment area) were calculated. Problem sub-catchments were expected to have higher export or loss rates.

- Other potential diffuse nutrient sources such as bird populations were considered along with point sources such as septic tanks. Bird population estimates for winter and summer were provided by SNH and these were added to the modelled nutrient budget and the budget estimated using nutrient concentrations measured in inflows. For modelling purposes, migratory wildfowl were considered to excrete 0.45 g P day^{-1}, with 60% of the total excreta expected to enter water bodies (Post *et al.*, 1998). For the budget based on measured nutrient concentrations, septic tanks were only considered as additional direct inputs where they were not accounted for by seeping into inflowing streams and were not therefore already included in the loadings (for example, dwellings located on the loch shore or in catchments with no inflows). For the budget based on export coefficients, the number of septic tanks in each inflowing sub-catchment was estimated using the OS maps and knowledge of the area, and added to the loadings based on land use export coefficients. For the purposes of estimating the impact of sewage on fresh waters, it was assumed that each person produces 0.8 kg of TP per year (Foy *et al.*, 2003). This figure along with an average family size of 4 people was used to calculate additional loadings from septic tanks.

This exercise provides an estimate of the nutrient loading to each loch under current land use.

2.13.2 Nutrient budgets estimated from measured data

Estimates from the desk-based study were compared with loadings derived from the inflow sampling to identify areas of P transport that were high compared with expected nutrient exports from current land use in the sub-catchments. Loadings derived from measured inflow concentrations were calculated as follows:

P loading (tonnes per year)	=	Estimated total annual flow corrected for rainfall (m^3)	x	Annual mean measured inflow TP concentration ($g\ L^{-1}$)	x	1000

2.14 Modelling water column TP concentrations from catchment inputs

Loch-specific catchment loadings in mass per area per time-based units (for example in $g\ P\ m^{-2}\ yr^{-1}$) can be converted into water column TP concentrations using a Vollenweider (1976) type model (Plate 1). Note that units of $mg\ P\ m^{-3}$ are equal to units of $\mu g\ P\ L^{-1}$. This model requires knowledge of the TP loading to the loch and two hydromorphological variables: the hydraulic loading and the water retention time of the loch. These hydromorphological parameters are influenced by catchment water yields, mean loch depth, loch surface area and catchment size. It should be noted that the Vollenweider model was derived from a relationship between the TP level in the water column of the lake and the flow-weighted mean inflow TP concentration (Equation 2 in Plate 1).

Predicted TP concentrations within the water column of each loch were calculated using Equation 1 (Plate 1) and are compared with annual mean measured concentrations in Table 23.

$$\mathbf{P_{lake} = L_P/q(1+\sqrt{\tau_w})} \qquad \textbf{equation 1}$$

Where:
- P_{lake} = lake P concentration ($mg\ P\ m^{-3}$)
- L_P = lake P loading ($g\ P\ m^{-2}\ yr^{-1}$)
- q = lake hydraulic loading ($m\ yr^{-1}$)
- τ_w = lake water retention time (years)

However: $\mathbf{L_P = P_{inflow} \times Vol_{inflow} / A}$

and $\mathbf{q = Vol_{inflow} / A}$

Where:
- P_{inflow} = Mean inflow P concentration ($mg\ P\ m^{-3}$)
- Vol_{inflow} = Annual inflow volume (m^3)
- A = Lake area (m^2)

$$\therefore \quad \mathbf{L_P/q = (P_{inflow} \times Vol_{inflow} / A) \times (A / Vol_{inflow})}$$

As the $\mathbf{Vol_{inflow}}$ and **A** terms cancel:

$$\mathbf{L_P/q = P_{inflow}}$$

Equation 1 can therefore be expressed as:

$$\mathbf{P_{lake} = P_{inflow}/(1+\sqrt{\tau_w})} \qquad \textbf{equation 2}$$

Plate 1. Phosphorus loading model of the relationship between TP concentration in the water column of the lake, TP loading from the catchment area (equation 1) and level of TP in the inflow (equation 2) (Vollenweider, 1976)

Note that there are limitations to the accuracy of models based on estimated data, and those based on a limited number of measurements of nutrient levels and flows estimated from other catchments. The results should be therefore be used only in an indicative and / or comparative way, and should not be assumed to be completely accurate.

Error is associated with the use of any general predictive model of lake P concentrations. The level of error increases with deviations from the assumptions of the models and with increasing complexity of catchments. Additional sources of error were introduced into the nutrient modelling exercise in the present study in a number of ways. Catchment areas can be predicted accurately using GIS data (DTM model), and whilst the areas of land use can also be measured accurately in a GIS, they depend on the original land use classification, which is subject to some generalities and there are unclassifiable areas. The export coefficients used to calculate export rates are by definition quite general and do not account for physical variations on the ground, or local weather patterns. The bird populations included in the models are estimates with unknown accuracy, and similarly the assumptions of a four person household using a septic tank, and each person producing 0.8 kg TP per year are broad estimates, and it is not possible to determine how accurate these estimates are without further comprehensive investment.

Accurate, current loch surface areas were used in calculating water column TP levels with the equation of Vollenweider (1976). However, the best available option for loch volume data was historical. As volume depends on surface area, this leads to a degree of mismatch. Measured water column TP concentrations are based on four spot samples of water and therefore cannot be expected to reflect the full range of long-term fluctuations.

All of these potential sources of inaccuracy should be appreciated when using the models. It is considered that model accuracy is, however, sufficient to highlight problem areas and allow a comparison between lochs and sub-catchments.

2.14.1 Comparison of modelled TP with measured TP

An outcome from this exercise is that it provides a means of assessing the degree of agreement between the TP concentration observed in the loch and levels predicted from known inputs and current land use. Elevated water column TP concentrations, where observed values are greater than predicted, suggest an unknown external P input to the loch and/or internal loading of P from the loch sediments. Internal P loading was assessed by sampling for P and Mn in samples taken at depth.

2.15 Chlorophyll *a* modelling

Ch*a* is routinely used in limnology as an estimate of phytoplankton abundance. The OECD (1982) produced equations relating water column loch TP and Ch*a* concentrations. Since then, further equations relating TP and Ch*a* have been produced, including those that resulted from Water Framework Directive related research and monitoring. Within the current study, TP-Ch*a* models were used in two ways.

1. In consideration of the efficiency with which phytoplankton utilise P, present Ch*a* levels were compared with concentrations predicted from TP levels.

2. The Ch*a* - TP models were used to estimate how lochs would respond to predicted changes in water column TP levels resulting from reduced nutrient loadings from the catchment areas.

A decrease in algal biomass, as indicated by a decrease in Ch*a* level, would be expected to result in an increase in water transparency. The relationships between Secchi depths, Ch*a* and TP concentrations were therefore also examined, as potentially useful for setting targets, where the aim is to ensure a recovery of loch macrophytes.

Note that as with modelling of water column TP concentrations, there are errors associated with using models linking TP and Ch*a* levels, so results may only be used in an indicative way.

3. RESULTS

This section presents the results from the field work and laboratory analyses, starting with detailed catchment descriptions, water chemistry of the lochs and inflows, trophic status and nutrient budgeting.

3.1 Catchment descriptions

The following section describes each loch and catchment, based on field observations made during sampling trips to the lochs and walking over the catchment areas, highlighting significant logistical issues and opportunities, as well as the general character of the catchments. More in-depth information on land use in each catchment is contained in later sections of this report. Ordnance Survey maps of the lochs, catchments and sub-catchments (i.e. inflow catchments) can be found in Figures 3-10.

Physical properties of seven of the lochs obtained from Murray and Pullar (1910) are shown in Table 5 below. Data for Dun's Dish are not included in Murray and Pullar (1910), but were obtained instead from Recorda Cos (2006). In the following catchment descriptions, data on area and depth are those in Table 1 and Table 5 respectively.

Table 5. Physical properties of each loch

Loch	Surface area (ha)	Mean depth (m)	Maximum depth (m)	Volume (m^3)	Catchment area (ha)
White Loch	60.3	4.27	11.6	2605150	n/a
Mochrum Loch	93.1	2.13	4	1925546	1036
Woodhall Loch	69.0	6.10	14.9	4077626	2331
Milton Loch	61.9	2.13	4.6	1274258	518
Kilconquhar Loch	38.4	1.23	1.8	453070	n/a
Dun's Dish	10.4	0.75	1	78000	113.4
Loch of Aboyne	15.4	1.83	3.4	283169	259
Loch Spynie	24.3	0.84	1.8	198218	777

3.1.1 White Loch

White Loch is surrounded by the Loch Inch Estate (Plate 2). Land use in the catchment area consists of parkland, woodland, low intensity cattle grazing (Plate 3) and a visitor centre in the grounds of a ruined castle on the east shore (lying mainly outside the catchment).

There are no surface inflows to the Loch, which is fed by direct rainfall, surface runoff and groundwater. White Loch is small in terms of surface area (56.5 ha), but is surprisingly deep, with a maximum depth of 11.6 m. The catchment, however, is very small (193.0 ha) and so the Loch is likely to have a long residence time and low flushing rate. A long residence time can lead to nutrient storage within and recycling from the sediments which can exacerbate the effects of enrichment.

There is a large wildfowl population on White Loch consisting of breeding and over-wintering ducks and geese (Plate 4). Figures provided by SNH estimate that in summer the population is likely to be in the region of 930 and in winter it could rise to 5000. These figures were used to estimate direct P and N inputs to the Loch as part of the nutrient budget. During surveying, an otter was sighted on the Loch. The estate house pictured in Plate 2 lies almost completely within the catchment area, and it is served by a septic tank located next to the main driveway, i.e. within the Loch's drainage basin.

White Loch flows into Black Loch, to which it is linked by a 400 m modified channel (Plate 5). However, the flow was observed to be very slow due to the shallow gradient of the channel.

No surface algal blooms were observed during any of the four sampling visits, although there were anecdotal reports of severe surface blooms in previous years. During summer sampling, the water was observed to be turbid and green, though there were dense stands of submerged macrophytes in the shallow sections. Floating and emergent vegetation was also observed to be widespread.

Plate 2. White Loch in Loch Inch Estate viewed from south shore

Plate 3. Low intensity grazing on west shore

Plate 4. Geese at White Loch

Plate 5. Modified outflow channel linking White Loch to Black Loch

3.1.2 Mochrum Loch

The majority of Mochrum Loch was found to be very shallow (~1 m deep), with an extremely rocky substrate. Navigation was therefore very difficult, as many rocks are concealed just beneath the water's surface. The maximum depth is approximately 4 m, although the deep basin is extremely small. Four inflows were located (see Figure 4). One of them (Inflow 3) is very small, but contained 'sewage fungus' during summer sampling. It is thought that septic tank effluents from a nearby property enter Inflow 3. Inflows 1 and 2 are of a reasonable size (1-2 m across). Inflow 4 is a very small and shallow stream flowing through boggy wet woodland. The outflow is regulated by hatches, and the water level of Mochrum Loch was observed to fluctuate by approximately 50 cm between sampling visits, depending on the position of the hatches.

The large catchment (935.4 ha) is characterised by wet heath and bog with carr along the shores and inflowing streams (Plates 6, 7 and 8). There are large areas of conifer plantation towards the west of the catchment and another large water body (Castle Loch), which flows into Mochrum Loch from the west via Inflow 1 (see Figure 4). The heathland and unimproved grassland to the north and east of the Loch are used for low intensity sheep grazing. A very large reedbed is located at Inflow 2, which flows into the south of the Loch (Plate 8). The reedbed extends along the inflowing stream for a considerable distance, estimated at 500 m. A very large number of otter spraints, slides and tunnels were observed at this reedbed, suggesting that there could be a breeding holt nearby. Mochrum Loch has a *Crassula helmsii* infestation and at the time of the winter survey was undergoing treatment for this. Efforts were made to ensure that sampling did not coincide with winter spraying activities, and all equipment was power-hosed following survey, to prevent spread of the species through distribution of plant fragments. Other macrophytes were observed during sampling, including *Littorella*, *Equisetum* and *Nuphar* (Plate 10). During summer sampling, Inflow 1 was found to be densely packed with coarse fish fry (Plate 11).

SNH provided information on the estimated bird population at the Loch. It is thought that around 700 waterfowl over-winter at the site, whilst approximately 750 breed there in the summer. These figures were used to estimate direct nutrient inputs to the Loch from avian effluents. On each sampling occasion, a large number of gulls and cormorants were observed on rocky islands near Inflow 2. Their presence has resulted in these rocks being thickly coated in guano.

No surface algal blooms were observed during any of the sampling visits.


Plate 6. Mochrum Loch in winter


Plate 7. Flush on northwest shore


Plate 8. Heath and carr


Plate 9. Reedbed at Inflow 2


Plate 10. Water lilies and horsetails


Plate 11. Inflow 1 with coarse fish fry

3.1.3 Woodhall Loch

Woodhall Loch is long and deep with a maximum depth of 14.9 m over a very small area near the north end. During the winter sampling trip, the southern half of the Loch and most of the margins were frozen, and it was not possible to launch a boat from the lay-by adjacent to the Loch. However, it was possible to carry the equipment across a boggy field towards the north end of the Loch and launch from an alternative point. For all subsequent surveys, the boat was launched from the lay-by and access was clear to all parts of the Loch.

Six inflowing streams of different sizes were located. During the February sampling, inflows 1, 2 and 6 were accessible and in March, all 6 inflows were sampled, however, during both summer sampling trips, some of the inflows were dry (Plate 12) and could not be sampled.

The very large catchment (3006.7 ha) is forested to the west (Plate 13), with agricultural land to the east used primarily for sheep grazing (Plate 14). The area is an important red kite breeding site, and many kites were observed on each sampling occasion. The Loch is very sheltered, with high ground on all sides. This, combined with the depth of the Loch, suggests that stratification could potentially occur during the summer. Angling is a popular activity on the Loch, but motorised boat use is minimal. *Phragmites*, *Equisetum*, *Nuphar* and submerged macrophytes were present in dense stands concentrated at the shallow north and south ends of the Loch (Plate 15).

Figures on the bird populations were provided by SNH. It is thought that around 300 wildfowl occupy the site throughout the year, and these figures were used to help construct the nutrient budget.

No surface algal blooms were observed during any of the sampling visits.

During the summer sampling trip, the rough slipway, which was previously blocked to machinery by three large boulders, had been opened up, and a slurry tank was observed at the water's edge.

Plate 12. Inflow 1 dry during summer sampling

Plate 13. Woodhall Loch viewed from the southeast

Plate 14. Low intensity sheep grazing to the northeast of the loch

Plate 15. Emergent and floating macrophytes

3.1.4 Milton Loch

Milton Loch is extremely shallow (generally ~1 m deep), with a very small proportion of the surface area overlying a deeper point of around 4.6 m depth. The catchment is small (363.1 ha) and agricultural in nature, with large areas of improved grassland used for reasonably high intensity cattle grazing, some arable land (Plates 16 and 17) and small wet areas of bog and carr on the western shore (Plate 18). There are several farm houses (with septic tanks) and farmyards within the catchment. Four very small streams were located flowing into the Loch.

During the winter sampling visit, Milton Loch was found to be completely frozen over (Plate 19) and no surveying was carried out. During the spring visit, gale force winds constrained the survey effort.

Submerged macrophytes were observed to be growing densely during the summer sampling, to the extent that there was significant interference to the signal from the depth sounder and accurate depth soundings could not be obtained.

No surface algal blooms occurred during sampling visits, although excessive growth of plants was observed by the author during the summer sampling trip. This was not a surface bloom of cyanobacteria, but consisted of small, flattened, green, higher plants measuring approximately 10 mm x 1 mm and distributed throughout the entire water column, at a density of approximately 200 units L^{-1}. It was not possible to obtain a confirmed identification of the plant, but it had some of the physical characteristics of the genus *Wolffiella* which belongs to the duckweed family (Lemnoideae). The genus can be submerged rather than confined to the surface, but it has not been reported in Europe.

There is a substantial bird population on the Loch. Figures provided by SNH estimate an overwintering population of 2,600 waterfowl and around 550 breeding birds in the summer. These figures were used to estimate nutrient inputs from birds in the nutrient budget, taking into account the seasonal variations described.

Plate 16. Mochrum east shore with farmhouse and yard

Plate 17. Agricultural fields and cattle on southwest shore

Plate 18. Carr on western shore

Plate 19. Milton Loch in February 2010

3.1.5 Kilconquhar Loch

Kilconquhar Loch is small (19.3 ha) and shallow (maximum depth 1.8 m), with a very small, surface catchment area (128.0 ha). There is no deep basin, as the bed is almost completely flat. The Loch is surrounded on all sides by reedbeds (Plate 20). The western shoreline is characterised by woodland and estate parkland, whilst to the east (Plate 21), a large area of woodland (containing a very large badger sett) and wet woodland / swamp gives way to ploughed arable land (Plate 22). To the north lies the village of Kilconquhar. Houses back directly onto the Loch (Plate 23), but are connected to mains drainage.

The natural outflow, as it is marked on the OS map in Figure 7, was observed during the winter survey to be a non-flowing ditch (Plate 24). An artificial outflow, located in the south east corner of the Loch, flowed into a culvert (Plate 25). The quantity of flow into this culvert could not be observed, but on the basis of the volume of sound it made, it was judged likely to be a relatively small discharge. There are no surface inflows to the Loch, and so it is fed by run-off, groundwater flow and direct precipitation. The lack of inflows and small outflow indicate that the Loch is likely to have a long residence time and a low flushing rate, which could exacerbate the effects of nutrient enrichment by leading to nutrient storage and recycling from the sediments. Dense stands of submerged macrophytes were present throughout the entire Loch. Figures for the bird population on the Loch were not available, but a large population was present during all the sampling visits.

No surface algal blooms were observed during any of the sampling visits.

Plate 20. Kilconquhar Loch viewed from the south, with surrounding reedbeds

Plate 21. Estate woodland

Plate 22. Ploughed arable fields with Kilconquhar Loch in the background

Plate 23. Houses backing onto Kilconquhar Loch

Plate 24. Natural outflow on eastern shore, now a non-flowing ditch

Plate 25. Artificial outflow in south eastern corner of Kilconquhar Loch

3.1.6 Dun's Dish

Dun's Dish is an extremely shallow, artificial loch, which was previously controlled by a now defunct sluice gate at the outflow. The water body is too shallow to survey by boat, at around 0.5 m deep, and so water samples were obtained from the shore. It was not possible to use a shore sampler as the shallowness caused the sampler to pick up sediments from the loch bed. Loch samples were therefore obtained when wading. It should be noted that even light winds were sufficient to suspend bed sediments within the water column. Previous work on the water body (Recorda Cos, 2006) found it to be very shallow, with a maximum depth of 1 m, and most of the water column being approximately 0.75 m deep. There is also evidence from historical maps that the basin is filling in with sediments very rapidly and getting smaller as succession occurs. The Loch is surrounded with a fringe of reedbeds and wet woodland, giving way to agricultural land rising steeply to the north.

The winter survey at Dun's Dish found the water body to be almost entirely frozen over with a small area of open water in the centre occupied by a large number of waterfowl (Plate 26).

Only one inflow was located (Plate 27), along with a series of drains from the surrounding fields (see Figure 8). Many of the drains were dry throughout the summer and could not be sampled. An additional problem relates to the courses of the drains. These cannot be modelled using a DTM in the same way as the inflowing streams, as their courses are artificial, often running through underground pipes. Without extensive survey of the drains, it is not possible to accurately determine their catchment areas. As a result, only limited use could be made of them in the nutrient budgeting exercise. During the spring survey, water clarity in Dun's Dish was extremely poor, as a consequence of resuspension of sediment due to wind-induced turbulence, but also from the increased concentrations of suspended solids in the inflow and field drains. The inflow and all of the field drains were observed to be extremely turbid at that time.

The catchment area to the north of the Loch had been ploughed (Plate 28) and is drained by a series of field-drains. One field drain, (Drain 4, Figure 8), contained a large amount of sewage fungus and typical human sewage detritus (Plate 29). This was located directly beneath Damside farmhouse and yard, at the top of the hill (Plate 30), and so it may reasonably be assumed that run-off and effluents from the farmyard and farmhouse enter it, thereby causing the sewage fungus. Laboratory analysis found the P levels in this drain to be extremely high. The drain flows into a very small area of wetland and reedbed before entering the loch (Plate 31). The open water did not appear to support submerged or floating-leaved aquatic macrophytes. Dun's Dish is extremely important for wildfowl, and provides habitat for a large population of these birds throughout the year.

No surface algal blooms of cyanobacteria were observed during sampling.

Plate 26. Dun's Dish

Plate 27. Inflow 1

Plate 28. Ploughed arable field to north

Plate 29. Sewage fungus in Drain 4

Plate 30. Damside Farm at top of hill (above Drain 4)

Plate 31. Wetland between Drain 4 and the loch

3.1.7 Loch of Aboyne

Loch of Aboyne is a small water body (14.4 ha) with a relatively small, hilly catchment (124.0 ha). The Loch is used regularly during the summer by a water-ski club and by anglers. There is a caravan park to the east, two golf courses, one to the east (with a lodge – Plate 33) and one to the west, and a conifer plantation on a slope of high gradient to the north (Plate 34). There is also a farm in the southeast of the catchment with grazing cattle. The deepest point in Loch of Aboyne is 3.4 m in depth. This is located in the western portion of the water body (see Figure 9). A large amount of weed, including *Potamogeton* and *Equisetum* (Plate 35), was observed throughout the Loch.

Loch of Aboyne is artificial and is thought to have been created circa 1840 by the creation of a dam and embankment along the south shore. On the hill to the north of the Loch, a pond was created to collect water to feed into it. A stream from this pond flows into the east shore of the Loch (Inflow 1), but this is not marked on the Ordnance Survey map. It is thought that historically, this stream was largely diverted out of the Loch's catchment area for abstraction needs elsewhere. It is not known how long this abstraction practice has been in place, but potentially, the impact on Loch of Aboyne could be large. The outflow at the northern edge of the dam was reported by a local landowner to flow during only 9 months of the year. The western golf course abstracts water from the Loch for irrigation, particularly during the summer, when water levels are already low, but as it lies mainly on the outflow side of the Loch, it does not drain the water body to any large extent. It was reported by the same landowner that the caravan park also abstracts water from the Loch. Abstraction is therefore one of the major pressures on this water body. The owner of the golf course to the east has stated that he does not abstract water from the Loch, and uses only organic fertilizers (i.e. derived from natural sources).

Inflow 2 comes from the agricultural area to the east of the road, and enters the Loch via conduits under the road. These were not visible or accessible, so the inflow was sampled to the east of the road. Inflow 3 drains the conifer plantation to the northwest, and is a very small runnel which was dry in the summer.

No accumulations of algae on the water's surface were observed during sampling, although the water was observed to be green and productive in the summer.

Plate 32. Loch of Aboyne

Plate 33. Golf lodge on north shore

Plate 34. Wet woodland and hillside conifer plantation to the northwest

Plate 35. Floating and emergent macrophytes

3.1.8 Loch Spynie

Loch Spynie (Plate 36) is shallow throughout (~1 m deep), with the deepest point reported as 1.8 m. It is surrounded by large areas of reedbed (Plate 38) and swamp, and has a large, linear catchment. The Loch and its catchment have a history of water level modification and drainage, for the purposes of flood prevention and land improvement. It is bounded on the north east by an embankment, which also runs between the Loch and the Spynie Canal on the western shore.

During the winter sampling trip, the Loch was found to be almost completely frozen over, with a small area of open water in the centre occupied by a large number of waterfowl and seabirds (Plate 37). It was possible to walk around the shore of the entire lake. The eastern side of the Loch is enclosed by an embankment, which separates a thick reedbed inside it from an area of wet woodland and swamp outside it (Plate 39). The water level in the wet woodland was approximately 1 m lower than the water level in the Loch, indicating that the embankment is impermeable. Presence of a manhole at the edge of the wet woodland suggested that there may be means for controlling the flow across the embankment from water body to swamp.

To the northwest, the Spynie Canal runs along the edge of the Loch (Plate 40), with only a narrow embankment approximately 3 m wide between the Loch and the Canal (see Figure 2 for location of the above-mentioned modifications). During the February survey, the water level in the Canal was at least 2 m lower than that of the Loch, indicating that the embankment is impermeable. To the west of the Loch, where the Canal diverts from the Loch's shore, a sluice joins the Loch to the Canal, and presumably this can be used to lower water levels in the Loch. The Canal discharges to the sea 2 km downstream of the Loch and as there is no lock gate, the Canal is subject to tidal influences.


Plate 36. Loch Spynie from north shore


Plate 37. Waterfowl at Loch Spynie


Plate 38. Reedbed to the west of Loch Spynie


Plate 39. Wet woodland and reed swamp to the east of Loch Spynie


Plate 40. The Spynie Canal to the northwest of the Loch


Plate 41. The only inflow at the west end of Loch Spynie

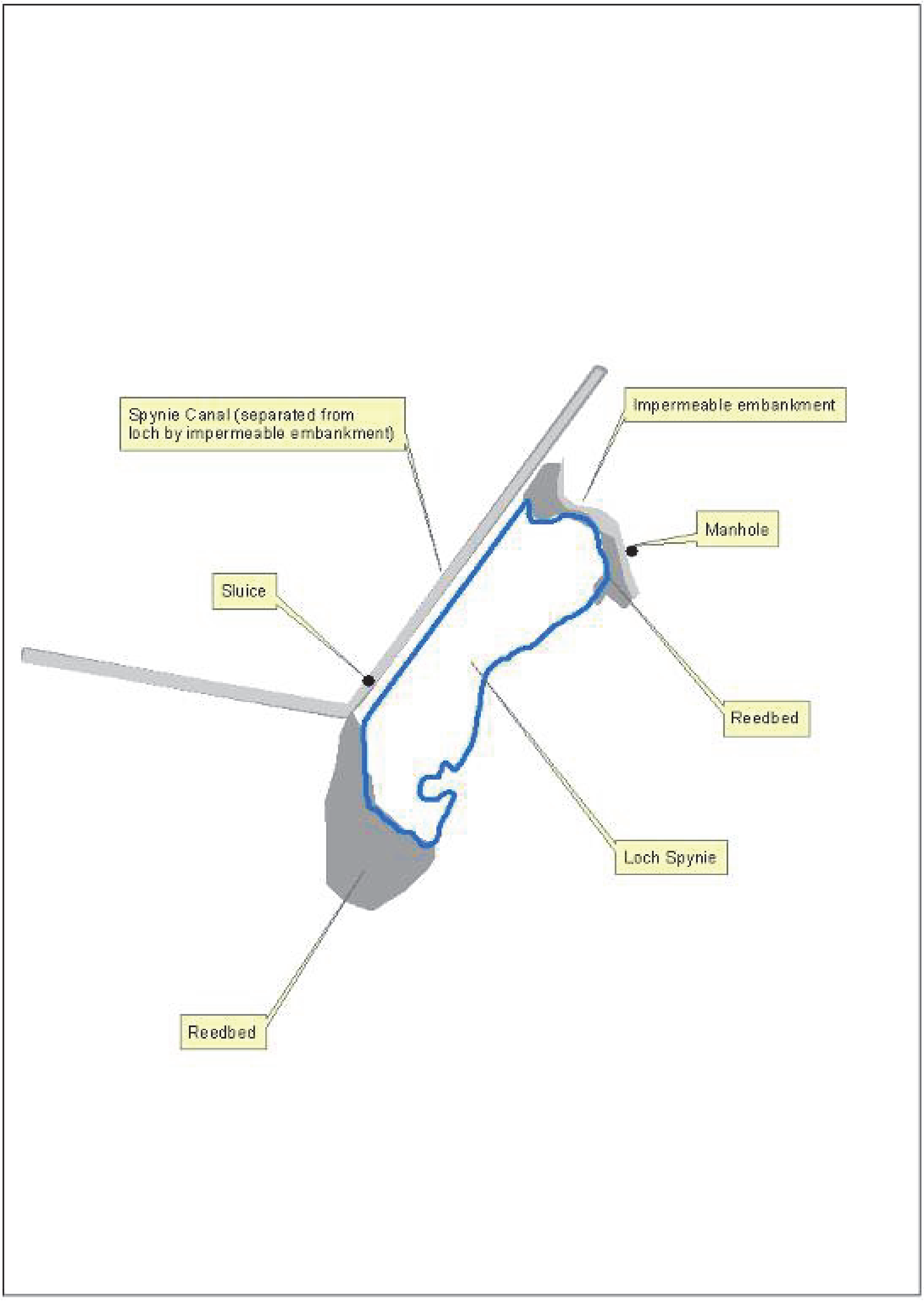


Figure 2. Modifications to Loch Spynie and surroundings

To the west of the Loch, a road runs along the top of a wide embankment. Inside the embankment there is a very large area of reedbed, swamp and wet woodland (Plate 38). Outside the embankment there is a large area of wet woodland. It is not known if there is exchange across this embankment, but running water was not observed.

To the south and south west, a woodland footpath and farm track line the Loch, running through non-wet woodland and reedbeds. The only inflow enters the Loch here (Plate 41), draining the catchment to the west. The inflowing water appeared very clear, and the substrate silty and stable. Another smaller ditch was found to the south of the Loch, but it did not appear to be running and so could not be sampled.

The outflow is located at the eastern end of the Loch, as indicated on the OS map. A weir and sluice are constructed over the outflow (Plate 42), enabling the flow in the outflow to be controlled. The outflow is a substantial stream of approximately 2.5 m in width and 20 cm depth.

Plate 42. Outflow controlled by weir and sluice

Plate 43. Pig farm on catchment edge

The catchment to the north and east is disconnected from the Loch by the embankments, with no flow coming from these areas. To the west, the catchment comprises wet woodland, reedbed and improved grassland, whilst to the south there is mature woodland, grassland and a pig farm, which is partially within the catchment area (Figure 10).

The bird population is very large throughout the year, and macrophyte growth was found to be very dense throughout the water body. No surface algal blooms were observed during any of the sampling trips.

3.2 Lochs, OS maps, catchment and sub-catchment areas

The watersheds of each loch catchment were determined using the methods given in Section 2.13.1, i.e. using a DTM in ArcGIS spatial analyst. The watersheds of each inflow to each loch were determined in the same way. Catchments, sub-catchments and other points of interest are illustrated in Figures 3-10.

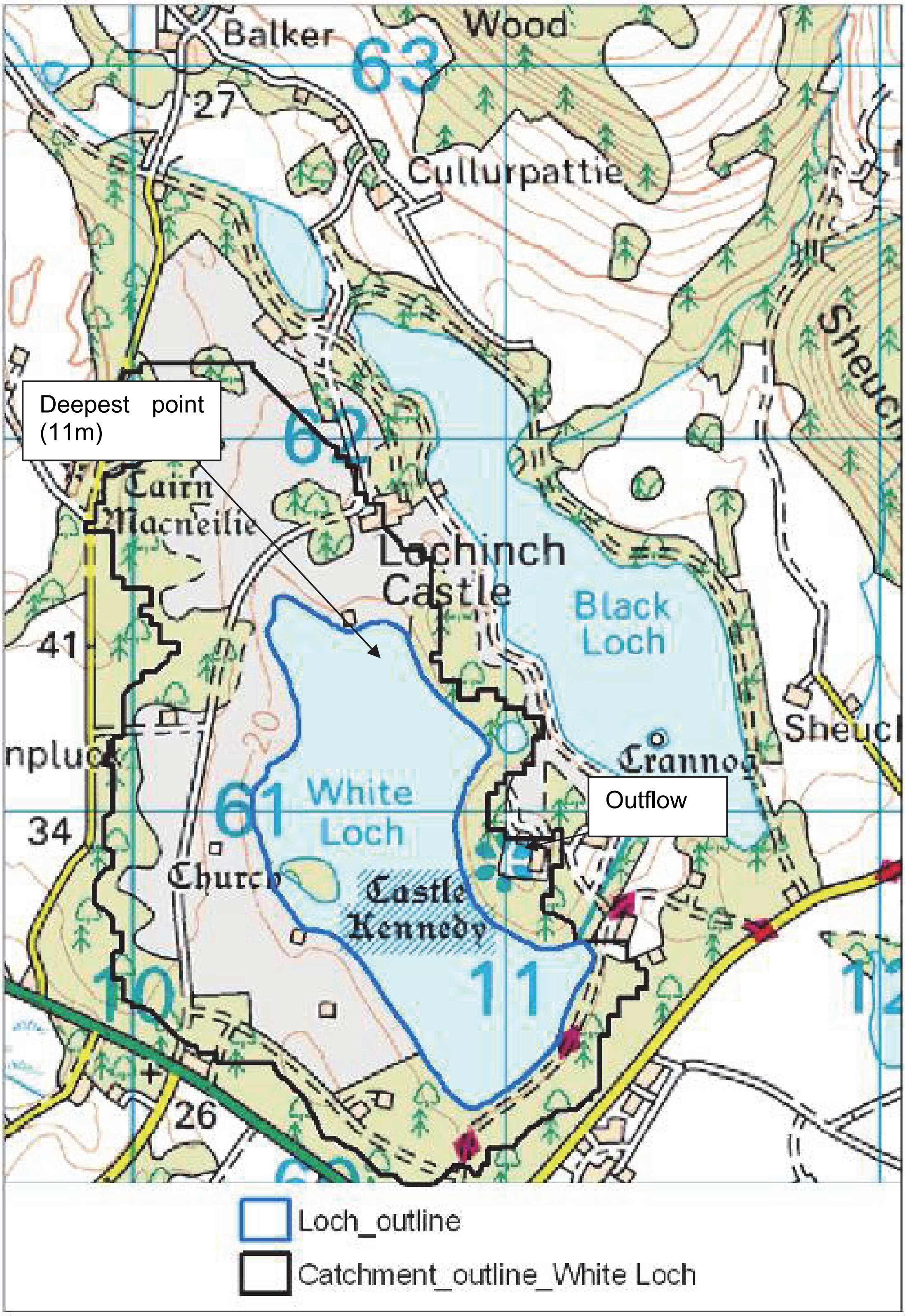


Figure 3. White Loch OS map and catchment area

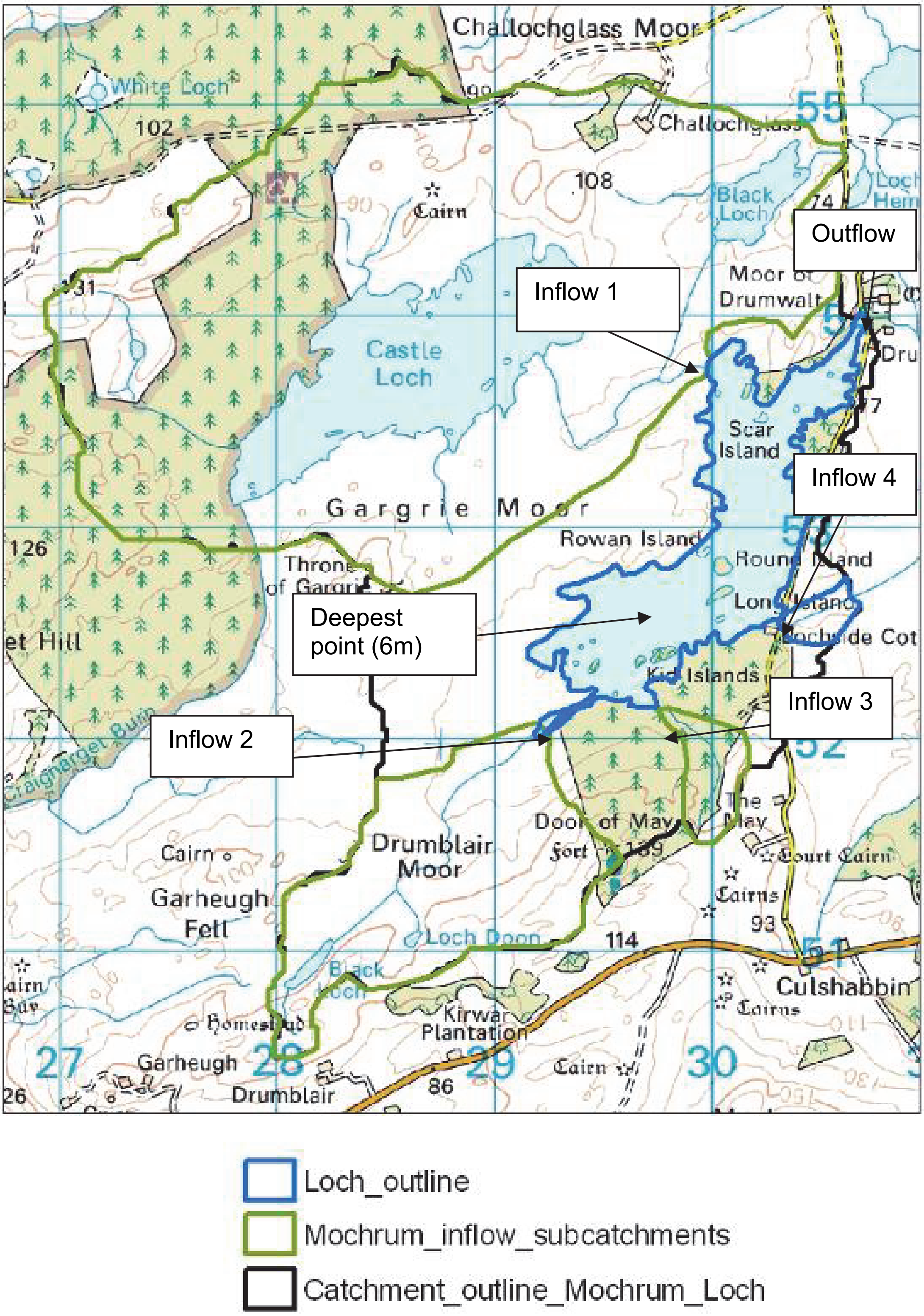


Figure 4. Mochrum Loch OS map, catchment and sub-catchment areas

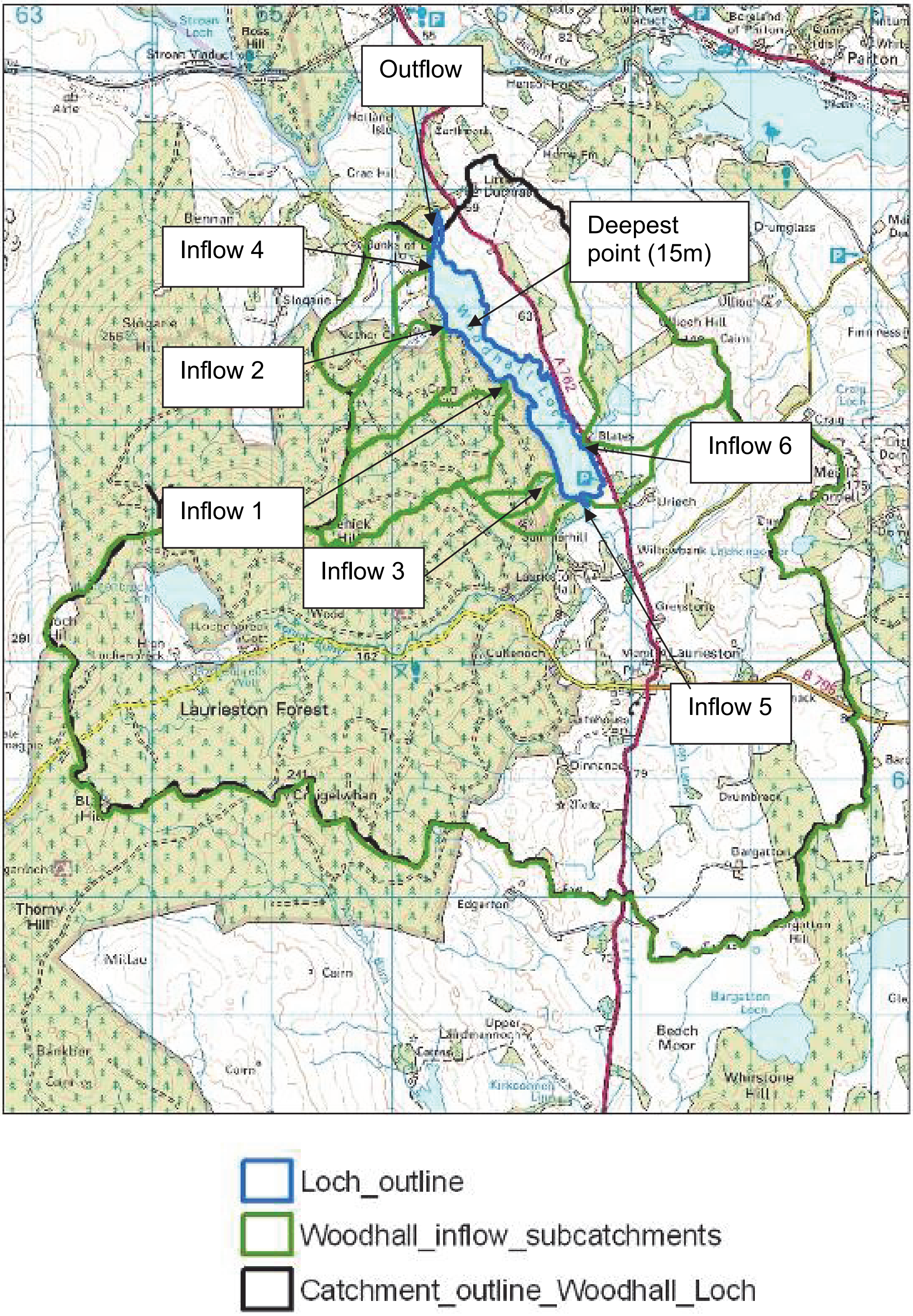


Figure 5. Woodhall Loch OS map, catchment and sub-catchment areas

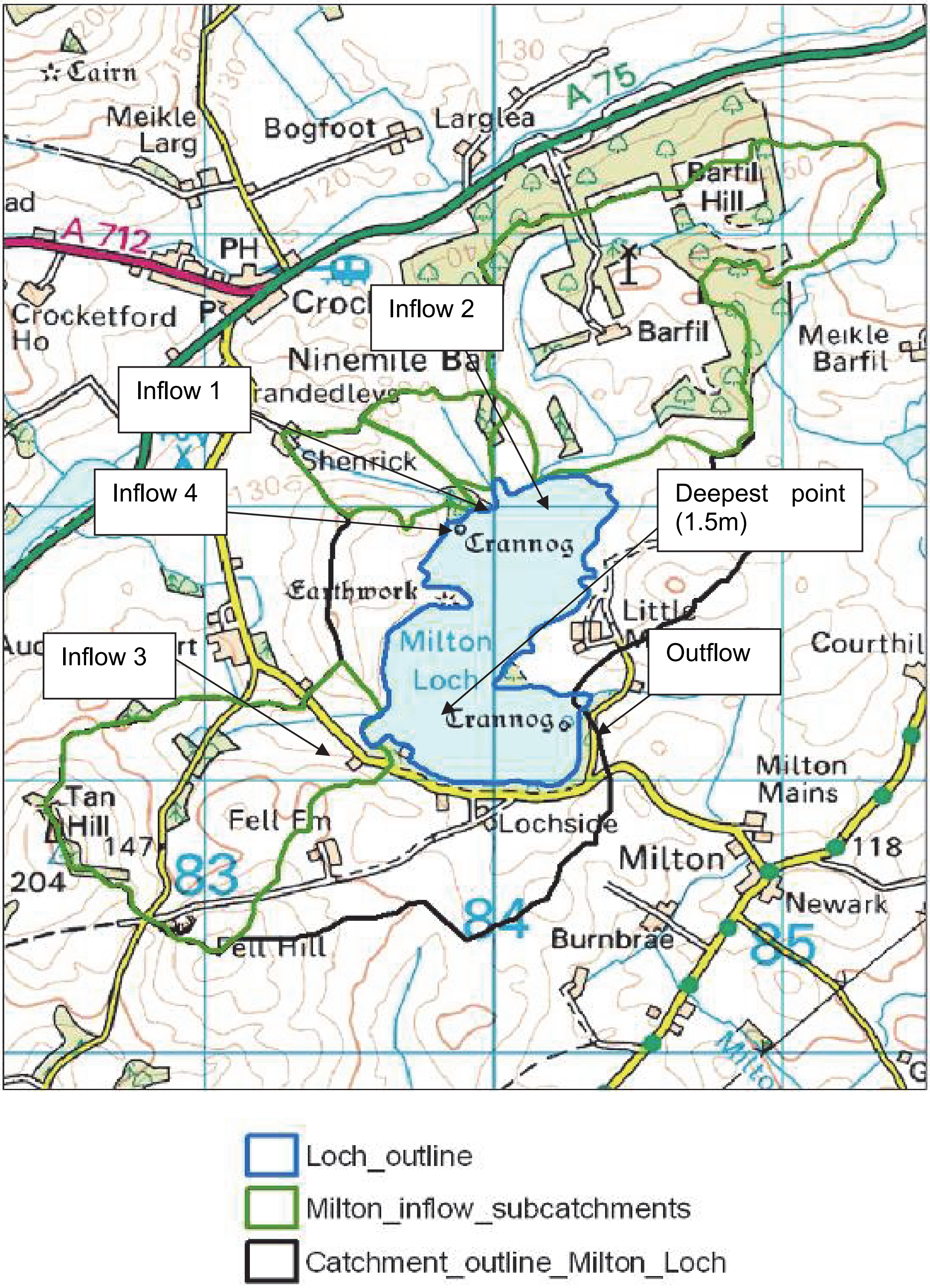


Figure 6. Milton Loch OS map, catchment and sub-catchment areas

Figure 7. Kilconquhar loch OS map and catchment area

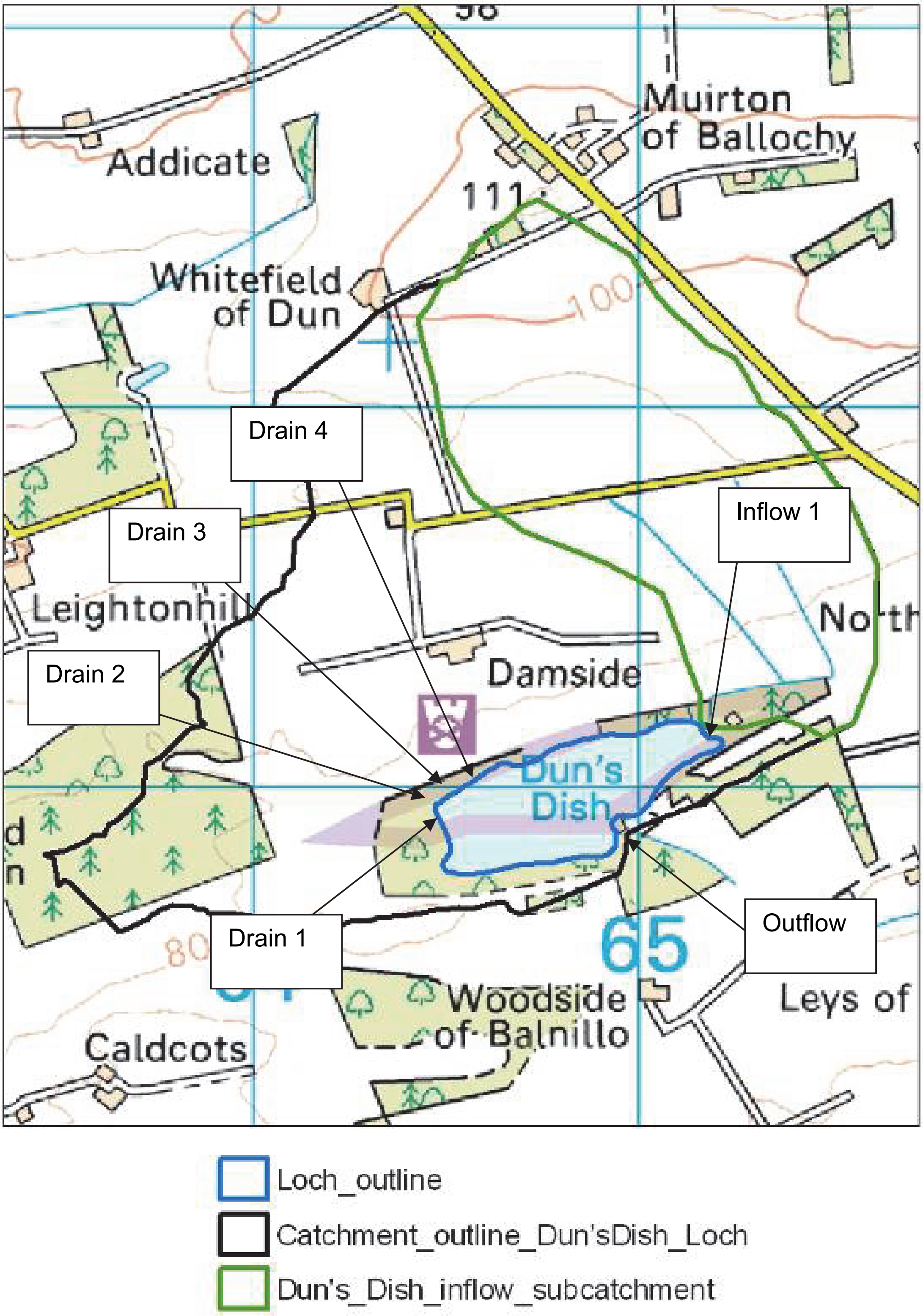


Figure 8. Dun's Dish OS map, catchment and sub-catchment areas

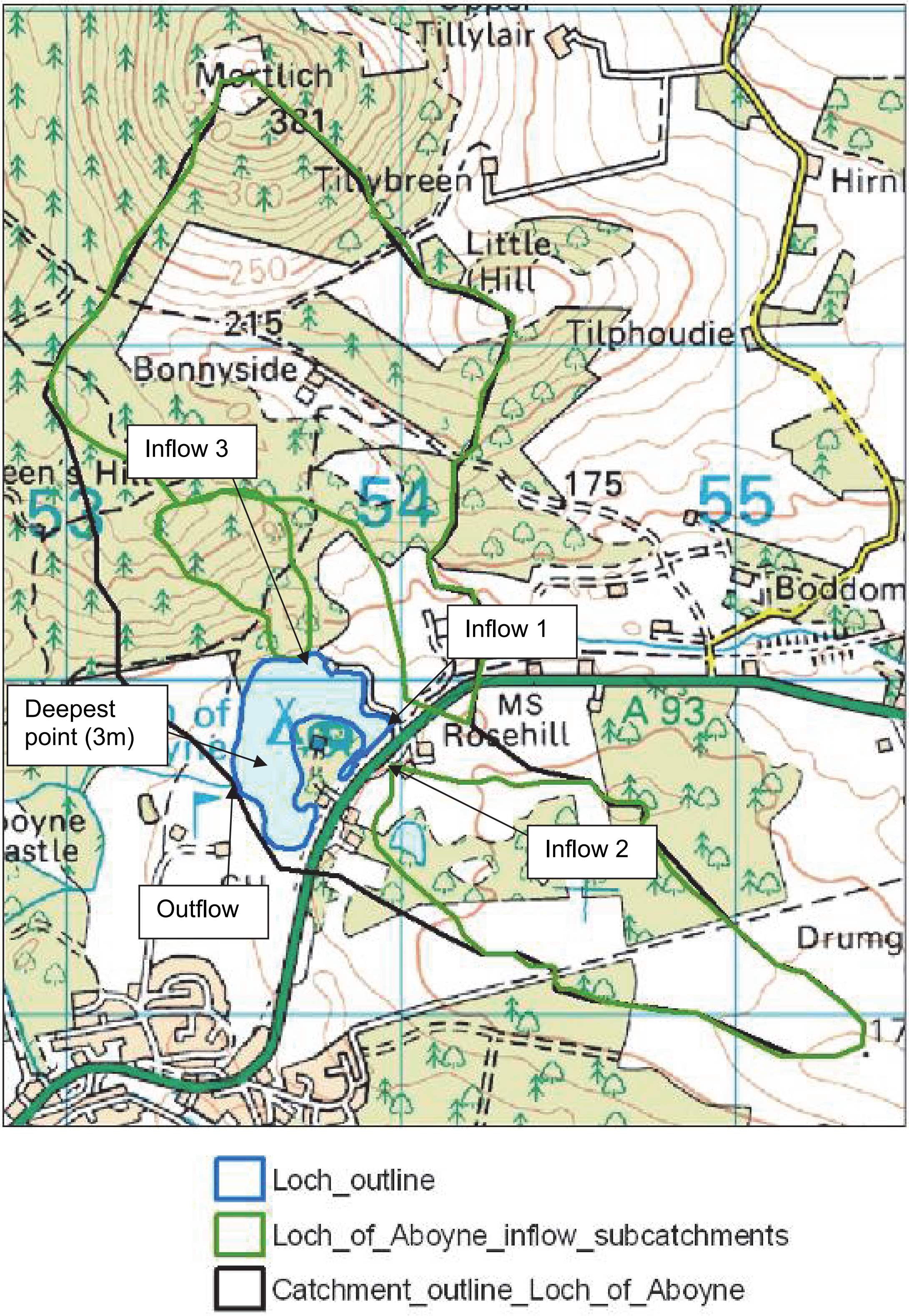


Figure 9. Loch of Aboyne OS map, catchment and sub-catchment areas

Figure 10. Loch Spynie OS map, catchment and sub-catchment areas

3.3 Modelled versus historical catchment areas

Loch catchment areas provided by Murray and Pullar (1910) were compared with those derived by the DTM model. The results are shown in Table 6.

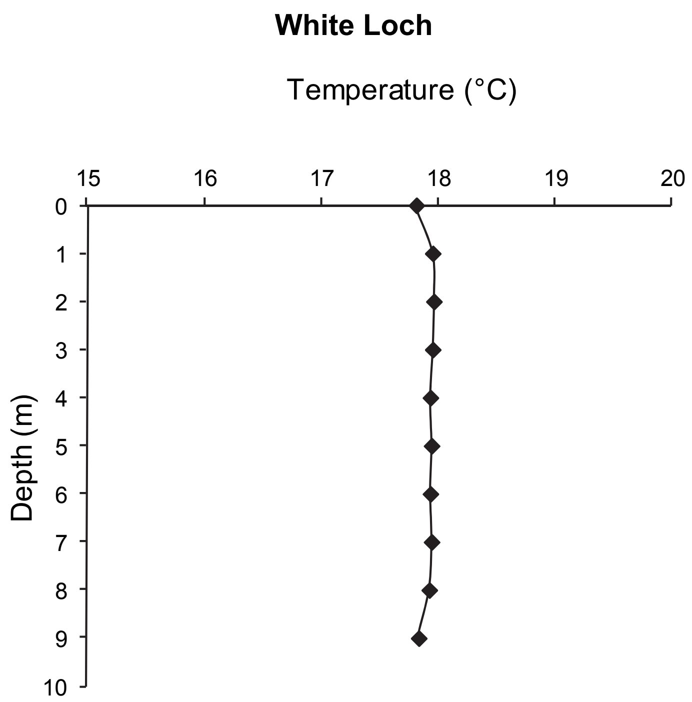
Table 6. Catchment areas from Murray and Pullar (1910) compared with areas modelled in ArcGIS

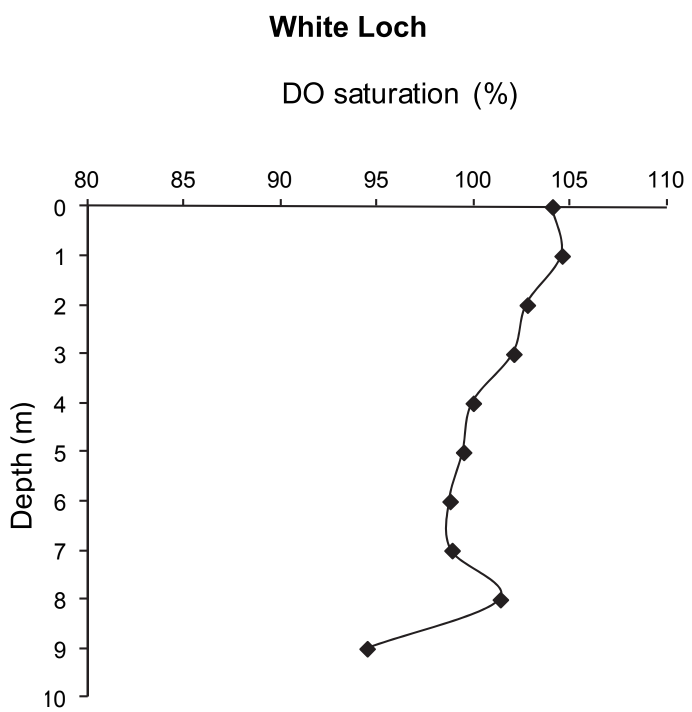
Loch	Catchment area 1910 (ha)	Catchment area modelled (ha)
White Loch	n/a	192
Mochrum Loch	1036	1053
Woodhall Loch	2330	2584
Milton Loch	518	365
Kilconquhar Loch	n/a	128
Dun's Dish	n/a	113
Loch of Aboyne	259	268
Loch Spynie	7767	668

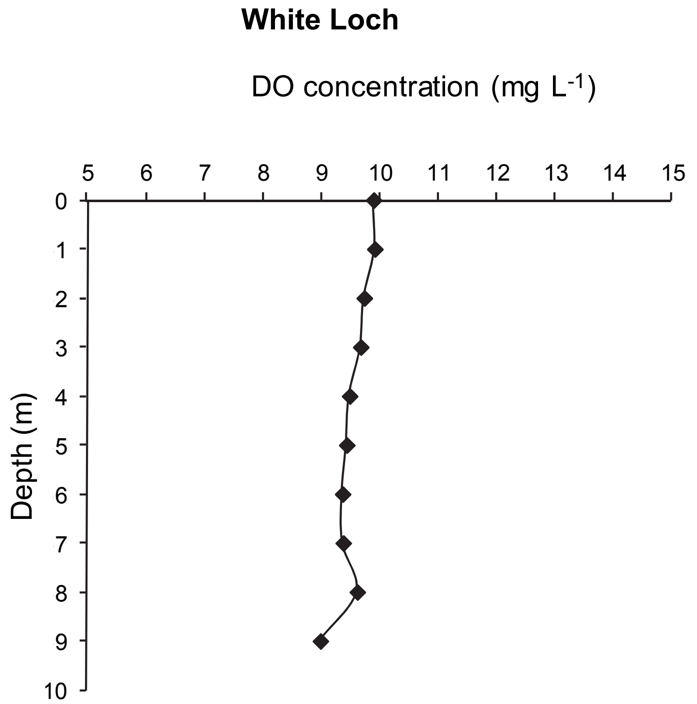
In general, there is reasonably good correspondence between the 1910 catchment areas and those derived by the DTM. The particular exception is Loch Spynie, where there is a huge discrepancy in catchment area. The situation regarding drainage and flows around Loch Spynie is very complex. It is to be assumed that previous to the engineering and drainage works that have taken place to restrict the area of the Loch, prevent flooding between Spynie Castle and Lossiemouth, and improve the boggy catchment, the catchment area was much larger than it is today, restricted as it now is on two sides by embankments and the Spynie Canal. Although the Canal was constructed in the early 1800s, it is not known what method was used for the original catchment estimation of Murray and Pullar (1910). For the purposes of this project and report, including the nutrient budgeting exercise, loch and catchment areas used were those modelled in ArcGIS using the DTM.

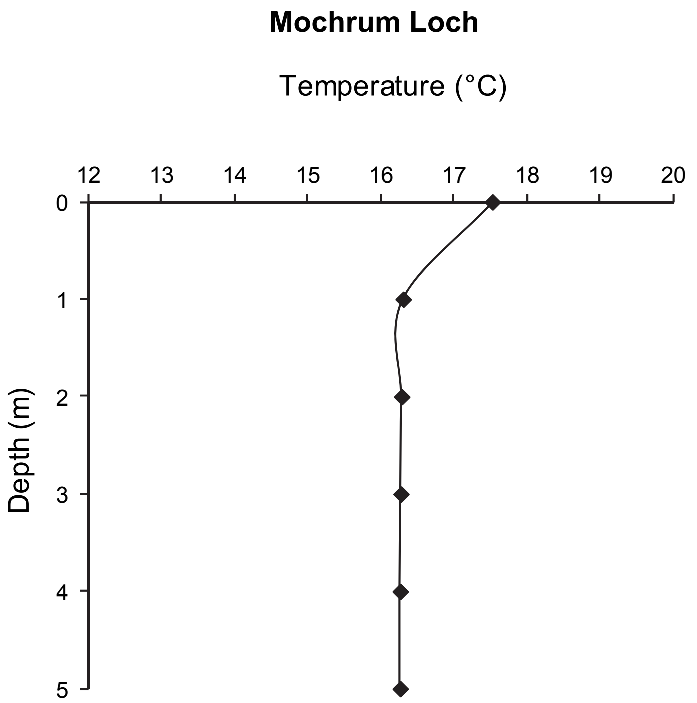
3.4 Temperature and dissolved oxygen profiles

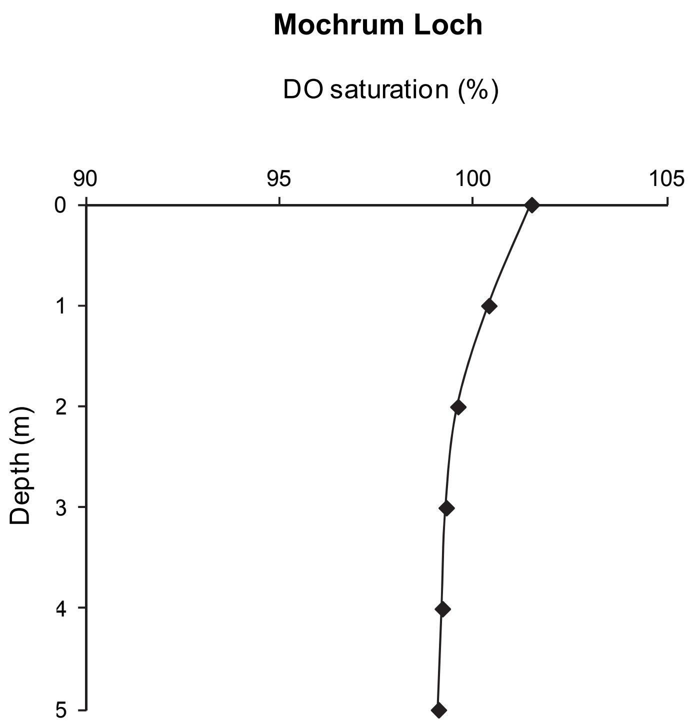
Figure 11 shows temperature and dissolved oxygen profiles (percent saturation and concentration) recorded in the lochs during the late summer sampling visits. Note that Loch Spynie, Kilconquhar Loch and Dun's Dish were too shallow to profile.

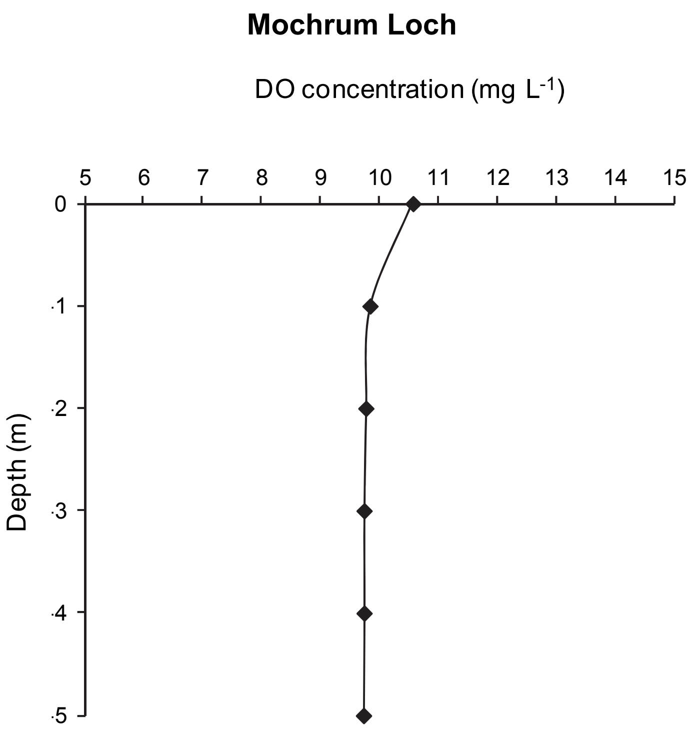




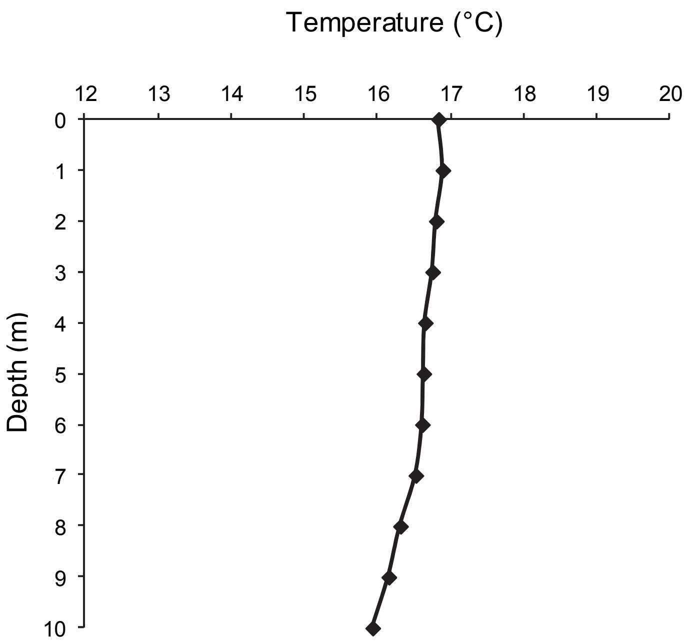

White Loch
DO concentration (mg L-1)
5 6 7 8 9 10 11 12 13 14 15
0 1 2 3 4 5 6 7 8 9 10
Depth (m)


Mochrum Loch
Temperature (°C)
12 13 14 15 16 17 18 19 20
0 1 2 3 4 5
Depth (m)

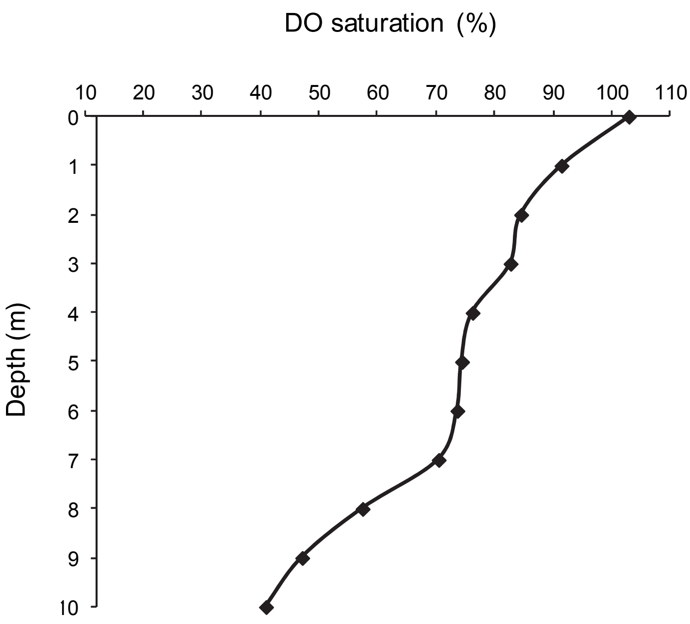

Mochrum Loch
DO saturation (%)
90
95
100
105
0
1
2
3
4
5
Depth (m)


Mochrum Loch
DO concentration (mg L-1)
5
6
7
8
9
10
11
12
13
14
15
0
-1
-2
-3
-4
-5
Depth (m)

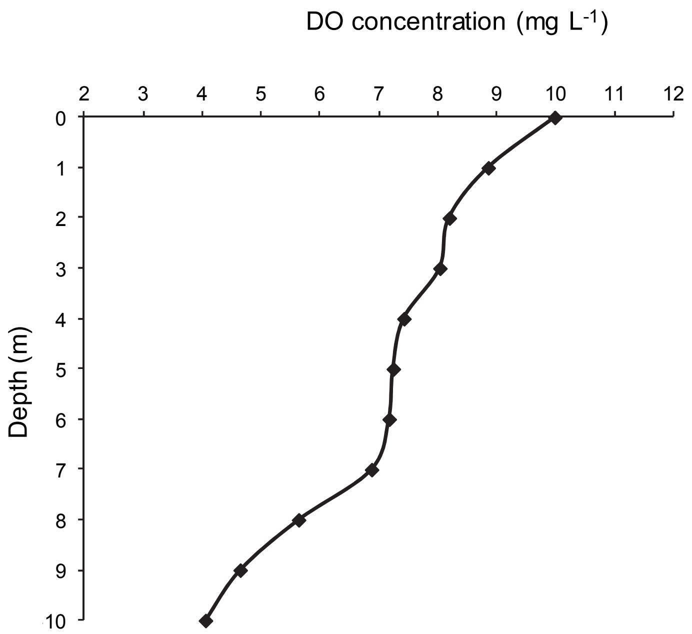
Woodhall Loch



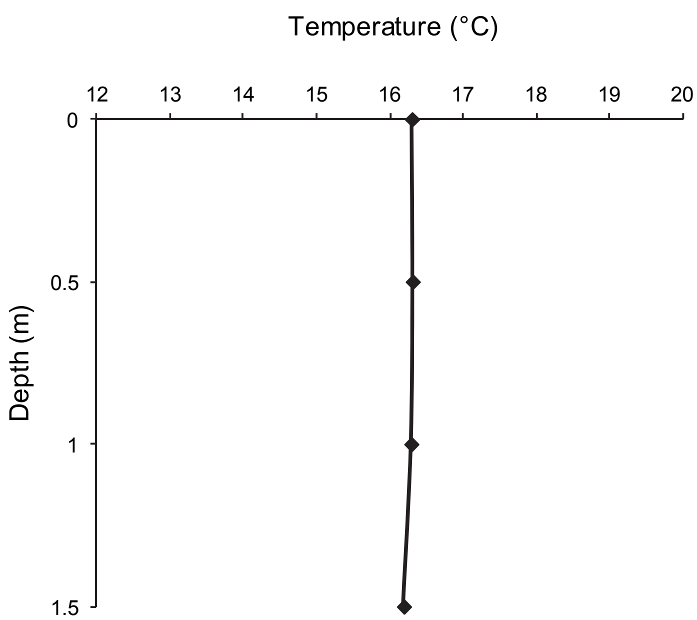
Woodhall Loch

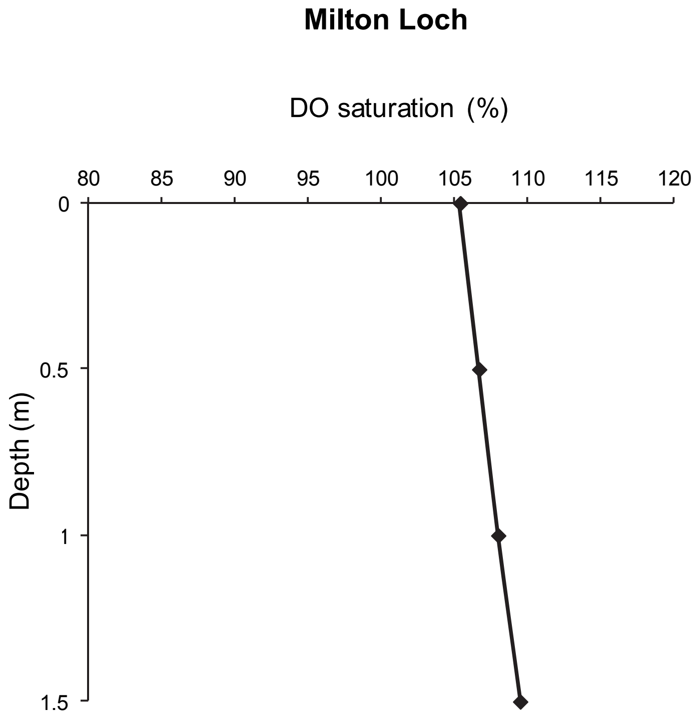


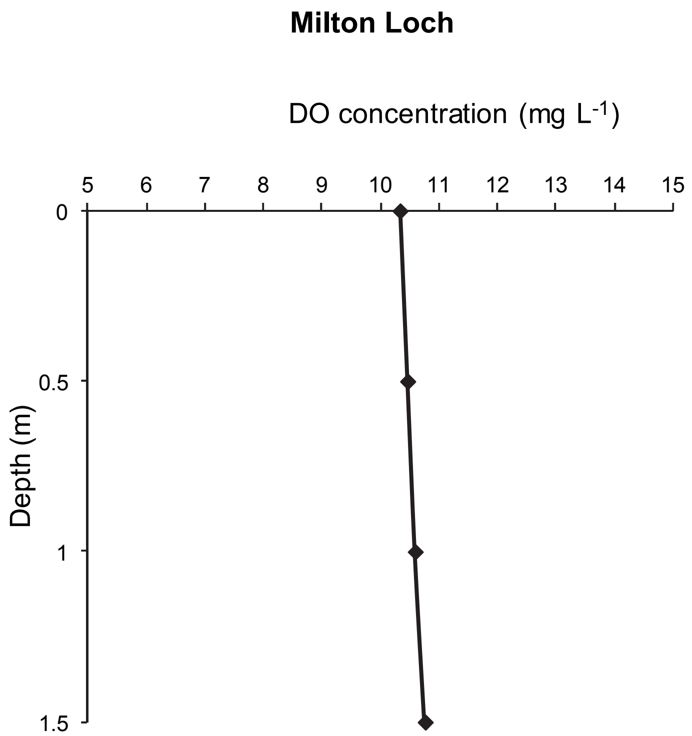
Woodhall Loch

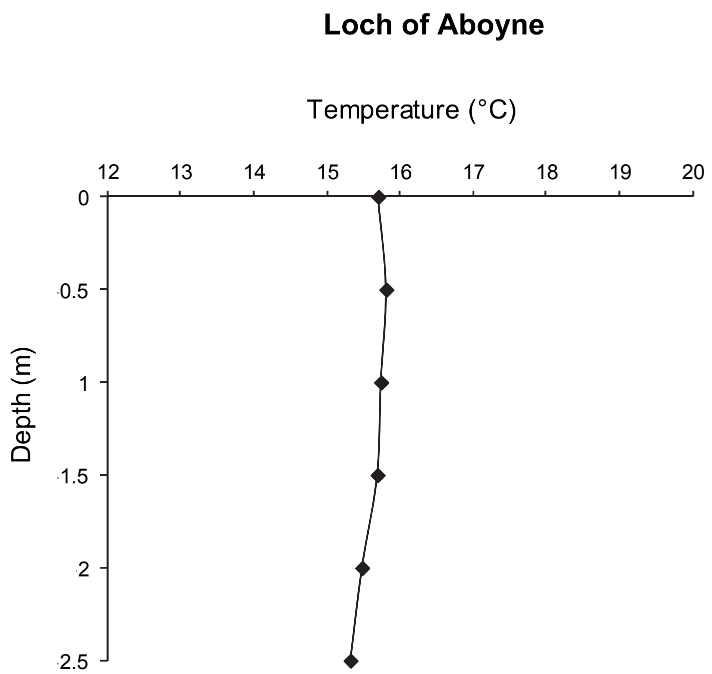


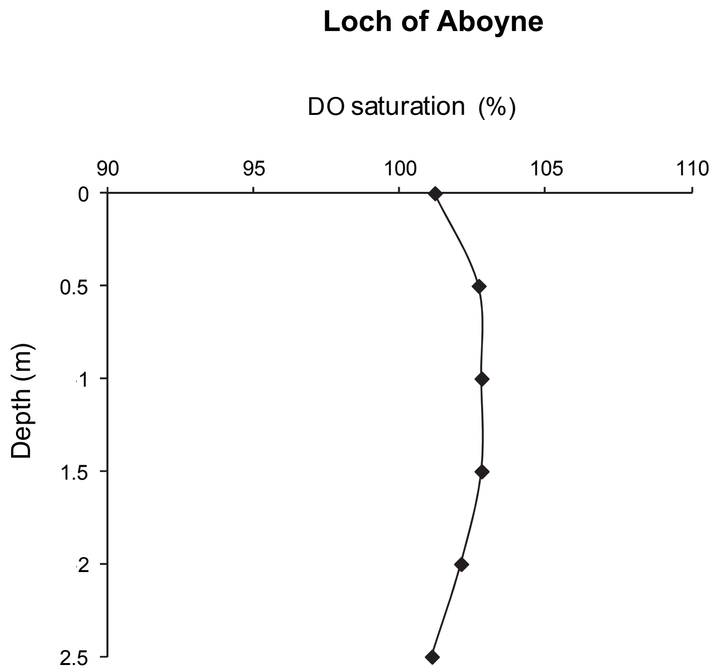
Milton Loch




Milton Loch
DO saturation (%)
80
85
90
95
100
105
110
115
120
0
0.5
1
1.5
Depth (m)


Milton Loch
DO concentration (mg L-1)
5
6
7
8
9
10
11
12
13
14
15
0
0.5
1
1.5
Depth (m)


Loch of Aboyne
Temperature (°C)
12
13
14
15
16
17
18
19
20
0
0.5
1
1.5
2
2.5
Depth (m)


Loch of Aboyne
DO saturation (%)
90
95
100
105
110
0
0.5
1
1.5
2
2.5
Depth (m)

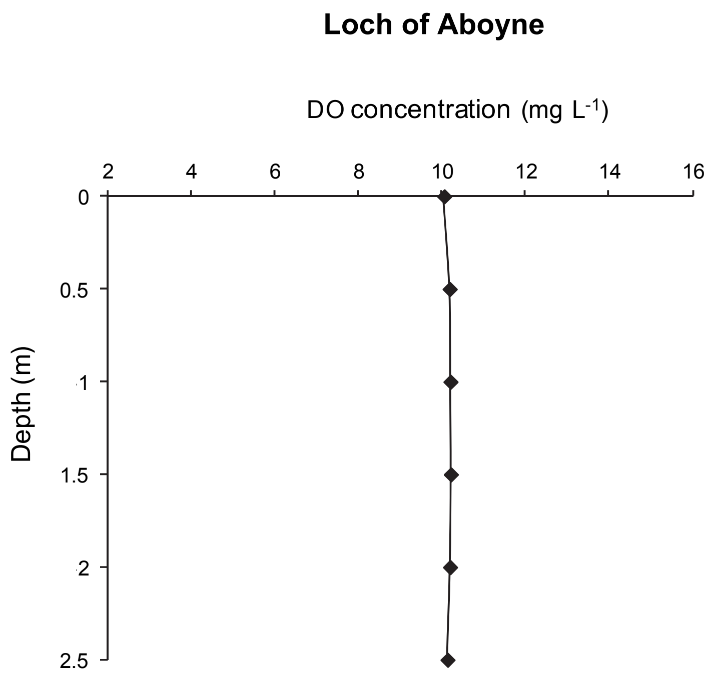


Figure 11. Temperature and dissolved oxygen profiles

Woodhall Loch showed a gradual decrease in temperature with depth, resulting in a 2°C temperature difference between the surface and deeper water. This was accompanied by a decrease in oxygen saturation from 100% (9.98 mg L^{-1}) at the surface to 40% (4.05 mg L^{-1}) near the substrate. No distinct thermocline was present. The other lochs did not show any such change with depth.

3.5 Nutrients and trophic status

The results of the water chemistry analyses and the derived trophic status based on the characteristics of each loch, as recommended by OECD (1982), are presented in the following sections. The raw laboratory data are provided in Appendix 3.

3.5.1 In-loch water quality

This section contains the results of the water chemistry analyses for the samples taken from the water column of each loch.

pH

Figure 12 shows pH measured in the surface samples from each loch throughout the year.

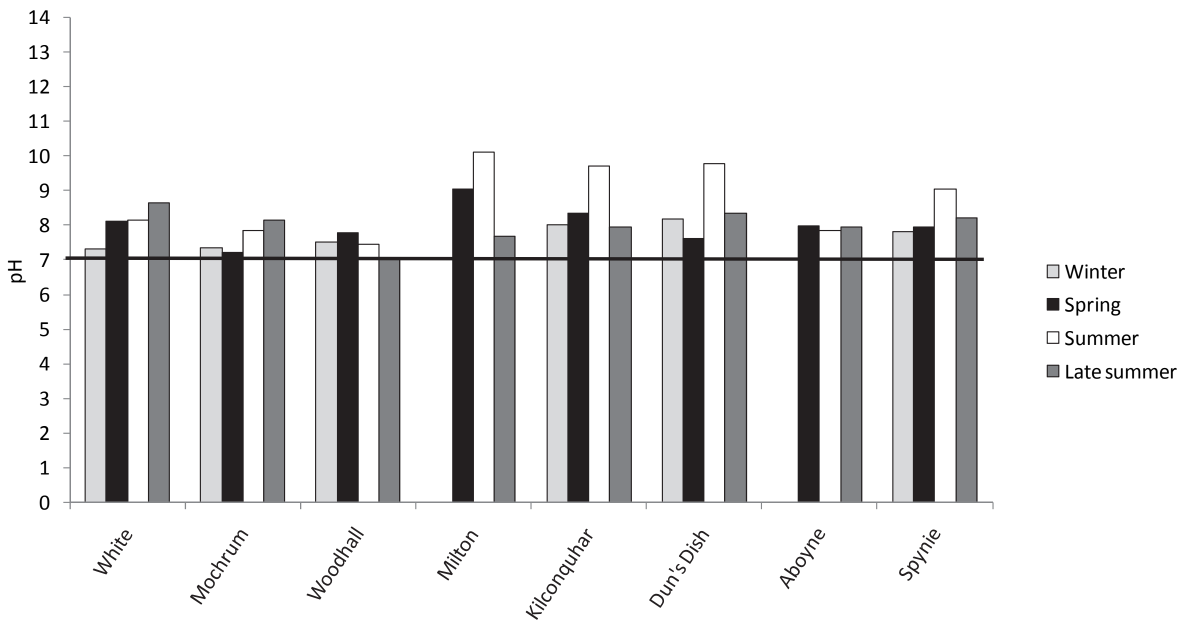


Figure 12. Seasonal pH in each loch

The pH in White Loch, Mochrum Loch, Woodhall Loch and Loch of Aboyne tended to be circumneutral with no distinct seasonal trends evident (neutral pH is indicated by the black horizontal line in Figure 12). Milton Loch, Kilconquhar Loch, Dun's Dish and Loch Spynie, however, showed a distinct trend of highest pH during the summer sampling. The highest pH of 10.12 was recorded in Milton Loch during the summer sampling, whilst the lowest pH of 7.03 was recorded in Woodhall Loch in late summer.

The pH in White Loch ranged from 7.30 in winter to 8.64 in late summer, with an annual mean of 8.05. pH in Mochrum Loch ranged from 7.21 in spring to 8.15 in late summer with a mean of 7.64. pH in Woodhall Loch ranged from 7.03 in late summer to 7.77 in spring with a mean of 7.44. pH in Milton Loch ranged from 7.69 in late summer to 10.12 in summer with a mean of 8.95. pH in Kilconquhar Loch ranged from 8.02 in winter to 9.72 in summer with a mean of 8.50. pH in Dun's Dish ranged from 9.62 in spring to 9.76 in summer with a mean of 8.48. pH in Loch of Aboyne ranged from 7.83 in summer to 7.97 in spring with a mean of 7.91. pH in Loch Spynie ranged from 7.93 in spring, to 9.04 in summer, with a mean of 8.24.

Alkalinity

Figures 13 and 14 show alkalinity measured in the surface samples from each loch throughout the year for the southern and northern lochs respectively.

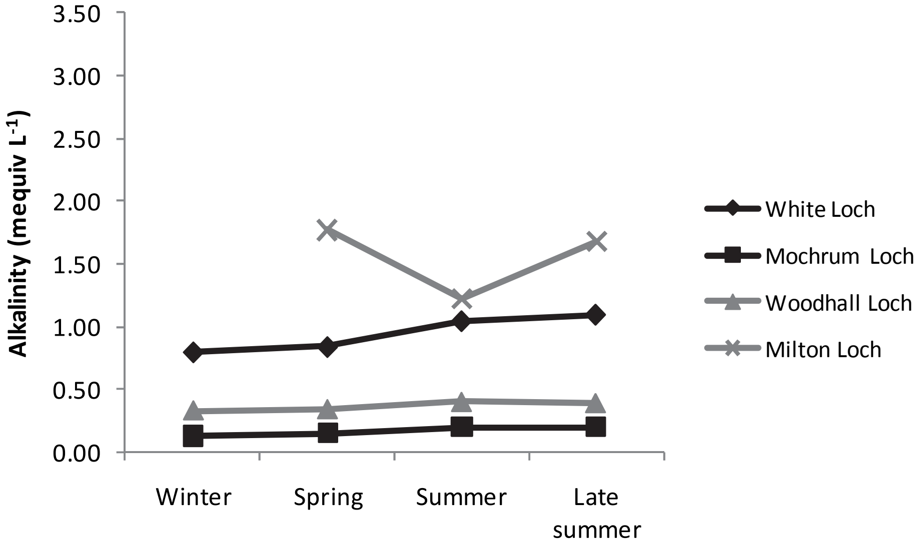


Figure 13. Alkalinity in the southern lochs

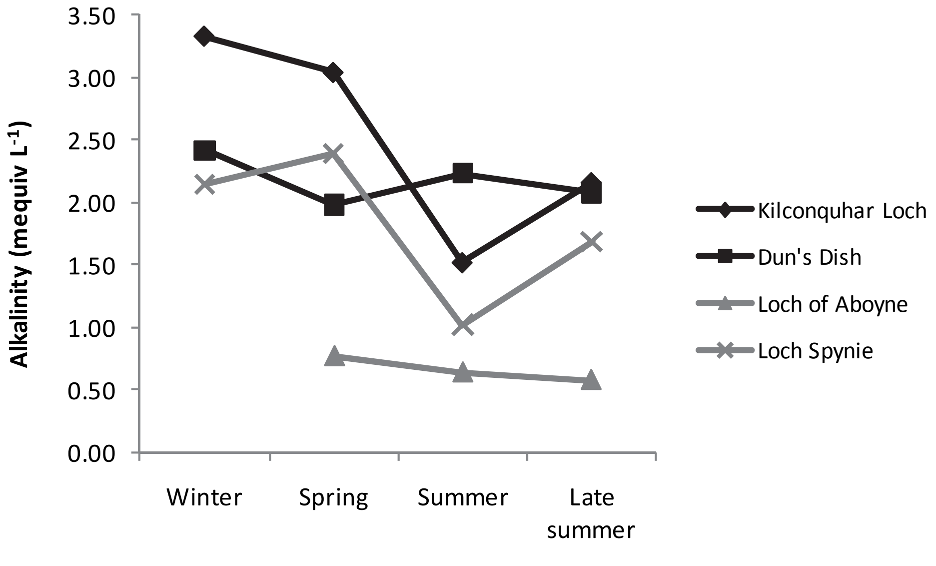


Figure 14. Alkalinity in the northern lochs

The highest measured alkalinities were found in three of the northern lochs – Kilconquhar Loch, Dun's Dish and Loch Spynie. In these lochs, the majority of samples returned alkalinities of >2 meq L^{-1}. The remaining five lochs were at the lower end of the range (<2 meq L^{-1}). No distinct seasonal trend was evident across the eight lochs.

The alkalinity in White Loch ranged from 0.80 meq L^{-1} in winter to 1.09 meq L^{-1} in late summer with an annual mean of 0.94 meq L^{-1}. Alkalinity in Mochrum Loch ranged from 0.13 meq L^{-1} in winter to 0.20 meq L^{-1} in summer and late summer, with a mean of 0.17 meq L^{-1}. Alkalinity in Woodhall Loch ranged from 0.33 meq L^{-1} in winter to 0.40 meq L^{-1} in summer with a mean of 0.37 meq L^{-1}. Alkalinity in Milton Loch ranged from 1.22 meq L^{-1} in summer to 1.77 meq L^{-1} in spring with a mean of 1.56 meq L^{-1}. Alkalinity in Kilconquhar Loch ranged from 1.52 meq L^{-1} in summer to 3.33 meq L^{-1} in winter with a mean of 2.51 meq L^{-1}. Alkalinity in Dun's Dish ranged from 1.98 meq L^{-1} in spring to 2.42 meq L^{-1} in winter with a mean of 2.18 meq L^{-1}. Alkalinity in Loch of Aboyne ranged from 0.58 meq L^{-1} in late summer to 0.77 meq L^{-1} in spring with a mean of 0.66 meq L^{-1}. Alkalinity in Loch Spynie ranged from 1.02 meq L^{-1} in summer to 2.39 meq L^{-1} in spring with a mean of 1.81 meq L^{-1}.

Total Phosphorus

Figures 15 and 16 show the TP concentrations in each loch on each of the sampling visits for the southern and northern lochs respectively. These TP concentrations were derived from surface water samples rather than composite samples, as only two lochs were deep enough to provide composite samples. Boundaries for trophic categories based on TP concentrations (OECD, 1982) are shown in Figure 34.

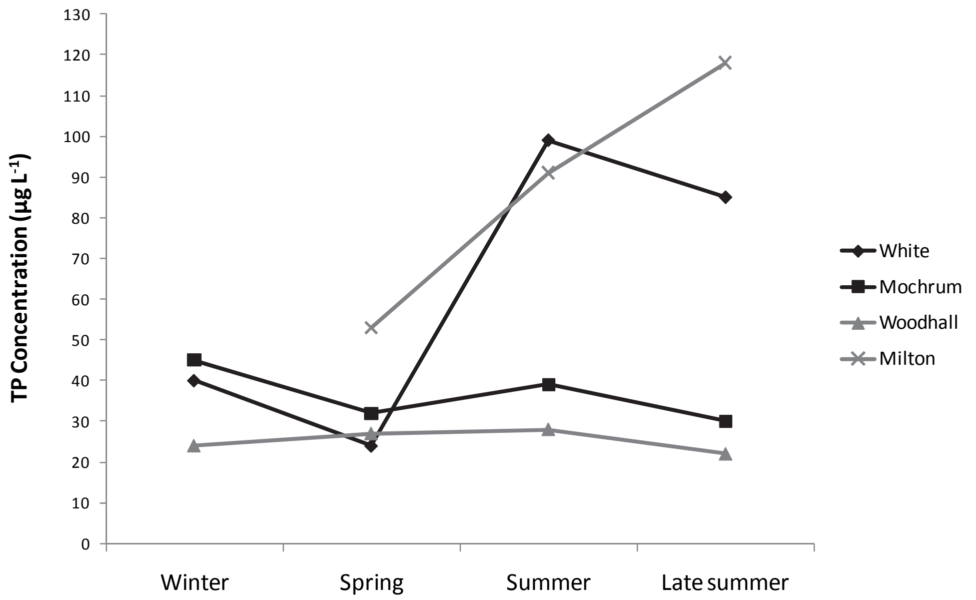


Figure 15. Total phosphorus concentrations in the southern lochs

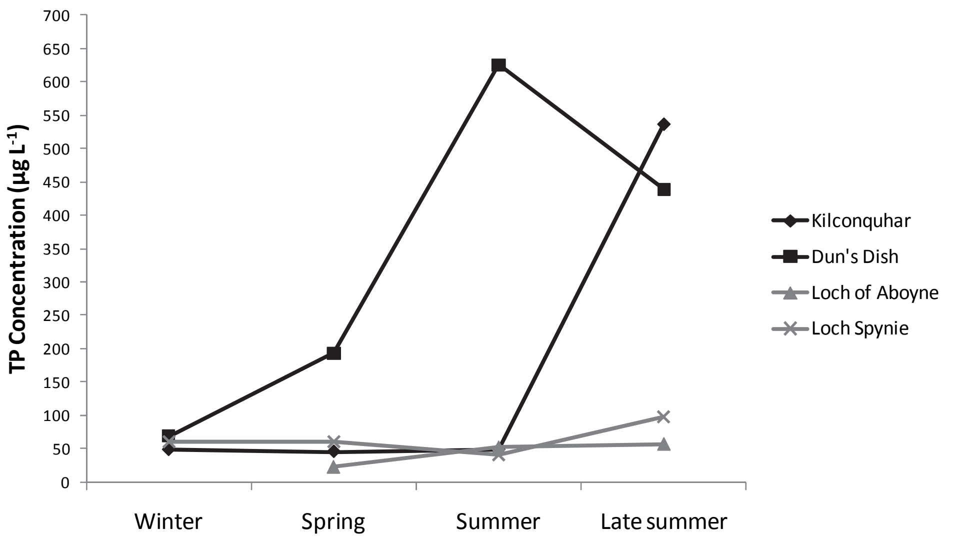
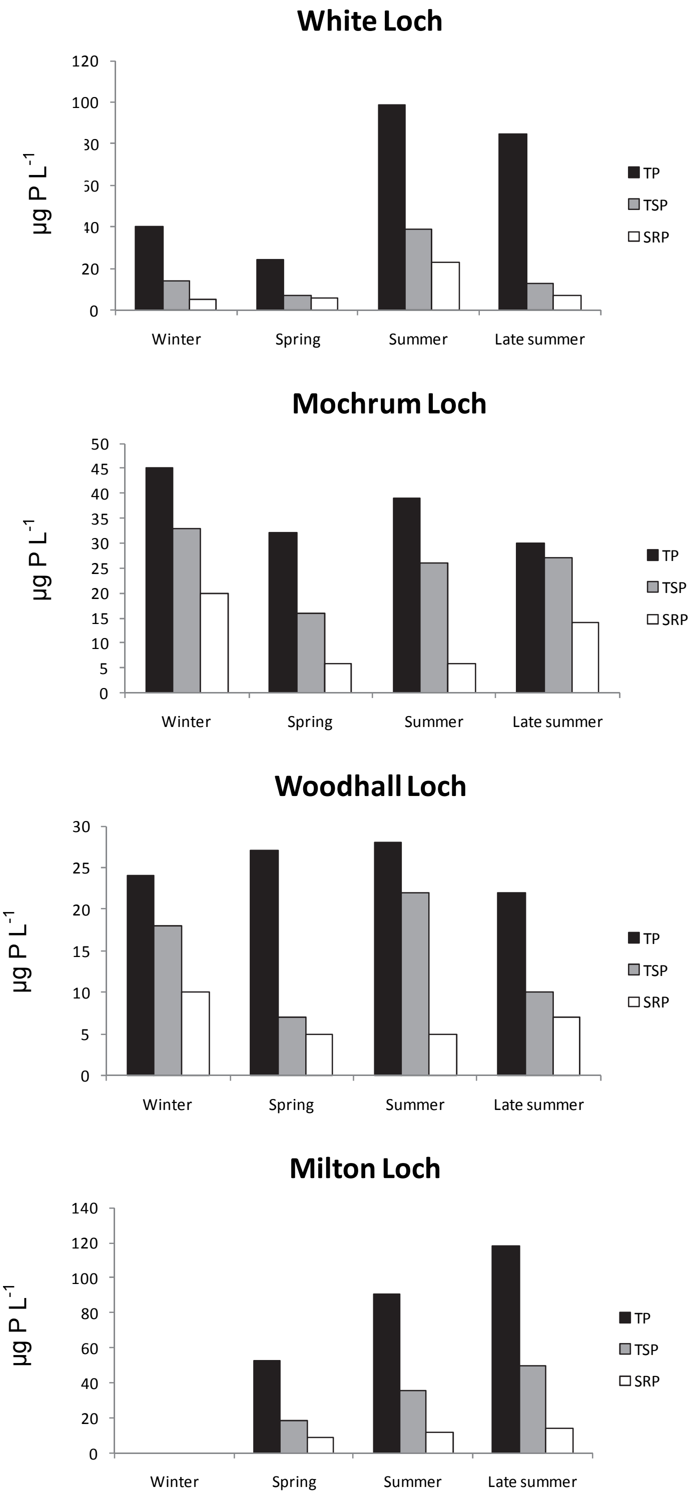


Figure 16. Total phosphorus concentrations in the northern lochs

The TP concentration for White Loch ranged from 24 µg P L^{-1} (spring) to 99 µg P L^{-1} (summer) with an annual mean of 62 µg P L^{-1}. The TP concentration for Mochrum Loch ranged from 30 µg P L^{-1} (late summer) to 45 µg P L^{-1} (winter) with a mean of 37 µg P L^{-1}. The TP concentration for Woodhall Loch ranged from 22 µg P L^{-1} (late summer) to 28 µg P L^{-1} (summer) with a mean of 25 µg P L^{-1}. The TP concentration for Milton Loch ranged from 53 µg L^{-1} (spring) to 118 µg P L^{-1} (late summer) with a mean of 87 µg P L^{-1}. The TP concentration for Kilconquhar Loch (Figure 17) ranged from 45 µg P L^{-1} (spring) to 536 µg P L^{-1} (late summer) with a mean of 169 µg P L^{-1}. The TP concentration for Dun's Dish ranged from 69 µg P L^{-1} (winter) to 625 µg P L^{-1} (summer) with a mean of 332 µg P L^{-1}. The TP concentration for Loch of Aboyne ranged from 23 µg P L^{-1} (spring) to 57 µg P L^{-1} (late summer) with a mean of 44 µg P L^{-1}. The TP concentration for Loch Spynie ranged from 41 µg P L^{-1} (summer) to 98 µg P L^{-1} (late summer) with a mean of 65 µg P L^{-1}. There was therefore a very general trend in the richer lochs for lower TP values in the first half of the year and higher concentrations later in the year.

Phosphorus fractions

Figure 17 shows the concentrations of three P fractions (TP, TSP and SRP) found in the water column of each loch on each sampling visit.



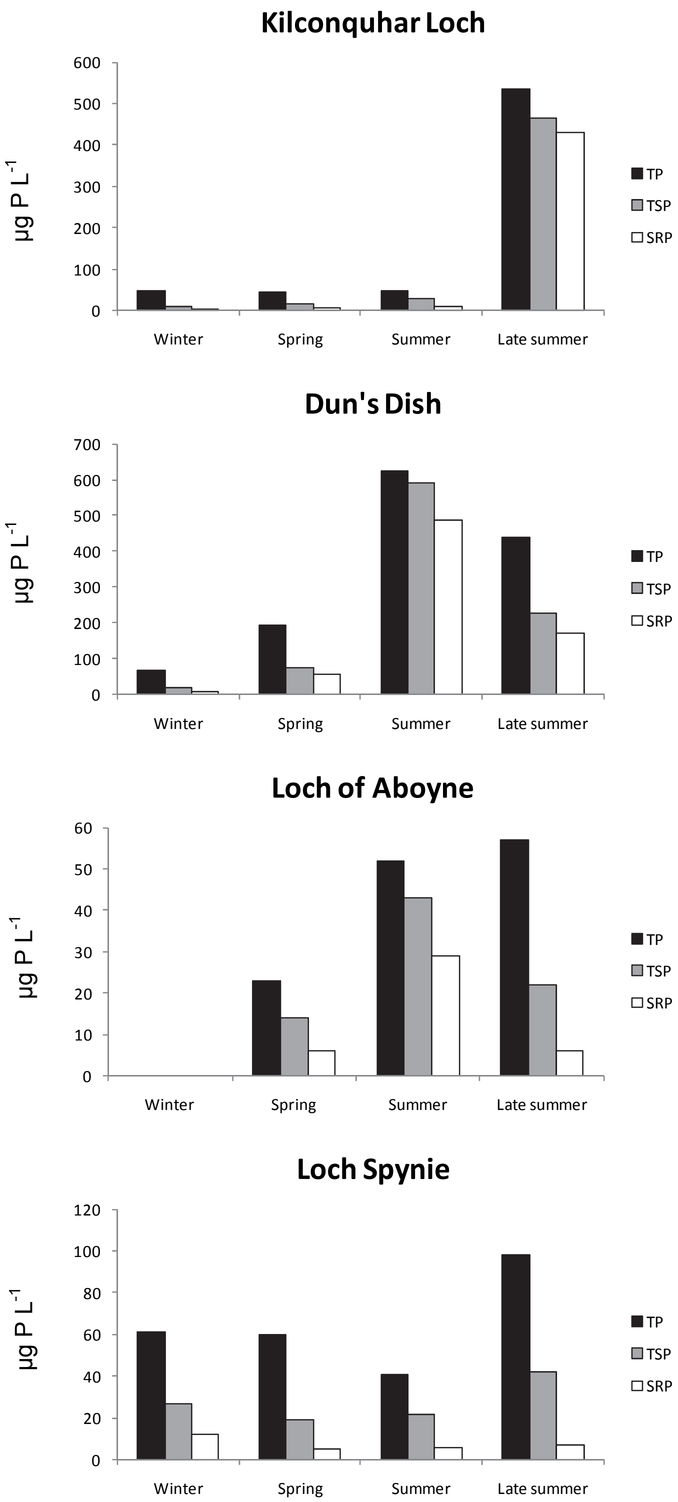


Figure 17. Phosphorus fractions (TP, TSP and SRP) in the water column of each loch

In Loch Spynie, SRP accounted for a very small proportion of TP in all four samples. In White Loch, Woodhall Loch and Milton Loch, the fraction of TP that was SRP was likewise very small throughout the year. For Mochrum Loch, the proportion of TP that was represented by SRP was small in spring and summer, but more substantial in winter and late summer. In Kilconquhar Loch, the fraction of TP present as SRP was large in late summer, when a spike in TP concentration occurred. In Loch of Aboyne, the proportion of TP measured as SRP was small in spring and late summer, but more substantial in the summer.

Nitrogen – nitrate, nitrite and TAN

Figures 18 and 19 show nitrate-nitrogen (NO_3 - N) concentrations throughout the year in the southern and northern lochs respectively.

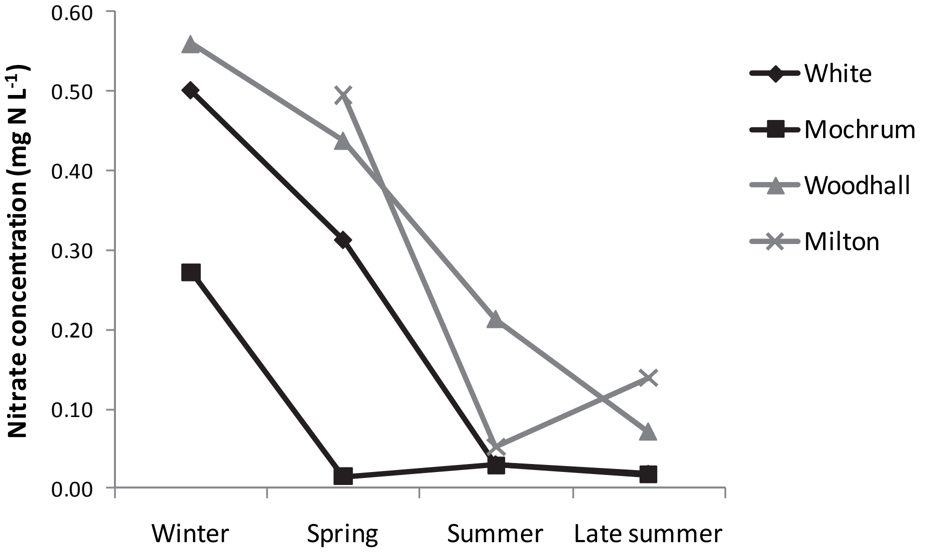


Figure 18. Seasonal NO_3–N concentrations in the southern lochs

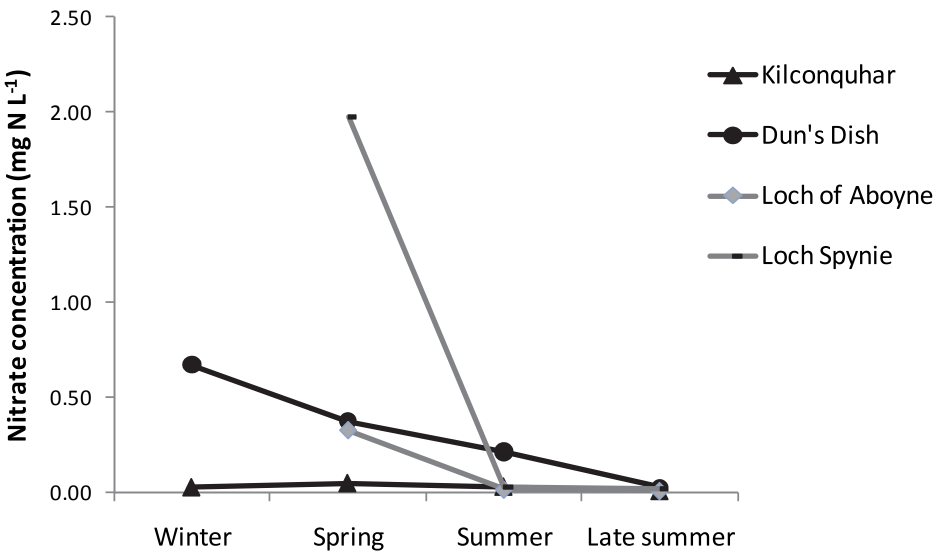


Figure 19. Seasonal NO_3–N concentrations in the northern lochs

All of the lochs except Kilconquhar Loch showed a general decline in nitrate concentrations throughout the year, with the highest concentrations occurring in winter and declining gradually into the summer. In Kilconquhar Loch, nitrate concentrations increased from winter to spring. The lowest nitrate concentration was found in Mochrum Loch in the spring, whilst the highest was in Loch Spynie in the spring.

Nitrate levels in White Loch ranged from 0.018 mg N L^{-1} in late summer to 0.5 mg N L^{-1} in winter, with an annual mean of 0.22 mg N L^{-1}. Nitrate concentrations in Mochrum Loch ranged from 0.015 mg N L^{-1} in spring to 0.272 mg N L^{-1} in winter, with a mean of 0.08 mg N L^{-1}. In Woodhall Loch, nitrate levels ranged from 0.071 mg N L^{-1} in late summer to 0.56 mg N L^{-1} in winter, with a mean of 0.32 mg N L^{-1}. Nitrate concentrations in Milton Loch ranged from 0.052 mg N L^{-1} in summer to 0.495 mg N L^{-1} in spring, with a mean of 0.23 mg N L^{-1}. Nitrate levels in Kilconquhar Loch ranged from 0.007 mg N L^{-1} in late summer to 0.047 mg N L^{-1} in spring, with a mean of 0.027 mg N L^{-1}. Nitrate concentrations in Dun's Dish ranged from 0.025 mg N L^{-1} in late summer to 0.067 mg N L^{-1} in winter, with a mean of 0.32 mg N L^{-1}. In Loch Spynie, nitrate levels ranged from 0.017 mg N L^{-1} in late summer to 1.98 mg N L^{-1} in spring, with a mean of 0.67 mg N L^{-1}.

Figures 20 and 21 show nitrite - nitrogen (NO_2-N) concentrations throughout the year in the southern and northern lochs respectively.

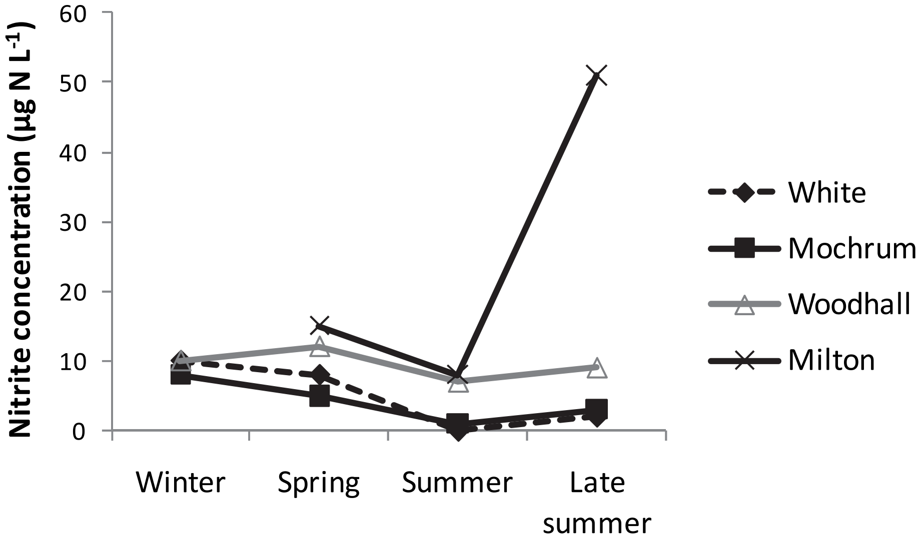


Figure 20. Seasonal NO_2- N concentrations in the southern lochs

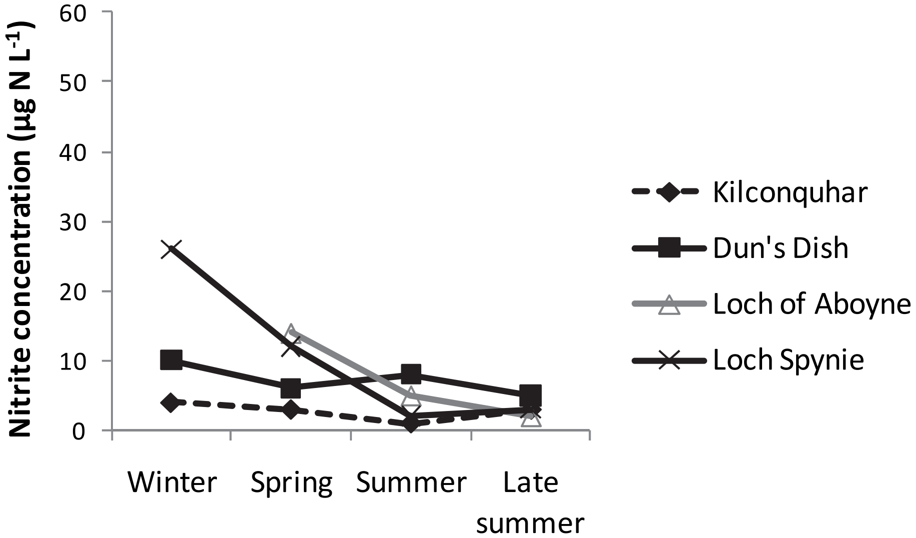


Figure 21. Seasonal NO_2-N concentrations in the northern lochs

A seasonal trend in nitrite concentrations was evident in all of the water bodies except Loch of Aboyne and Dun's Dish. In the remaining six lochs, there was a decline in nitrite from higher concentrations in winter to the lowest concentrations in summer. The nitrite levels in these six lochs then underwent a slight rise in concentration in late summer except those in Loch Milton. The latter exhibited an extremely large increase in nitrite levels. The highest concentration of 51 µg N L^{-1} was recorded for Loch Milton in late summer.

In White Loch, the nitrite level ranged from <1 µg N L^{-1} in summer to 10 µg N L^{-1} in winter, with an annual mean of 5 µg N L^{-1}. The nitrite concentration in Mochrum Loch ranged from 1 µg N L^{-1} in summer to 8 µg N L^{-1} in winter, with a mean of 4 µg N L^{-1}. Nitrite level in Woodhall Loch ranged from 7 µg N L^{-1} in summer to 12 µg N L^{-1} in spring, with a mean of 10 µg N L^{-1}. In Milton Loch the concentration of nitrite ranged from 8 µg N L^{-1} in summer to 51 µg N L^{-1} in late summer, with a mean of 25 µg N L^{-1}. Nitrite level in Kilconquhar Loch ranged from 1 µg N L^{-1} in summer to 4 µg N L^{-1} in winter, with a mean of 3 µg N L^{-1}. In Dun's Dish nitrite concentration ranged from 5 µg N L^{-1} in late summer to 10 µg N L^{-1} in winter, with a mean of 7 µg N L^{-1}. Nitrite level in Loch of Aboyne ranged from 2 µg N L^{-1} in late summer to 14 µg N L^{-1} in spring, with a mean of 7 µg N L^{-1}. Nitrite concentration in Loch Spynie ranged from 2 µg N L^{-1} in summer to 26 µg N L^{-1} in winter, with a mean of 11 µg N L^{-1}.

Figures 22 and 23 show TAN concentrations measured in the southern and northern lochs respectively on each sampling visit.

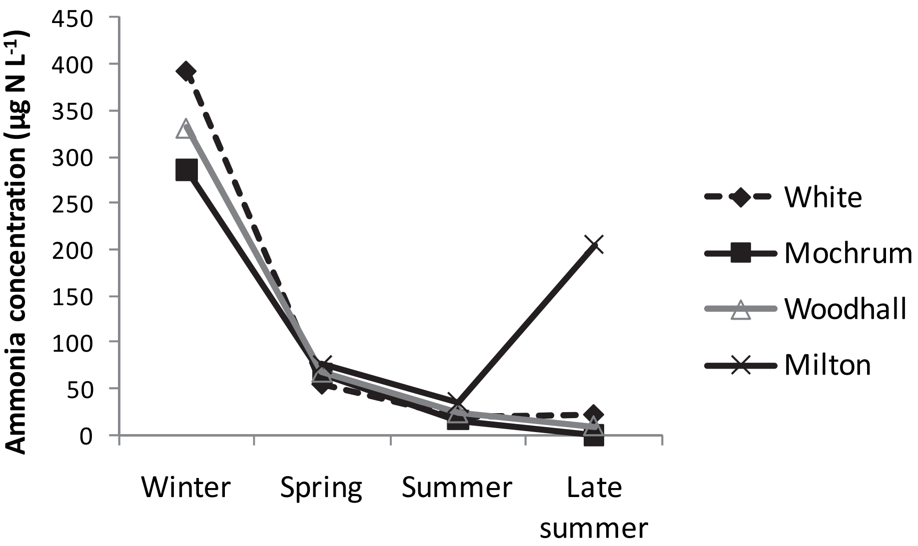


Figure 22. Seasonal TAN concentrations in the southern lochs

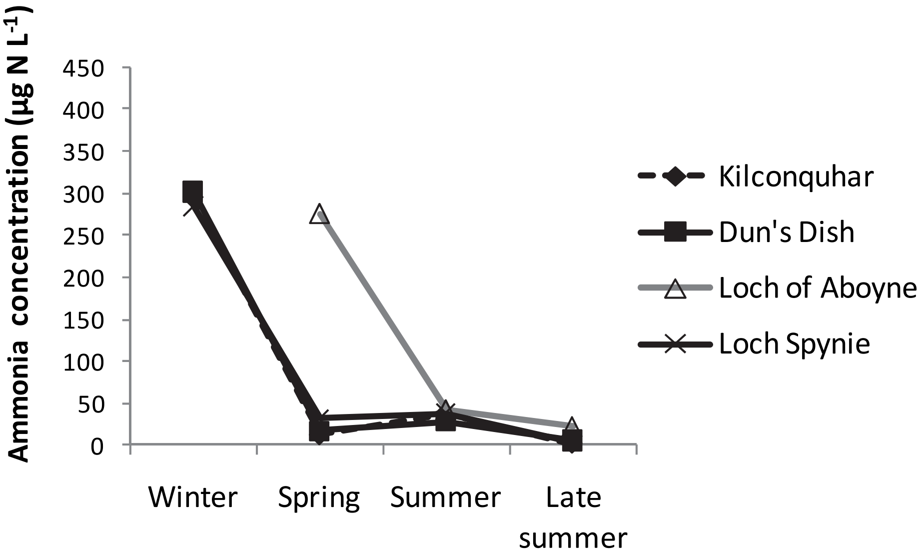


Figure 23. Seasonal TAN concentrations in the northern lochs

A pronounced seasonal effect on TAN concentration was evident across all eight lochs, with the highest concentrations found in winter and a gradual decrease occurring as the year progressed. For seven of the lochs, the lowest concentrations were recorded in summer / late summer. In Milton Loch, however, a very high TAN concentration was recorded in late summer. The highest concentration of 393 µg N L^{-1} was recorded in White Loch in winter, and the lowest concentration of <1 µg N L^{-1} was found in Mochrum Loch in late summer.

TAN level in White Loch ranged from 20 µg N L^{-1} in summer to 393 µg L^{-1} in winter, with an annual mean of 122 µg N L^{-1}. TAN concentration in Mochrum Loch ranged from below the limit of detection in late summer to 286 µg N L^{-1} in winter, with a mean of 92 µg N L^{-1}. In Woodhall Loch TAN level ranged from 9 µg N L^{-1} in late summer to 331 µg N L^{-1} in winter, with a mean of 108 µg N L^{-1}. TAN concentration in Milton Loch ranged from 35 µg N L^{-1} in summer to 205 µg N L^{-1} in late summer, with a mean of 105 µg N L^{-1}. The level of TAN in Kilconquhar Loch ranged from 2 µg N L^{-1} in late summer to 296 µg N L^{-1} in winter, with a mean of 87 µg N L^{-1}. In Dun's Dish, TAN concentration ranged from 6 µg N L^{-1} in late summer to 302 µg N L^{-1} in winter, with a mean of 88 µg N L^{-1}. TAN level in Loch of Aboyne ranged from 43 µg N L^{-1} in summer to 275 µg N L^{-1} in spring, with a mean of 114 µg N L^{-1}. TAN in Loch Spynie ranged from 4 µg N L^{-1} in late summer to 284 µg N L^{-1} in winter with a mean of 90 µg N L^{-1}.

Silica

Figure 24 shows silicate concentrations within the lochs on each sampling visit.

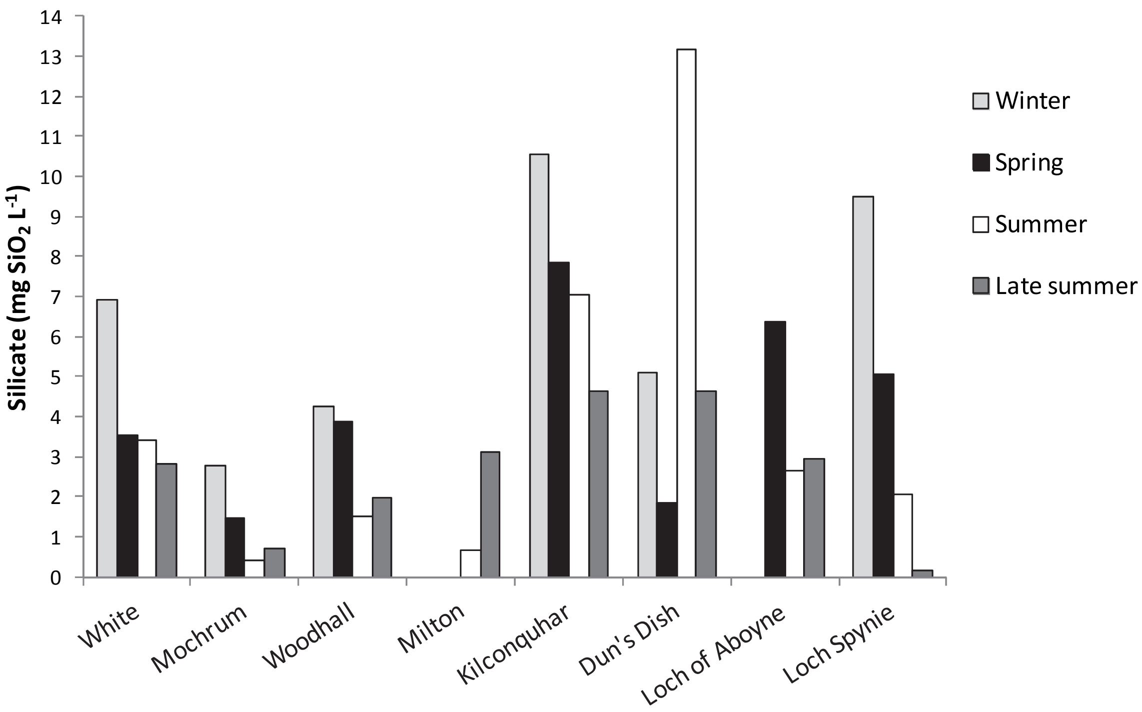


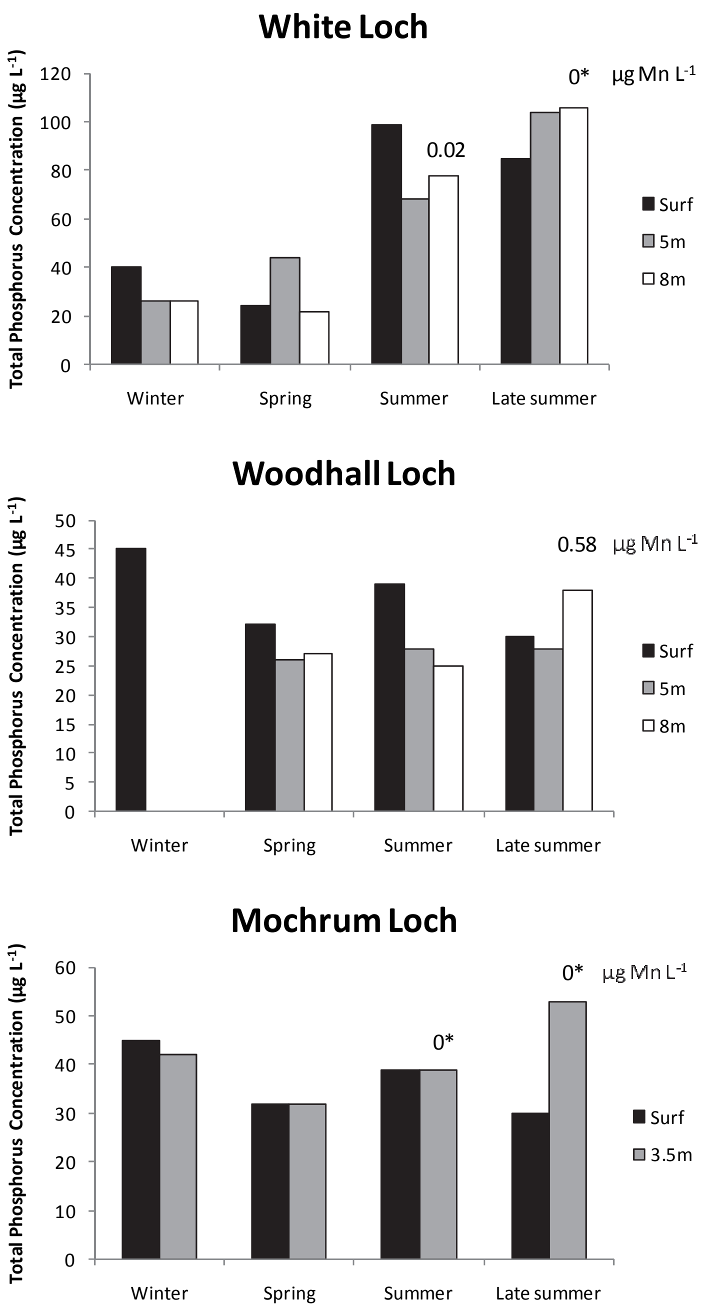
Figure 24. Seasonal SiO_2 concentrations

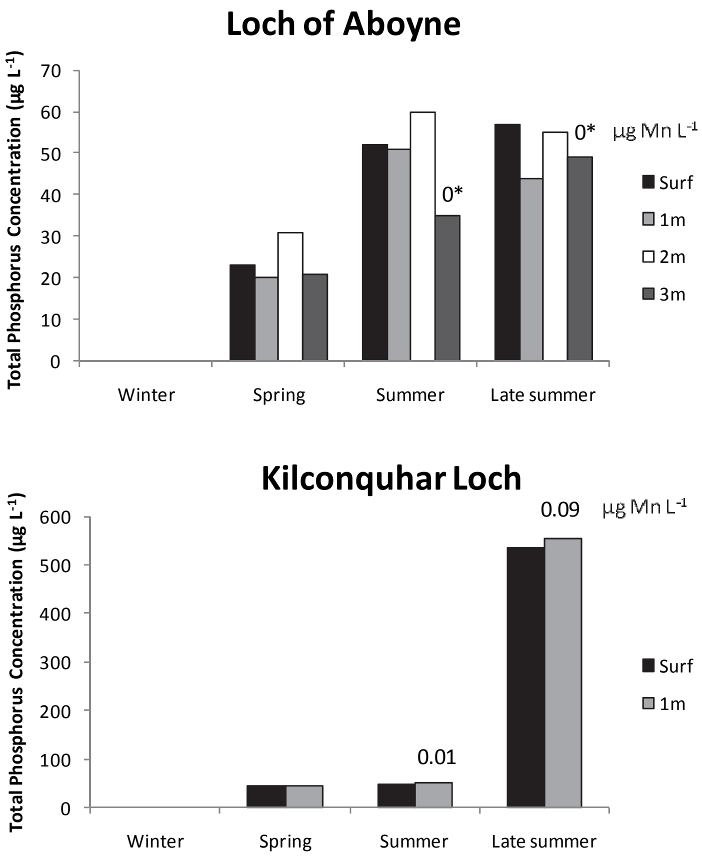
In six of the eight lochs, there was a seasonal effect on silicate concentrations, with a pronounced decrease throughout the year from winter maxima. This seasonal effect was not evident in Dun's Dish, where levels of silica fluctuated more randomly. Fewer data were available for Milton Loch, but late summer concentrations were higher than spring and summer concentrations.

SiO_2 level in White Loch ranged from 2.18 mg L^{-1} in late summer to 6.90 mg L^{-1} in winter, with an annual mean of 4.16 mg L^{-1}. The SiO_2 concentration in Mochrum Loch ranged from 0.42 mg L^{-1} in summer to 2.76 mg L^{-1} in winter, with a mean of 1.43 mg L^{-1}. In Woodhall Loch, SiO_2 level ranged from 1.5 mg L^{-1} in summer to 4.24 mg L^{-1} in winter, with a mean of 2.89 mg L^{-1}. SiO_2 concentration in Milton Loch ranged from <0.1 mg L^{-1} in spring to 3.12 mg L^{-1} in late summer, with a mean of 1.26 mg L^{-1}. Levels of SiO_2 in Kilconquhar Loch ranged from 7.04 mg L^{-1} in summer to 10.54 mg L^{-1} in winter, with a mean of 7.51 mg L^{-1}. SiO_2 concentration in Dun's Dish ranged from 1.84 mg L^{-1} in spring to 13.18 mg L^{-1} in summer, with a mean of 6.18 mg L^{-1}. SiO_2 level in Loch of Aboyne ranged from 2.66 mg L^{-1} in summer to 6.37 mg L^{-1} in spring, with a mean of 3.99 mg L^{-1}. In Loch Spynie, the concentration of SiO_2 ranged from 0.13 mg L^{-1} in late summer to 9.51 mg L^{-1} in winter, with a mean of 4.19 mg L^{-1}.

TP and manganese

Figure 25 shows the concentrations of TP at the different depths of water column at which it was measured. Mn concentrations are also included where these are available.





Mn 0* - below limit of detection

Figure 25. TP and manganese concentrations in deeper water

In general, measured TP concentrations did not increase with increasing depth. However, in late summer, highest TP levels were determined in the samples taken from the deeper/deepest sampling location in White Loch, Woodhall Loch, Mochrum Loch and Kilconquhar Loch. In contrast, TP concentrations in the water samples taken at the greatest depth were not the highest for any of the sampling dates for Loch of Aboyne.

Manganese concentration was generally below the limit of detection and was recorded only at trace levels in all water samples, aside from those taken at Woodhall Loch, where the highest Mn concentration of 0.58 µg L^{-1} was measured in the sample taken in late summer, at 8m depth. This level is, however, still very low.

Chlorophyll *a*

Figures 26 and 27 present Ch*a* concentrations for the southern and northern lochs respectively on each sampling visit.

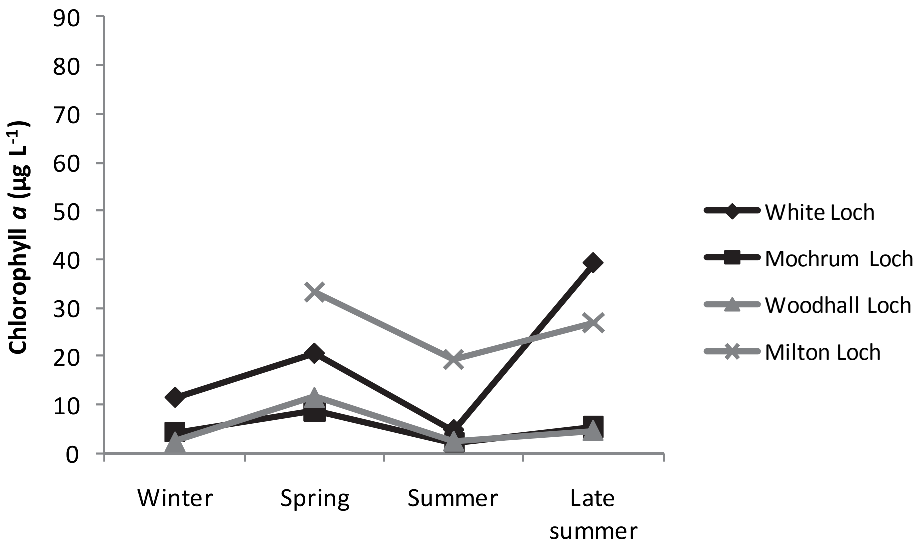


Figure 26. Seasonal chlorophyll a concentrations in the southern lochs

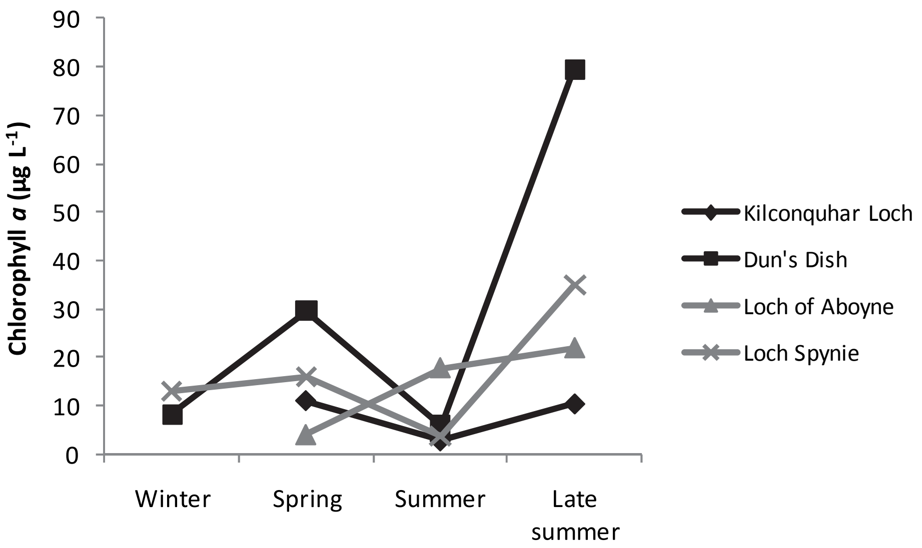


Figure 27. Seasonal chlorophyll a concentrations in the northern lochs

For all of the lochs except Loch of Aboyne, there was a distinct seasonal pattern of higher Ch*a* concentrations occurring in spring and late summer, and lower values being observed in winter and summer. Loch of Aboyne was the only water body that did not show this pattern, a gradual increase in Ch*a* concentration occurring as the year progressed.

Ch*a* level measured in White Loch ranged from 4.79 µg L^{-1} in summer to 39.15 µg L^{-1} in late summer, with an annual mean of 18.9 µg L^{-1}. Ch*a* concentration in Mochrum Loch ranged from 2.22 µg L^{-1} in winter to 5.47 µg L^{-1} in spring, with a mean of 5.17 µg L^{-1}. In Woodhall

Loch, Cha level ranged from 2.39 µg L^{-1} in winter to 11.63 µg L^{-1} in spring, with a mean of 5.34 µg L^{-1}. Cha concentration in Milton Loch ranged from 19.32 µg L^{-1} in summer to 33.34 µg L^{-1} in spring, with a mean of 26.56 µg L^{-1}. Cha level in Kilconquhar Loch ranged from 2.74 µg L^{-1} in summer to 11.11 µg L^{-1} in spring, with a mean of 8.09 µg L^{-1}. In Dun's Dish, Cha concentration ranged from 5.81 µg L^{-1} in summer to 79.5 µg L^{-1} in late summer, with a mean of 30.79 µg L^{-1}. Cha level increased from 4.1 µg L^{-1} in spring to 21.88 µg L^{-1} in late summer in Loch of Aboyne. The mean Cha concentration was 14.59 µg L^{-1}. Cha level in Loch Spynie ranged from 3.76 µg L^{-1} in summer to 34.99 µg L^{-1} in late summer, with a mean of 16.93 µg L^{-1}.

Suspended solids

Figure 28 shows the concentration of suspended solids in each loch on each sampling visit.

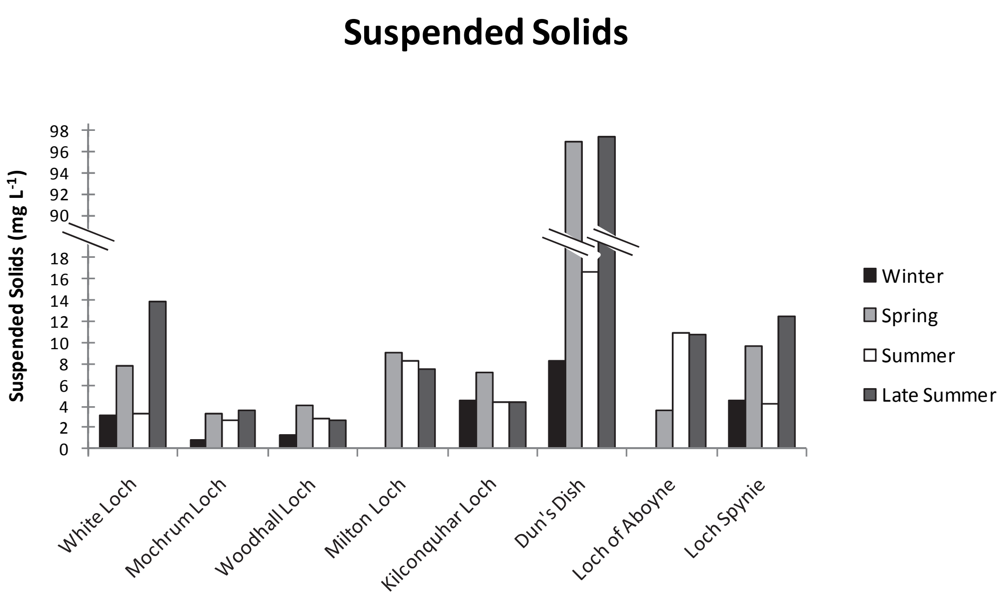
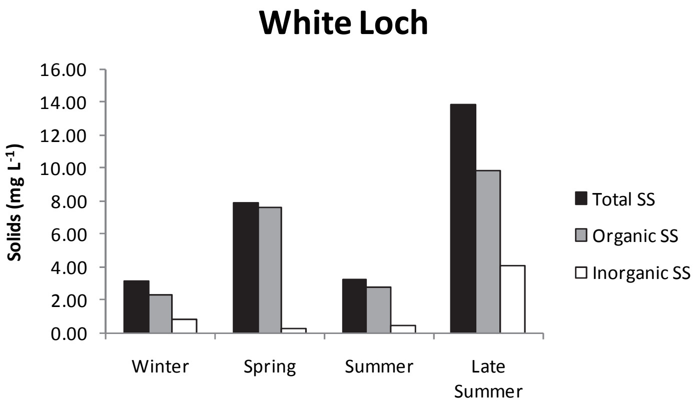
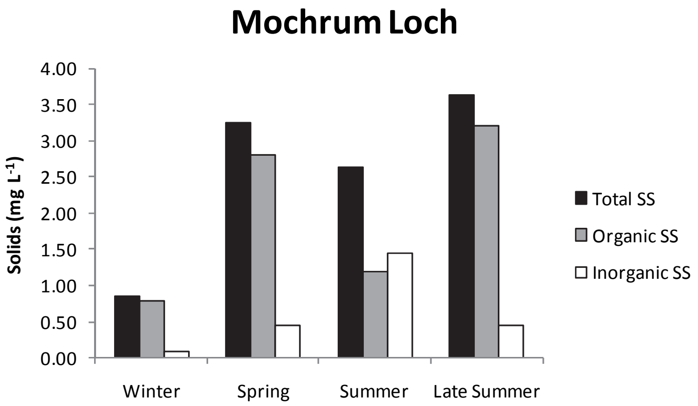


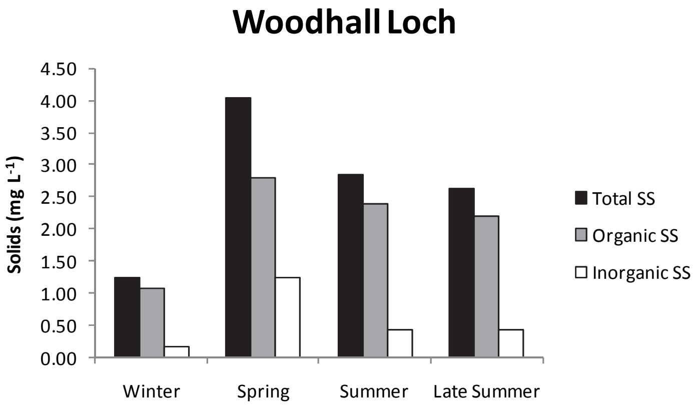
Figure 28. Water column suspended solids concentrations in samples from each loch

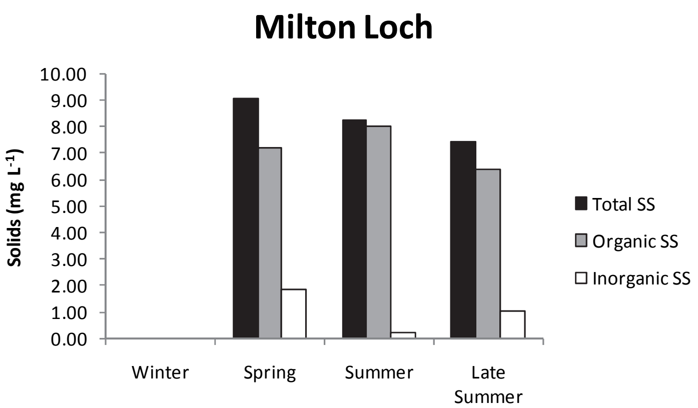
The maximum concentration of suspended solids of 99 mg L^{-1} was found in Dun's Dish in spring. This level was considerably greater than any of the concentrations measured in the other lochs. Mochrum and Woodhall Lochs had the lowest levels of SS with concentrations of 0.86 and 1.24 mg L^{-1} respectively occurring in winter in these water bodies. Measured SS levels were highest in spring in Woodhall Loch, Milton Loch and Kilconquhar Loch, but in late summer in White Loch, Mochrum Loch, Dun's Dish and Loch Spynie. As for Cha concentrations, Loch of Aboyne differed from the other water bodies, as the highest concentration of SS was determined in summer.

Figure 29 shows the concentration of organic and inorganic suspended solids in each loch on each sampling visit.









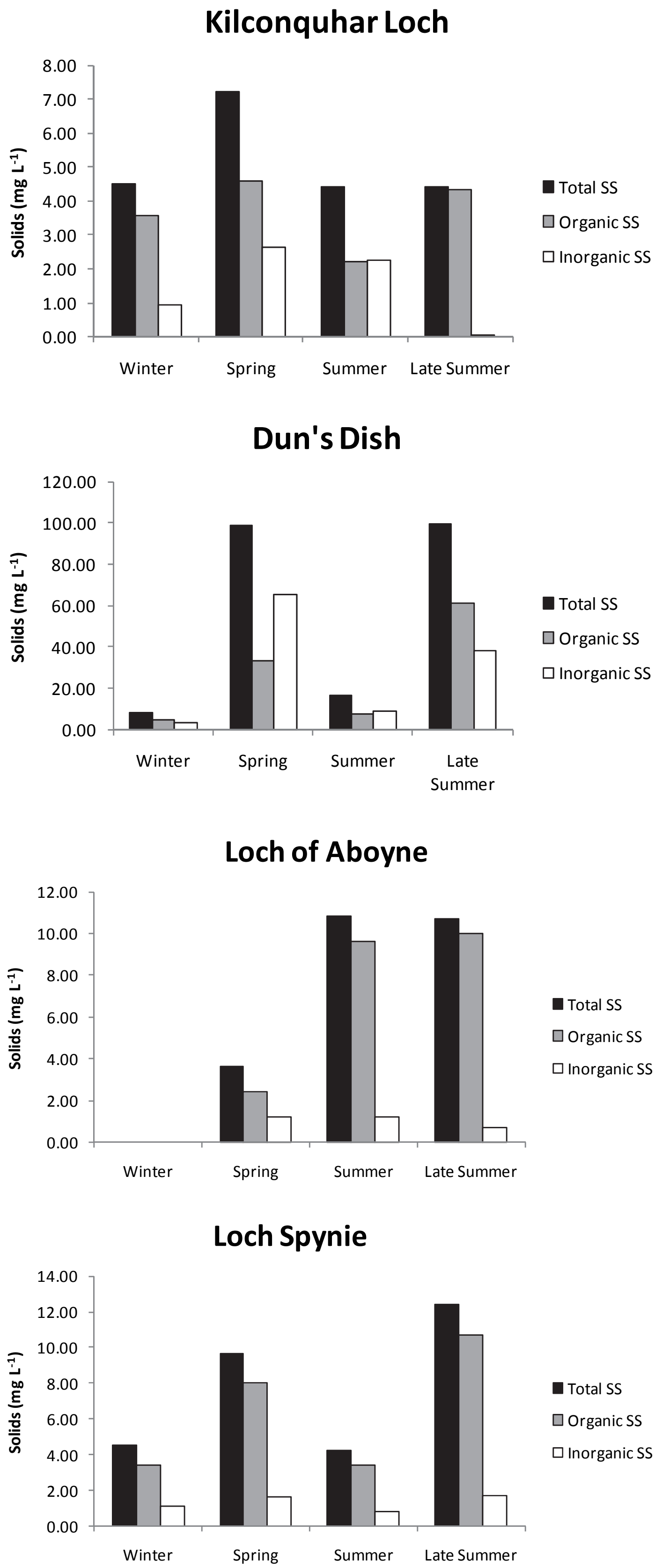


Figure 29. Levels of total, organic and inorganic suspended solids in each loch

Secchi Depth

Figures 30 and 31 show the Secchi depth for each loch on each sampling visit.

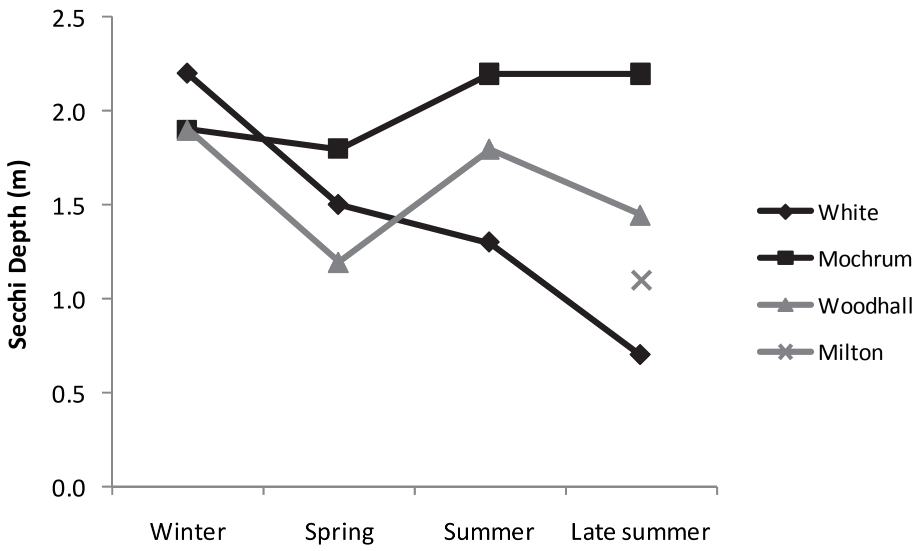


Figure 30. Seasonal Secchi depth in the southern lochs

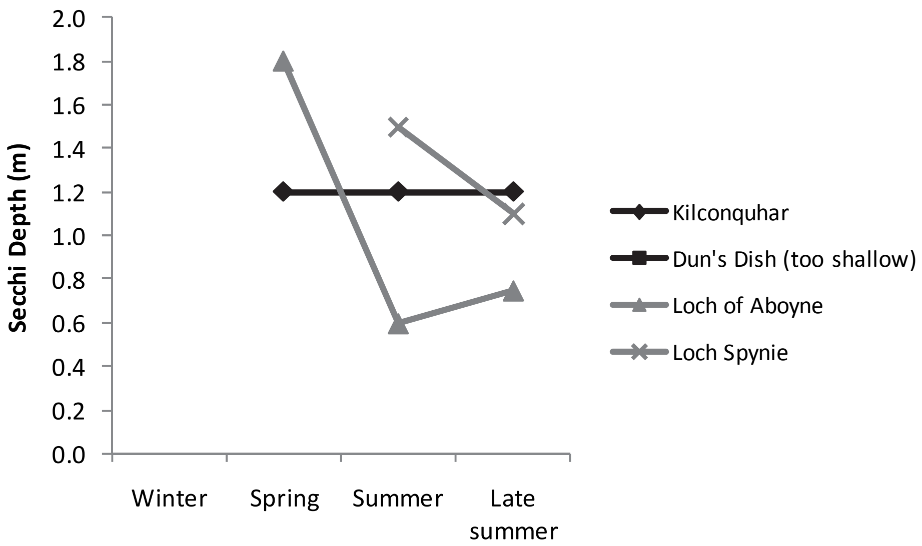


Figure 31. Seasonal Secchi depth in the northern lochs

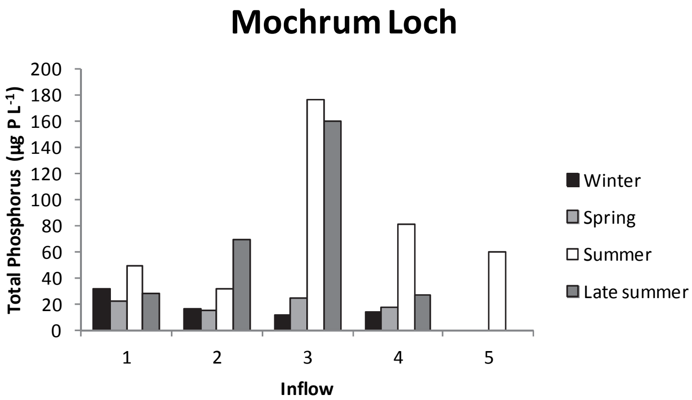
Secchi depth in Mochrum Loch and Woodhall Loch decreased from winter to spring, but increased from spring to summer. In Woodhall Loch, White Loch and Loch Spynie, Secchi depth decreased from summer to late summer. In Kilconquhar Loch, Secchi depth was consistent from spring to late summer, as was the case in Mochrum Loch from summer to late summer. Secchi depth in White Loch decreased from winter to spring, summer and late summer. In Loch of Aboyne, Secchi depth decreased from spring to summer, but increased slightly from summer to late summer.

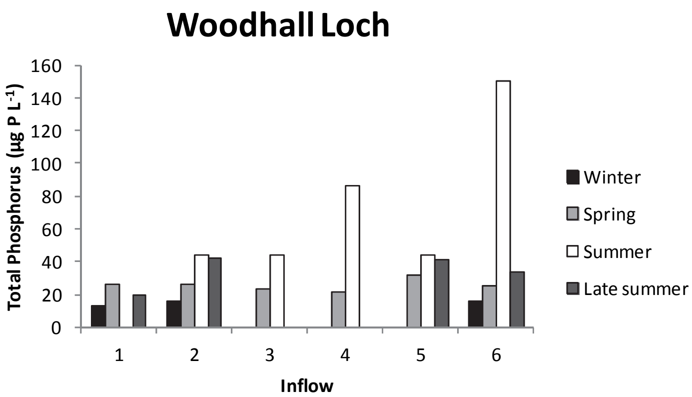
3.5.2 Inflowing rivers

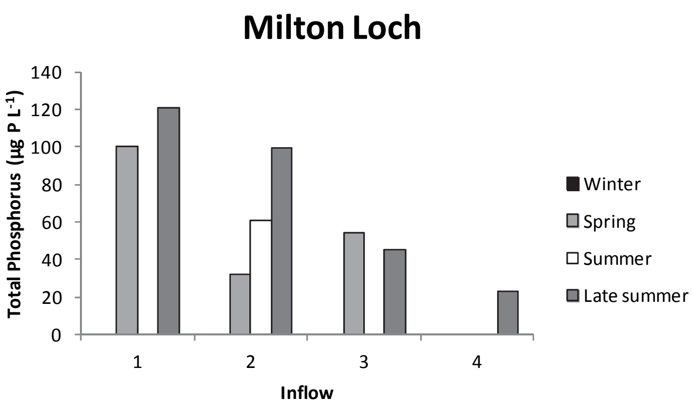
TP and BOD_5 results for the streams and rivers flowing into the target lochs are presented below. Figures 3 to 10 illustrate the locations and delineated sub-catchments of each surface inflow. Note that many inflows were dry during the summer sampling visit and so results could not always be obtained for this period.

Total Phosphorus

Figure 32 shows the TP concentrations for each inflowing stream or drain. The annual mean of these figures was used to produce P budgets for the sub-catchments of each loch.







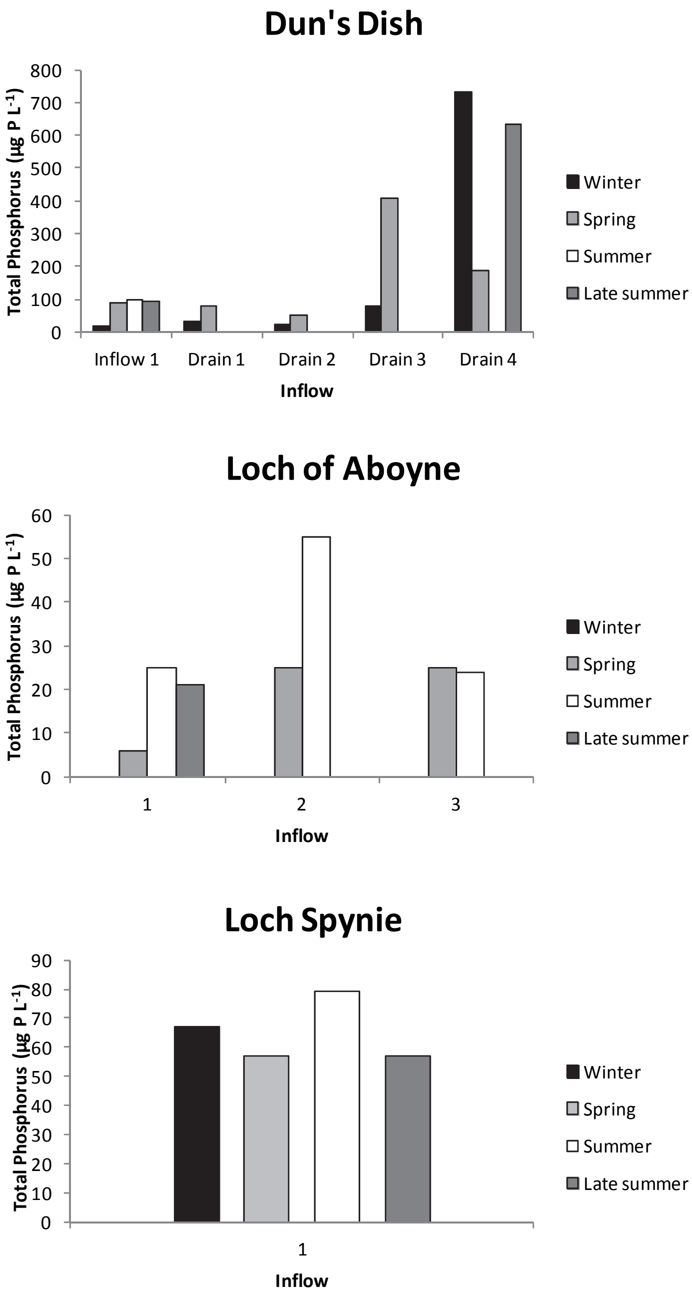
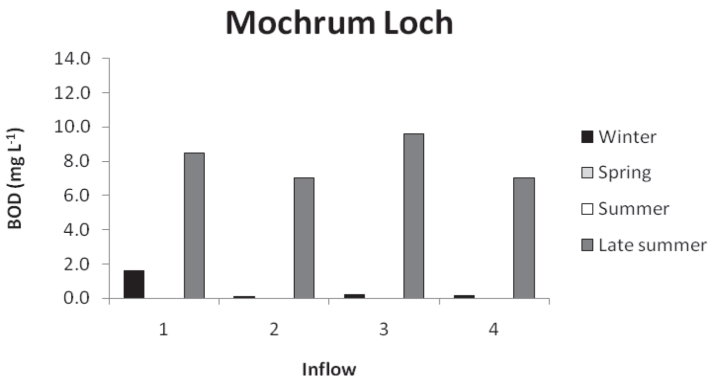


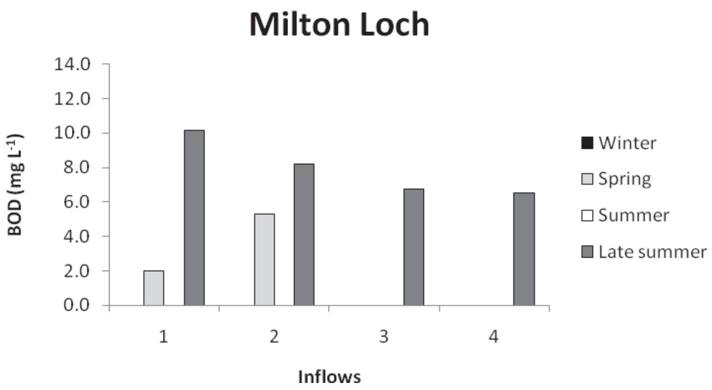
Figure 32. TP concentration in each inflowing river

TP concentrations in the inflowing streams of Mochrum Loch ranged from 11 to 176 µg P L^{-1}. There was a tendency for summer TP concentrations to be higher than those in the other samples. The highest TP levels were found in Inflow 3. In Woodhall Loch inflows, TP levels ranged from 13 to 150 µg P L^{-1}. As with inflows at Mochrum Loch, the highest concentrations of TP were found in the summer samples, with the maximum level of TP being determined in the summer sample from Inflow 6. Milton Loch inflow TP concentrations ranged from 23 to 121 µg P L^{-1} and Inflow 1 had the highest TP levels. For Dun's Dish, Drain 4 had by far the highest TP concentrations with a maximum of 734 µg P L^{-1} in the winter sample. In Loch of Aboyne inflows, TP concentrations ranged from 6 to 55 µg P L^{-1}. Similar levels of TP were found in each of the three inflows, with the exceptions of concentrations determined in the spring sample from inflow 1 and the summer sample from inflow 2, these samples accounting for the minimum and maximum levels measured, respectively. In Loch Spynie, TP concentrations ranged from 57 to 79 µg P L^{-1} in its one inflow.

Biochemical Oxygen Demand (BOD_5)

Figure 33 shows the measured BOD_5 for each inflowing river or drain for each of the six lochs with surface inflows. Note that due to inflowing streams running dry in the summer, summer inflow samples were not available for any lochs other than Dun's Dish and Loch Spynie.





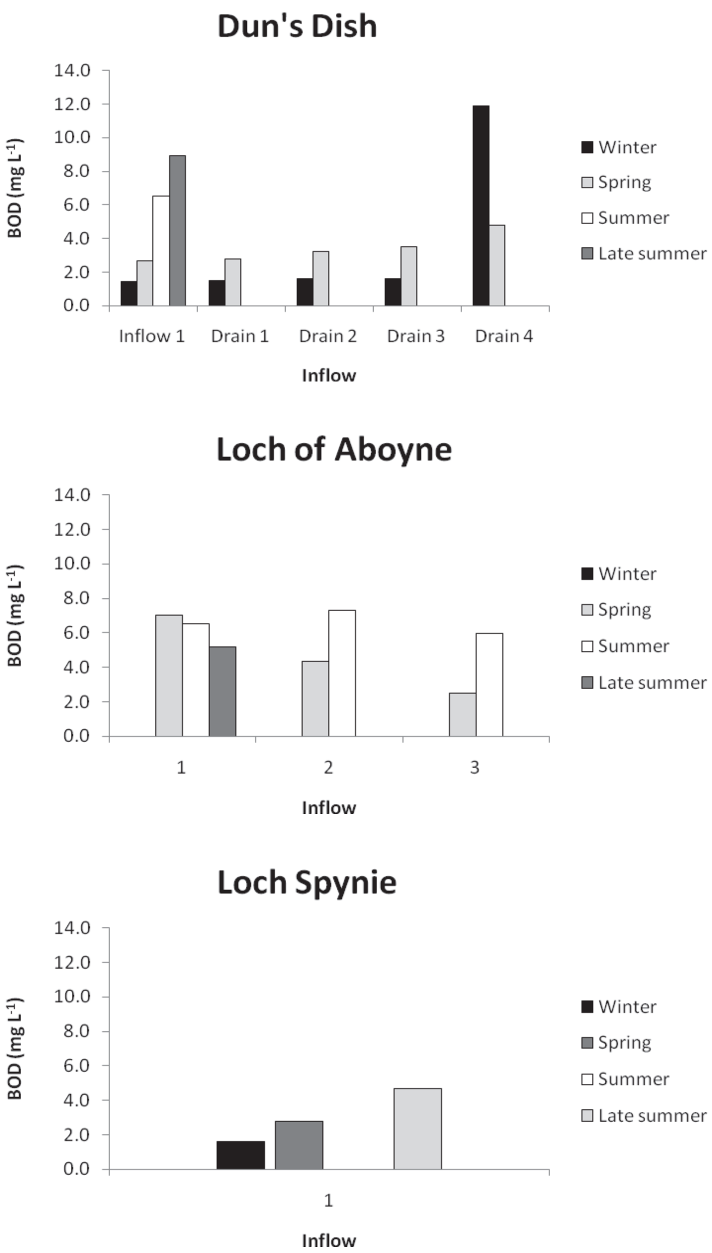


Figure 33. BOD_5 concentrations in samples from each inflowing river

Elevated BOD_5 was noted in the late summer samples from inflows 1 to 4 at Mochrum Loch and Milton Loch. BOD_5 was also higher in the late summer samples taken from the inflows at Woodhall Loch than in the samples taken at other times of year. There was no summer sample for the inflow to Loch Spynie, but BOD_5 was higher in the sample taken in late summer than in the winter and spring samples. Limited data were available for the drains flowing into Dun's Dish (due to drying out), but the winter sample showed an extremely high BOD_5 of 11.9 mg L^{-1} in drain 4. In drains 1 to 3, BOD_5 was higher in the spring sample than in the winter sample. In Inflow 1 at Loch of Aboyne, highest BOD_5 was measured in the spring, whereas Inflows 2 and 3 showed an increase in BOD_5 from spring to summer. Late summer samples were not available for these inflows due to their drying out.

3.5.3 *Trophic status of the lochs*

OECD trophic status parameters (OECD, 1982) were used to assign trophic status to each loch examined, based on measured characteristics. The trophic status of each loch according to OECD (1982) was then compared with the trophic status recorded in the documentation for the notified feature of interest. Table 7 shows the expected trophic status of each water body, as described for the site designation, and the trophic status defined by OECD (1982) and measured characteristics.

Table 7. Trophic status parameters for each loch

Loch	Mean TP ($\mu g\ P\ L^{-1}$)	Mean chlorophyll *a* ($\mu g\ L^{-1}$)	Maximum chlorophyll *a* ($\mu g\ L^{-1}$)	Mean Secchi depth (m)	Minimum Secchi depth (m)	Trophic status	Expected trophic status
White Loch	62	18.98	11.5	1.4	1.0	Eutrophic	Eutrophic
Mochrum Loch	37	5.17	8.7	2.0	1.8	Eutrophic	Oligotrophic
Woodhall Loch	25	5.34	11.6	1.6	1.0	Mesotrophic	Oligotrophic
Milton Loch	87	26.56	33.3	1.1	1.1	Eutrophic	Eutrophic
Kilconquhar Loch	169	8.09	11.1	1.2	1.2	Hypertrophic	Eutrophic
Dun's Dish	332	30.79	79.5	n/a	n/a	Hypertrophic	Eutrophic
Loch of Aboyne	44	14.59	21.9	1.1	0.6	Eutrophic	Mesotrophic
Loch Spynie	65	16.93	34.9	1.3	1.1	Eutrophic	Eutrophic

Figure 34 shows all TP concentrations with upper eutrophic, mesotrophic and oligotrophic TP boundaries as defined by OECD (1982).

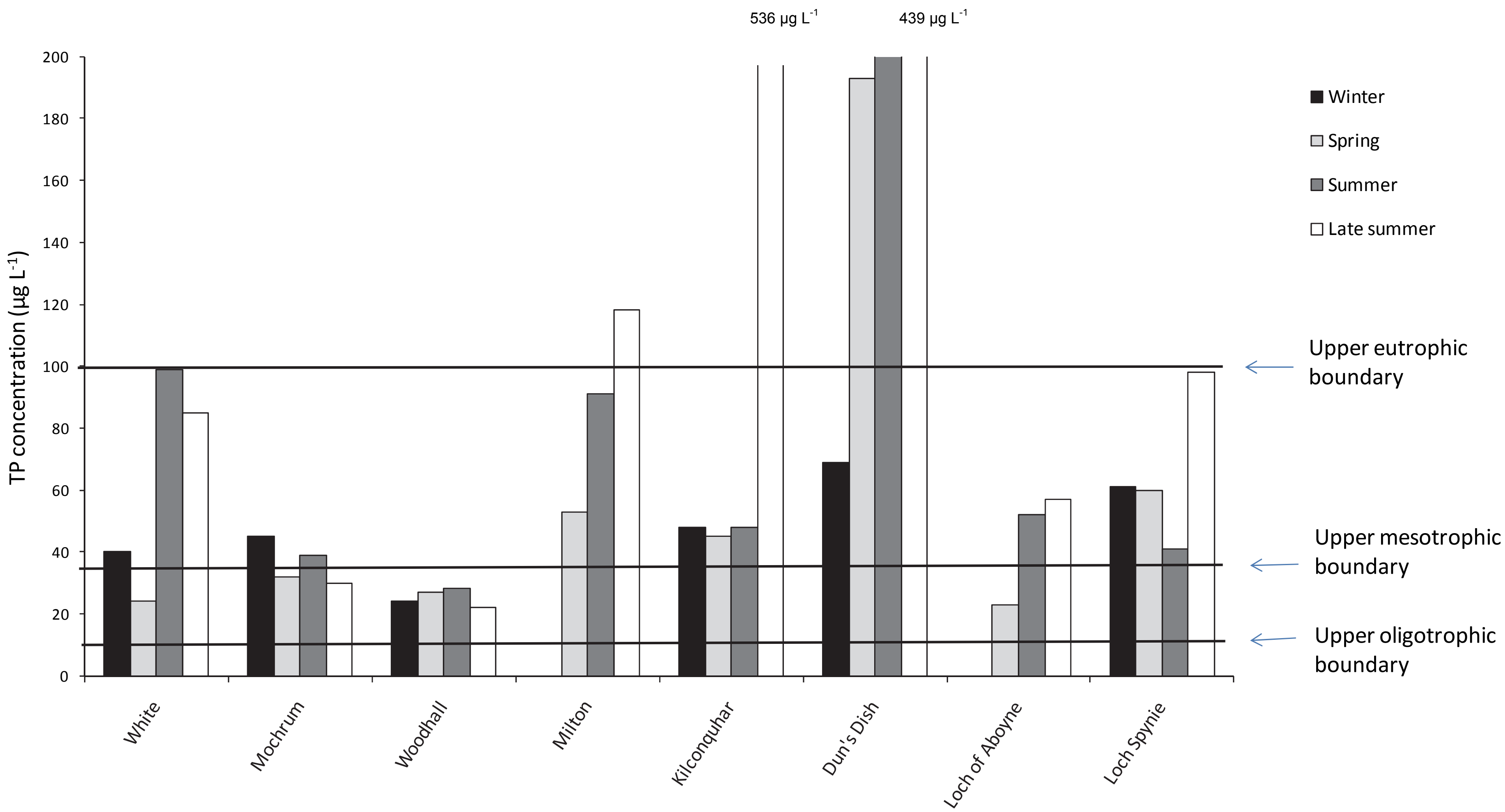


Figure 34. TP for each loch with upper eutrophic, mesotrophic and oligotrophic boundaries illustrated (OECD, 1982)

Water column TP concentrations in winter, summer and late summer samples from White Loch were within the eutrophic category, according to OECD (1982). The spring sample exhibited a lower TP level, which fell within the mesotrophic category. Mochrum Loch had winter and summer water column TP concentrations which were within the eutrophic category, with spring and late summer TP levels falling within mesotrophic boundaries. TP concentrations in all four samples from Woodhall Loch fell well within the mesotrophic boundary. TP levels in the spring and summer samples from Milton Loch were indicative of eutrophic conditions, whilst the level in the late summer sample defined the water body as hypertrophic. Winter, spring and summer TP concentrations measured in samples from the water column of Kilconquhar Loch were within the eutrophic category, but analysis of TP level in the late summer sample indicated the water body was hypertrophic. Only the TP concentration in the winter sample from Dun's Dish was eutrophic, with the remaining three samples all being hypertrophic. For Loch of Aboyne, TP level in the spring sample was mesotrophic whilst summer and late summer TP concentrations were eutrophic. All four samples from Loch Spynie contained TP levels which ranged across the eutrophic category.

3.6 Macrophytes

Surveys of macrophyte species present in the lochs were not carried out within the remit of this project; however, some historical data were provided by SNH from the Scottish Loch Survey Project (SLSP), which included comprehensive surveys of submerged and emergent macrophytes in six of the eight target lochs. The species found and the dates they were recorded during the SLSP are presented in Table 8. Historical SLSP macrophyte data are not available for White Loch or Mochrum Loch.

Table 8. Macrophyte species recorded for six lochs during the SLSP

Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Date surveyed	9/9/96	17/9/96	8/7/97	15/7/97	20/9/88	28/9/87
Emergent and edge species						
Acorus calamus			✓			
Agrostis stolonifera	✓	✓	✓	✓	✓	✓
Alisma lanceolatum	✓	✓				
A. plantago-aquatica	✓			✓		
Caltha palustris	✓	✓	✓	✓	✓	✓
Carex lasiocarpa	✓					
Carex nigra	✓	✓				
Carex panicea	✓					
Carex rostrata	✓	✓	✓	✓	✓	✓
Carex viridula ssp. *oedocarpa*	✓					
Carex vesicaria	✓					
Epilobium palustre					✓	
Epilobium hirsutum						✓
Eleocharis acicularis	✓					
Eleocharis multicaulis	✓					
Eleocharis palustris	✓	✓	✓	✓	✓	
Equisetum fluviatile	✓	✓	✓	✓	✓	✓
Equisetum palustre		✓				
Filipendula ulmaria					✓	
Galium palustre	✓	✓		✓	✓	
Glyceria fluitans	✓	✓			✓	
Glyceria maxima			✓			
Hydrocotyle vulgaris	✓	✓			✓	
Hippuris vulgaris			✓			✓
Iris pseudacorus			✓		✓	✓
Juncus acutiflorus	✓	✓		✓		
Juncus articulatus	✓	✓		✓	✓	
Juncus bulbosus	✓					
Juncus conglomeratus	✓			✓		
Juncus effusus	✓	✓	✓	✓	✓	✓

Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun’s Dish	Loch of Aboyne	Loch Spynie
Date surveyed	9/9/96	17/9/96	8/7/97	15/7/97	20/9/88	28/9/87
Littorella uniflora	✓					
Lythrum salicaria	✓	✓				
Mentha spp.				✓		
Mentha aquatica	✓		✓		✓	✓
Menyanthes trifoliata	✓	✓	✓		✓	
Mimulus spp.				✓		
Mimulus guttatus				✓		✓
Montia fontana	✓					
Myosotis laxa	✓	✓		✓		
Myosotis scorpioides	✓	✓	✓	✓	✓	✓
Nasturtium officinale					✓	✓
Oenanthe crocata	✓					
Persicaria hydropiper	✓	✓				
Persicaria amphibia		✓	✓	✓	✓	✓
Phalaris arundinacea	✓	✓	✓	✓		
Phragmites australis	✓		✓		✓	✓
Potentilla palustris	✓	✓		✓	✓	
Rannunculus flammula	✓	✓		✓	✓	
Ranunculus lingua			✓			
Schoenoplectus lacustris	✓					✓
Senecio aquaticus					✓	
Sparganium emersum	✓					
Sparganium erectum	✓	✓			✓	✓
Stachys palustris					✓	✓
Typha latifolia		✓	✓	✓	✓	✓
Veronica scutellata	✓	✓				
Veronica beccabunga		✓	✓	✓	✓	✓
Viola palustris	✓					
Rorippa palustris	✓					
Rorippa nasturtium-aquaticum		✓	✓	✓		
Schoenoplectus lacustris		✓	✓			

Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Date surveyed	9/9/96	17/9/96	8/7/97	15/7/97	20/9/88	28/9/87
Submerged and floating species						
Apium inundatum	✓					
Callitriche spp.				✓		
Callitriche stagnalis	✓	✓	✓			
Callitriche hermaphroditica		✓				✓
Callitriche hamulata					✓	✓
Ceratophyllum demersum						✓
Chara aspera		✓	✓			✓
Chara virgata			✓			
Eleogiton fluitans	✓					
Elodea canadensis	✓	✓			✓	✓
Fontinalis antipyretica	✓	✓				✓
Hydrocotyle vulgaris					✓	
Isoetes lacustris	✓					
Lemna minor	✓	✓	✓	✓	✓	✓
L. trisulca	✓	✓				
Littorella uniflora	✓	✓		✓	✓	
Lobelia dortmanna	✓					
Myriophyllum alterniflorum	✓				✓	
M. spicatum			✓			
Nuphar lutea	✓					
Nymphaea alba	✓		✓		✓	
Nymphoides peltata			✓			
Nitella flexilis	✓				✓	
Nitella translucens						✓
Nuphar x *spenneriana*	✓					
Persicaria amphibia		✓	✓	✓		
Potamogeton alpinus	✓				✓	
Potamogeton berchtoldii					✓	
Potamogeton compressus					✓	
Potamogeton crispus				✓		
Potamogeton gramineus	✓				✓	✓

Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Date surveyed	9/9/96	17/9/96	8/7/97	15/7/97	20/9/88	28/9/87
Potamogeton natans	✓	✓			✓	✓
Potamogeton obtusifolius	✓				✓	
Potamogeton pectinatus			✓			✓
Potamogeton polygonifolius	✓					
Potamogeton perfoliatus		✓			✓	✓
Potamogeton praelongus					✓	
Potamogeton pusillus		✓	✓	✓		✓
Ranunculus trichophyllus					✓	✓
Sparganium spp.		✓				
Sparganium angustifolium	✓				✓	
Sparganium natans	✓					
Zannichellia palustris		✓	✓	✓		✓
Total number of taxa found	64	43	32	30	44	34

3.7 Zooplankton and phytoplankton

3.7.1 Phytoplankton

Table 9 shows the genus (or species where identification was possible) of phytoplankton identified for each loch. The proportional contribution by biovolume for each algal group is shown in Figure 35. The dominant groups for spring and summer (the growing seasons) in each loch are summarized in Table 10.

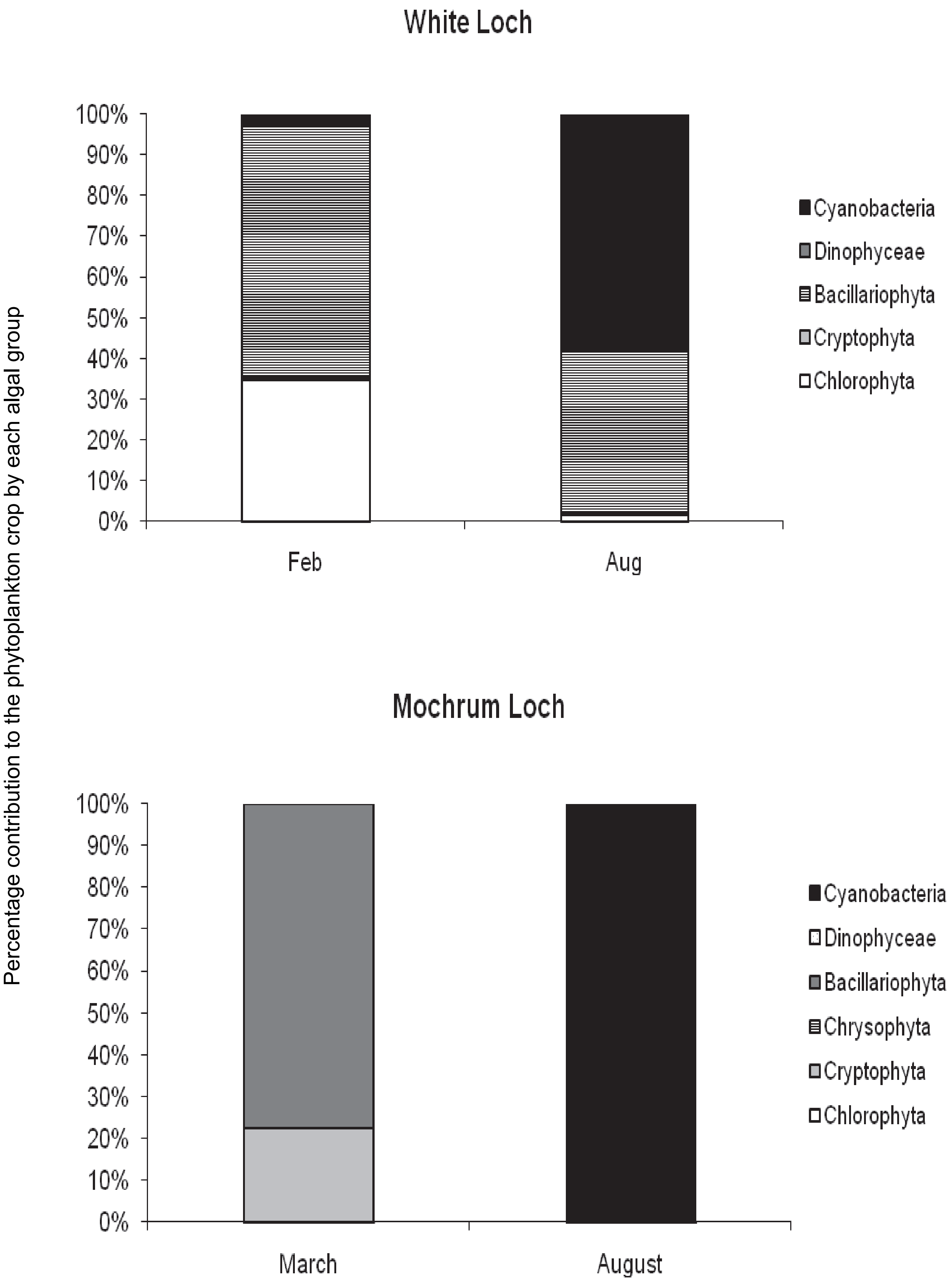
Table 9. Genus (or species) of phytoplankton found in each loch

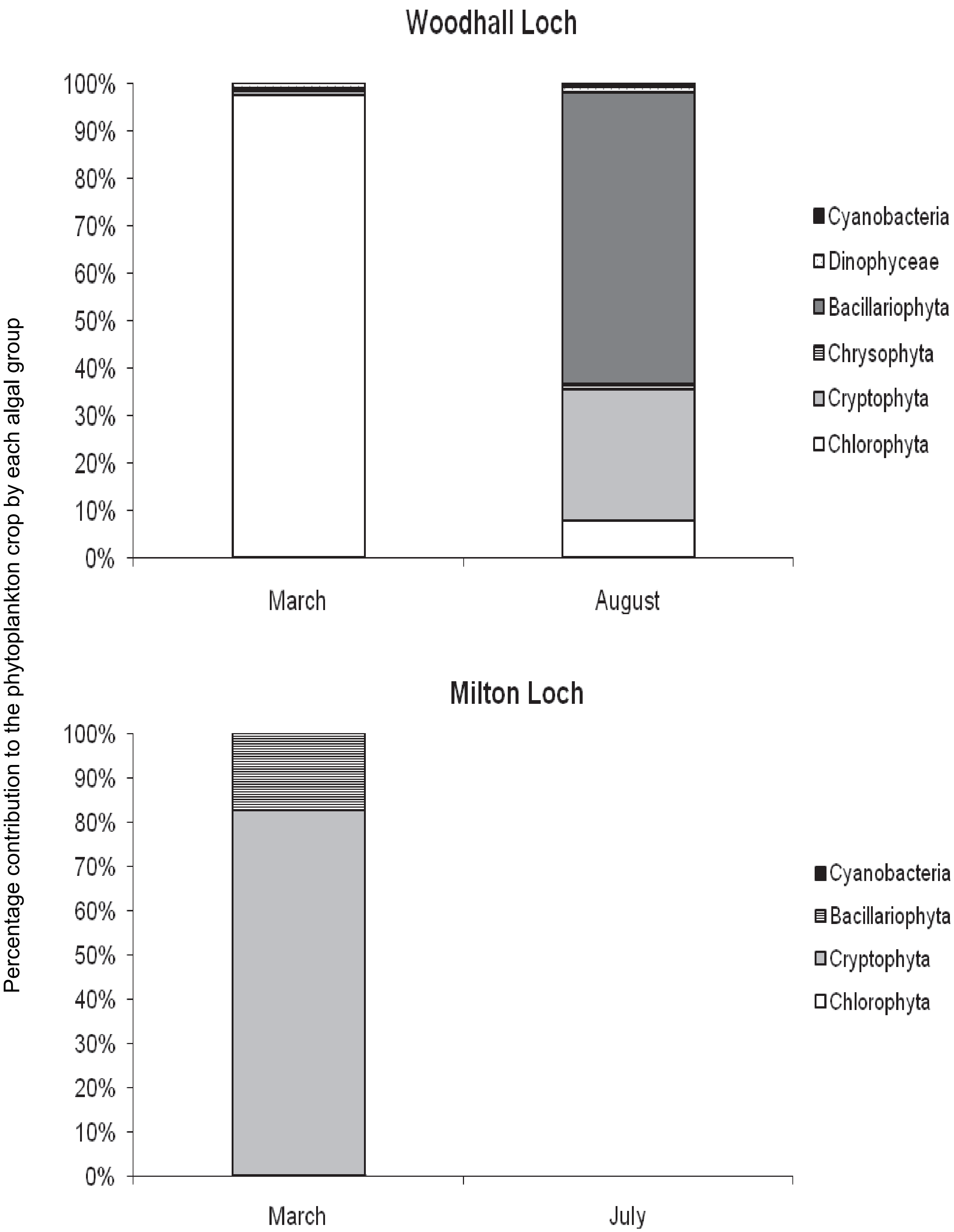
	White Loch	Mochrum Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Chlorophyta								
Ankistrodesmus spp	✓						✓	
Ankyra judayi		✓	✓					
Chlamydomonas spp		✓	✓		✓	✓	✓	✓
Chlorella spp	✓	✓	✓	✓	✓	✓	✓	✓
Chlorella vulgaris							✓	
Closteriopsis spp	✓		✓	✓	✓		✓	✓
Closterium acutum					✓	✓		
Coelastrum spp	✓							
Cosmarium spp								✓
Crucigenia spp		✓						
Dictyosphaerium pulchellum	✓	✓						
Eudorina spp	✓							
Micractinium spp		✓						
Monoraphidium contortum	✓	✓			✓	✓		✓
Oocystis solitaria							✓	✓
Pediastrum boryanum	✓	✓			✓		✓	
Pseudoquadrigula britannica								✓
Quadrigula spp		✓					✓	
Scenedesmus spp	✓	✓			✓	✓	✓	✓

	White Loch	Mochrum Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun’s Dish	Loch of Aboyne	Loch Spynie
Staurodesmus spp					✓			
Tetraedron spp		✓			✓		✓	✓
Tetrastrum triangulare					✓			
Cyanobacteria								
Anabaena spp	✓				✓	✓	✓	✓
Anabaena spiroides	✓							
Chroococcus spp	✓	✓	✓	✓				✓
Coelosphaerium naegelianum	✓						✓	✓
Gomphosphaeria spp		✓						
Micrococcus geminata	✓	✓					✓	
Oscillatoria agardhii	✓							
Pseudanabaena spp	✓							
Cryptophyta								
Cryptomonas spp	✓	✓	✓	✓	✓	✓	✓	✓
Rhodomonas spp	✓	✓	✓	✓	✓	✓	✓	✓
Dinophyta								
Ceratium spp	✓							
Gymnodinium spp	✓	✓	✓		✓		✓	✓
Crysophyta								
Dinobryon spp		✓			✓		✓	✓
Mallomonas spp		✓	✓		✓		✓	✓
Bacillariophyta								
Asterionella formosa		✓					✓	✓
Aulacoseira spp	✓							
Diatoma spp							✓	✓
Fragilaria capucina			✓					
Gomphonema spp					✓	✓		✓

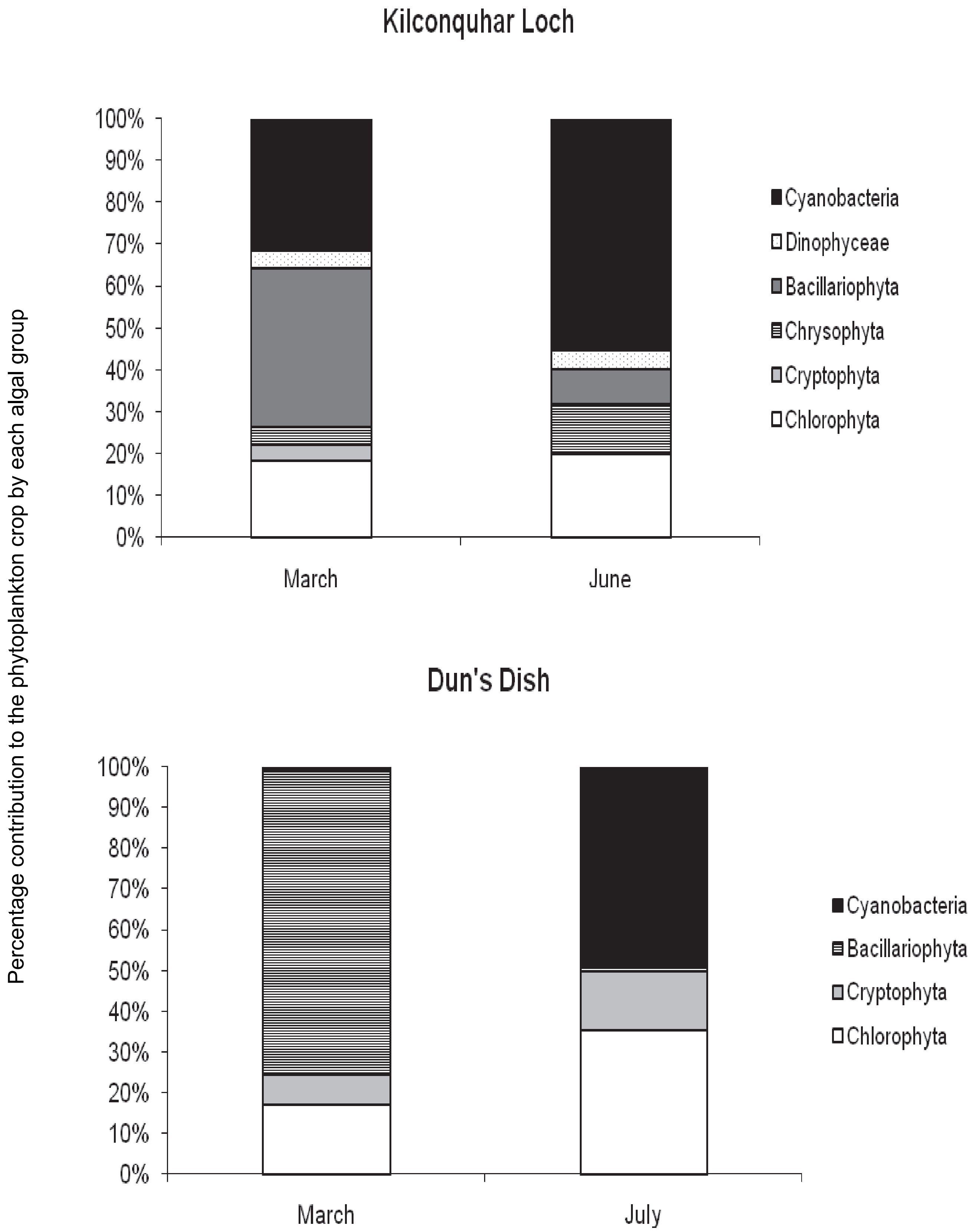
	White Loch	Mochrum Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Gyrosigma spp						✓		
Navicula spp		✓				✓	✓	✓
Nitzschia spp	✓		✓		✓	✓		✓
Stephanodiscus spp	✓			✓			✓	
Synedra acus					✓			
Tabellaria flocculosa	✓							
Total number of genus/species found	24	21	11	6*	19	12	22	22

Note that data were only available for one sample from Milton Loch, but there were two samples from each of the other lochs.


White Loch
Percentage contribution to the phytoplankton crop by each algal group
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Feb
Aug
Cyanobacteria
Dinophyceae
Bacillariophyta
Cryptophyta
Chlorophyta
Mochrum Loch
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
March
August
Cyanobacteria
Dinophyceae
Bacillariophyta
Chrysophyta
Cryptophyta
Chlorophyta



Woodhall Loch
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
March
August
Cyanobacteria
Dinophyceae
Bacillariophyta
Chrysophyta
Cryptophyta
Chlorophyta
Percentage contribution to the phytoplankton crop by each algal group
Milton Loch
March
July
Cyanobacteria
Bacillariophyta
Cryptophyta
Chlorophyta


Kilconquhar Loch
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
March
June
Cyanobacteria
Dinophyceae
Bacillariophyta
Chrysophyta
Cryptophyta
Chlorophyta
Percentage contribution to the phytoplankton crop by each algal group
Dun's Dish
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
March
July
Cyanobacteria
Bacillariophyta
Cryptophyta
Chlorophyta

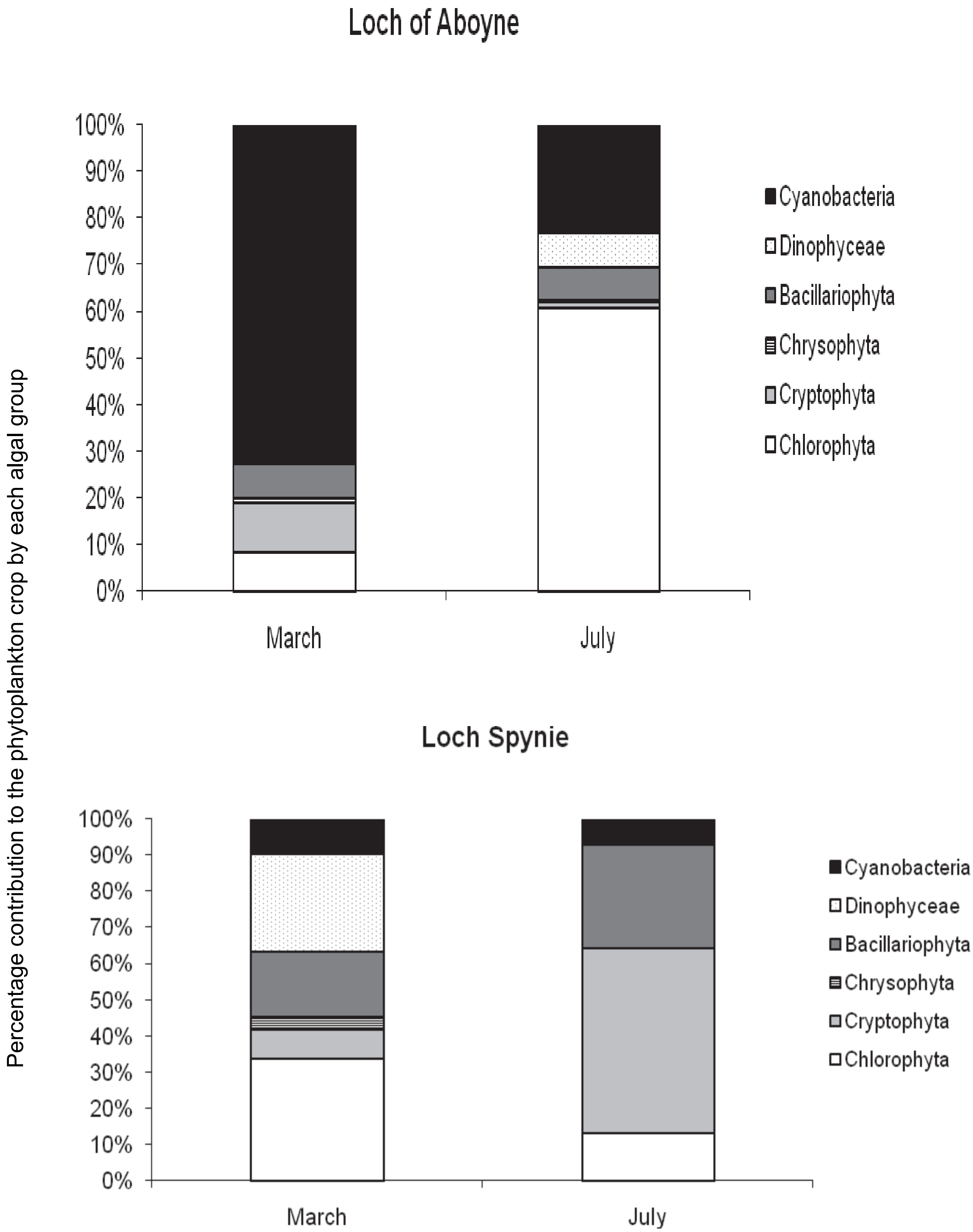


Figure 35. Phytoplankton groups - percentage contribution by biovolume

Table 10. Summary of the dominant phytoplankton groups in spring and summer

Loch	Spring	Summer
White Loch	diatoms and green algae	cyanobacteria and diatoms
Mochrum Loch	diatoms	cyanobacteria
Woodhall Loch	green algae	diatoms
Milton Loch	Cryptophyta	n/a
Kilconquhar Loch	diatoms	cyanobacteria
Dun's Dish	diatoms	cyanobacteria
Loch of Aboyne	cyanobacteria	green algae
Loch Spynie	green algae and dinophyceae	diatoms and Cryptophyta

In spring, diatoms dominated the phytoplankton of three water bodies (Mochrum Loch, Kilconquhar Loch and Dun's Dish). Diatoms and green algae were both prevalent in White Loch, and one group did not dominate the other. Green algae were also abundant in Loch Spynie in spring, along with dinophyceae. Cyanobacteria were dominant in the spring sample taken from Loch of Aboyne, while Cryptophyta dominated the Milton Loch spring sample and green algae dominated in Woodhall Loch.

In summer, cyanobacteria dominated three water bodies (Mochrum Loch, Kilconquhar Loch and Dun's Dish), whilst cyanobacteria and diatoms were both prevalent in White Loch. Diatoms dominated in the summer sample from Woodhall Loch, green algae in Loch of Aboyne and a mixture of diatoms and Cryptophyta was present in Loch Spynie. The summer sample taken from Milton Loch decomposed despite being preserved in the usual way, and so phytoplankton data could not be obtained from this sample.

3.7.2 Zooplankton

Table 11 summarizes the spring and summer (growing season) dominant zooplankton groups found in each loch.

Table 11. Summary of the dominant zooplankton groups in spring and summer

Loch	Spring	Summer
White Loch	Rotifera	Copepoda
Mochrum Loch	Rotifera	Copepoda
Woodhall Loch	Rotifera	Copepoda and Cladocera
Milton Loch	Copepoda	Rotifera
Kilconquhar Loch	Rotifera	Rotifera
Dun's Dish	n/a	n/a
Loch of Aboyne	Rotifera	Cladocera
Loch Spynie	n/a	Rotifera

Zooplankton samples could not be obtained for all of the water bodies. Dun's Dish was too shallow to obtain any zooplankton samples, whilst a spring sample could not be obtained for Loch Spynie, as the wind was too strong at time of survey to allow a boat to be launched.

Rotifera were dominant in spring in five of the six lochs for which zooplankton samples could be obtained (White Loch, Mochrum Loch, Woodhall Loch, Kilconquhar Loch and Loch of Aboyne). Copepoda were dominant in spring in Milton Loch.

In summer, Copepoda were dominant in two lochs (White Loch and Mochrum Loch), Cladocera in one (Loch of Aboyne) and Rotifera in three lochs (Milton Loch, Kilconquhar

Loch and Loch Spynie). In Woodhall Loch, Copepoda and Cladocera were both abundant, and one group did not dominate the other.

3.8 Hydrometric data

None of the inflowing or outflowing rivers of the target loch catchments were gauged. Surrogate flows were estimated using data from the nearest gauged catchments with similar land use to the target catchments. Total annual flows were calculated for the gauged catchments and then corrected for catchment size and rainfall differences between the target catchments and the gauged catchments to produce surrogate flow estimates. Flow data and rainfall data were therefore required to carry out this exercise.

3.8.1 Flow data

The nearest gauged catchments with land uses similar to the target catchments were scaled for catchment size and rainfall differences to obtain surrogate flows (Smith, 1977). Data for gauged flows were downloaded from the National River Flow Archive (NRFA), which is managed by the Centre for Ecology and Hydrology (CEH). It receives, stores and queries historical flow data that have been provided by the Scottish Environment Protection Agency (SEPA) and the Environment Agency (EA). Only a subset of gauged rivers have long term data in a freely downloadable format from the NRFA, so this was a factor in deciding which gauged river should be used as a surrogate for each target sub-catchment.

In general, the gauged rivers had much larger catchments than the sub-catchments of the target lochs, but were similar in terms of land use. The gauged rivers used are described in Table 15.

Table 15. Locations of gauged rivers used for flow estimation in the target catchments

	Gauging Station	Distance to loch (km)	Grid reference	Catchment Area (km^2)
White Loch	Luce at Airyhemming	7	NX180599	171
Mochrum Loch	Luce at Airyhemming	13	NX180599	171
Woodhall Loch	Urr at Dalbeattie	16	NX821610	199
Milton Loch	Urr at Dalbeattie	10	NX821610	199
Kilconquhar Loch	Eden at Kemback	16	NO414157	307
Dun’s Dish	North Esk at Logiemill	5.5	NO699640	732
Loch of Aboyne	Dee at Park Head	25.5	NO798983	1844
Loch Spynie	Findhorn at Forres	23	NJ018583	782

Data were available in the form of one mean daily flow measurement per day from 1967 to 2008. The most recent 10 years of data were used to produce an estimate of 10-year average flows. The mean daily flow measurement was provided in cumecs ($m^3 s^{-1}$), so to arrive at a mean annual flow, each daily measurement was multiplied by 86400 (the number of seconds in a day), and the total flow for each day was summed to give a total for the year. The mean over the 10 years was then determined.

If water chemistry for the inflowing streams had been measured monthly for 2010, then it would be possible to estimate monthly flows for each target sub-catchment and so produce monthly flow-weighted concentrations of nutrients. Since chemistry was measured four times throughout the year, it was instead considered optimal to use these measurements to produce an annual mean concentration for each measured inflow.

The mean annual flow was then corrected for differences in catchment size and rainfall between the gauged catchments and the target catchments. Rainfall correction factors are shown in Table 13. Potential evapotranspiration (PET) (400 mm) was subtracted from all rainfall measurements before calculating the rainfall correction factors by dividing rainfall at each loch by rainfall at the relevant gauging station.

The 10-year mean annual discharges calculated for each target catchment and inflow are given in Appendix 4.

3.8.2 Rainfall data

Two types of rainfall data were available: monthly average rainfall for the period 1971-2000 and monthly rainfall for 2010. The former were used to produce the rainfall correction factors used to produce estimated surrogate flows (see above), whilst the latter were used to compare monthly rainfall during the survey year with the long term averages.

Monthly average rainfall 1971-2000

Average annual rainfall data for the relevant areas of Scotland were obtained from the Met Office website (http://www.metoffice.gov.uk/climate/uk/averages/) accessed on 28th November, 2010. Mean annual rainfall for the period 1971-2000, recorded at the nearest gauging station to each loch, was the primary measure used to estimate mean rainfall for the study sites. For the southern lochs, however, the nearest gauging station, Eskdalemuir, was located between 58 and 159 km away. Since rainfall patterns were likely to vary over this distance, a mean rainfall map for the same period produced by the Met Office was used to refine the mean rainfall estimates. The map used analyses that were based on 1 km grid point Met Office datasets and therefore could provide an estimate of mean rainfall closer to the location of each loch site. Comparisons between gauging stations and the map found that estimates from the northern gauging stations gave a good indication of actual rainfall levels at the northern loch sites, whilst the southern estimates had to be revised upwards to reflect mean rainfall at the southern sites more accurately. Since a range of rainfall levels was given by the map, the midpoint was used as the rainfall estimate for the appropriate southern site (see Tables 12 and 13).

Table 12. Annual mean rainfall (mm) recorded at the weather stations nearest the target loch sites for the period 1971 – 2000 and for 2010

Loch	Name of weather Station	Distance from loch (km)	Grid reference	Annual mean rainfall (mm) 1971 - 2000	Annual rainfall (mm) 2010
White Loch	Eskdalemuir	159	NX253987	1634.6	1562.9
Mochrum Loch	Eskdalemuir	130	NX253987	1634.6	1562.9
Woodhall Loch	Eskdalemuir	80	NX253987	1634.6	1562.9
Milton Loch	Eskdalemuir	58	NX253987	1634.6	1562.9
Kilconquhar Loch	Leuchars	26	NO455215	653.9	828.8
Dun’s Dish	Leuchars	44	NO455215	653.9	828.8
Loch of Aboyne	Braemar	39	NO145915	912.7	813.4
Loch Spynie	Kinloss	19	NJ065615	624.4	761.6

Table 13. Revised table showing annual mean rainfall figures estimated for the period 1971 – 2000

	Annual mean rainfall for loch (mm)	Annual mean rainfall for gauging station (mm)	Rainfall correction factor (after subtraction of PET)
White Loch	1125	1000	1.208
Mochrum Loch	1750	1000	2.250
Woodhall Loch	1750	1500	1.227
Milton Loch	1375	1500	0.886
Kilconquhar Loch	654	1000	0.423
Dun's Dish	816	1000	0.693
Loch of Aboyne	816	1000	0.693
Loch Spynie	624	1000	0.373

Monthly rainfall for 2010

Monthly rainfall data for 2010 were also available from the Met Office for each of the relevant weather stations except Kinloss (see Table 14). These 2010 data were compared with the long-term average data for the period 1971-2000 shown above (Figure 36). As figures were not available for Kinloss, Nairn weather station was used as the nearest alternative, at 30 km from Loch Spynie (compared to Kinloss at 19 km). Note that rainfall data for November and December 2010 were not available at the time of writing this report, so rainfall figures from November and December 2009 were used for estimating annual nutrient loadings from 2010 rainfall.

Table 14. Monthly rainfall (mm) for 2010 at the four weather stations

Month	Eskdalemuir	Leuchars	Braemar	Nairn
January	71.3	53.4	60.2	32.3
February	48.8	54.7	15.6	53.7
March	150.2	62.6	38.2	37.5
April	74.6	28.8	50.8	43.0
May	36.6	59.2	26.6	42.4
June	32.8	20.8	43.4	34.6
July	249.0	124.2	93.0	104.7
August	95.8	44.6	81.0	79.3
September	151.6	114.2	118.6	105.8
October	108.6	57.6	86.2	46.2
November (2009)	431.6	139.8	169.8	74.6
December (2009)	112.0	68.9	30.0	107.5

Comparing rainfall in 2010 with the long term average

To determine if 2010 was wetter or drier than the long-term average, long-term mean and monthly rainfall figures for 2010 were plotted on column/line charts (see Figure 36).

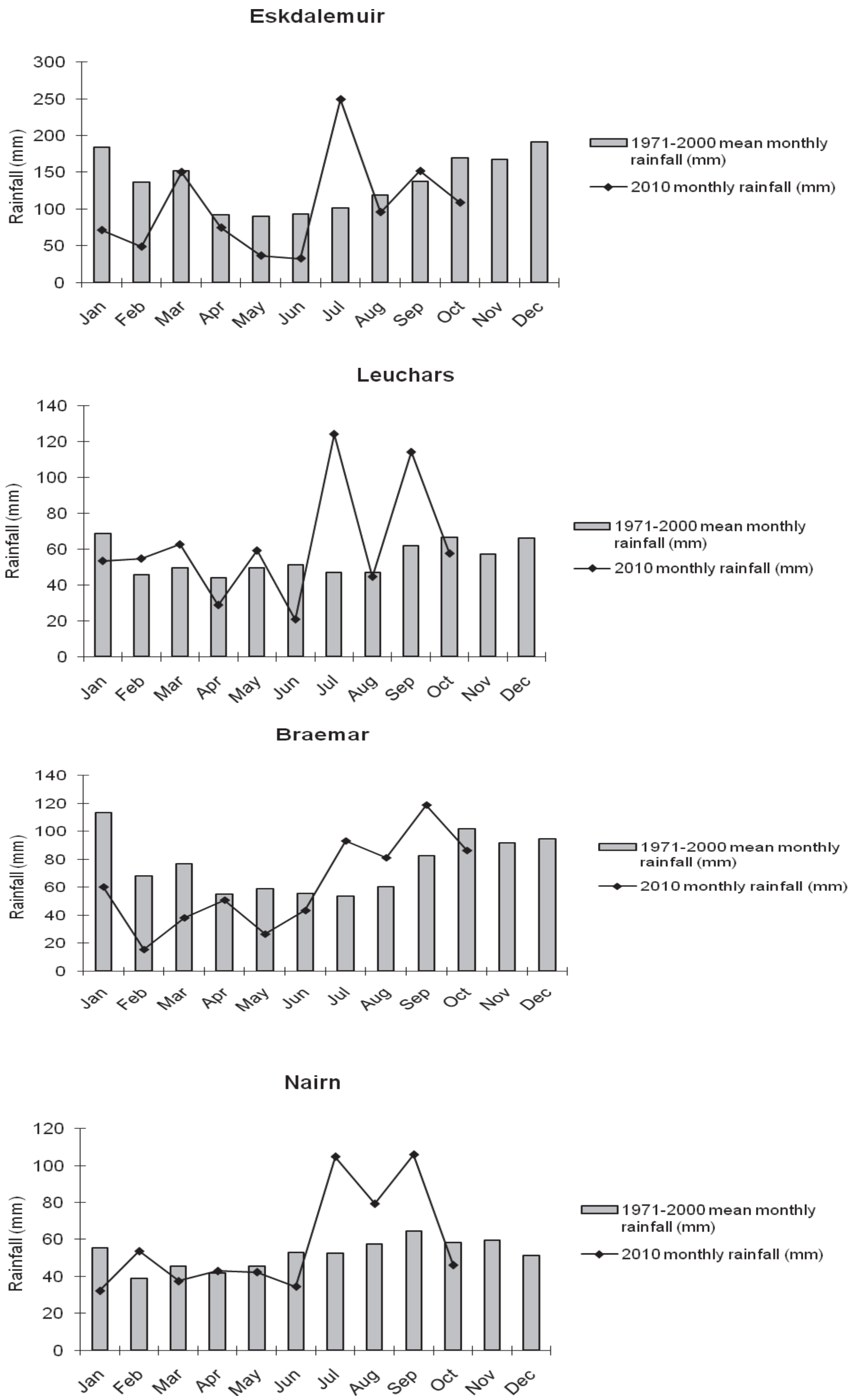


Figure 36. Long term average rainfall and mean monthly rainfall for 2010

At Eskdalemuir, which is the weather station closest to the four southern lochs, rainfall in the first half of the year was similar to the long term average, but the summer was wetter than normal. For the remaining stations, both the summer and the late summer were wetter than usual. Higher than average rainfall has the potential to increase the rates of nutrient and particulate export from land to the receiving water bodies, but also to increase dilution and flushing rates in the lochs.

3.9 Nutrient budgeting exercise

3.9.1 Desk-based nutrient budget

Delineation of loch catchment boundaries

Catchment boundaries were delineated for each water body using a DTM within ArcGIS (spatial analyst). The watersheds for each of the lochs are shown on Ordnance Survey backgrounds in Figures 3 - 10, illustrating the extent and character of each catchment area. The results of the DTM modelling were ground-truthed by close examination of OS maps and several estimated catchment boundaries were refined manually to improve accuracy. Table 16 details the calculated areas for each drainage basin and sub-catchment.

Land use classification

LCM2000 data (© NERC (CEH) 2000) were used to produce catchment land use maps (Figures 37 – 44). Using these maps, the total area of each LCM2000 land use type within each catchment and sub-catchment was calculated. Definitions of land use types obtained from the Centre for Ecology and Hydrology (CEH) are shown in Table 17 and further details are available in Jackson (2000). Figures 45 – 52 show the top five land use types by area for each loch catchment.

Table 16. Areas of each sub-catchment (m^2) and catchments in total

Loch	Inflow	Area (m^2)
White	Total	1929800
Mochrum	Total	10532035
	1	5995681
	2	1236998
	3	151488
	4	64489
Woodhall	Total	25844026
	1	997848
	2	519490
	3	105965
	4	630594
	5	19228430
	6	1361084
Milton	Total	3658632
	1	137147
	2	972865
	3	695625
	4	102880
Kilconquhar	Total	1280000
Dun's Dish	Total	1133500
	1	895199
Aboyne	Total	2687142
	1	1233346
	2	583466
	3	127834
Spynie	Total	6688100
	1	6137819

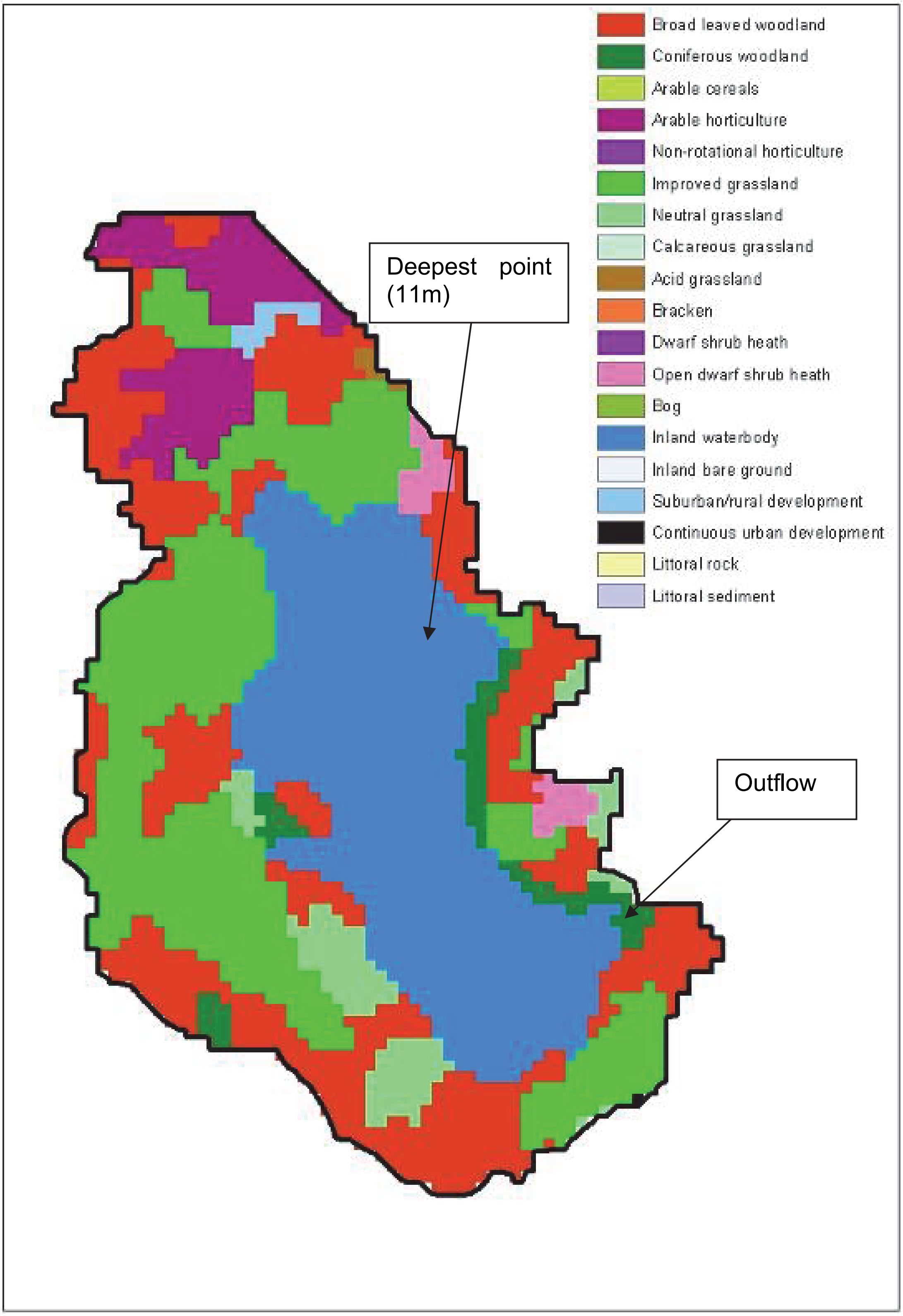


Figure 37. White Loch catchment area with LCM land use parcels (LCM2000 © NERC (CEH) 2000)

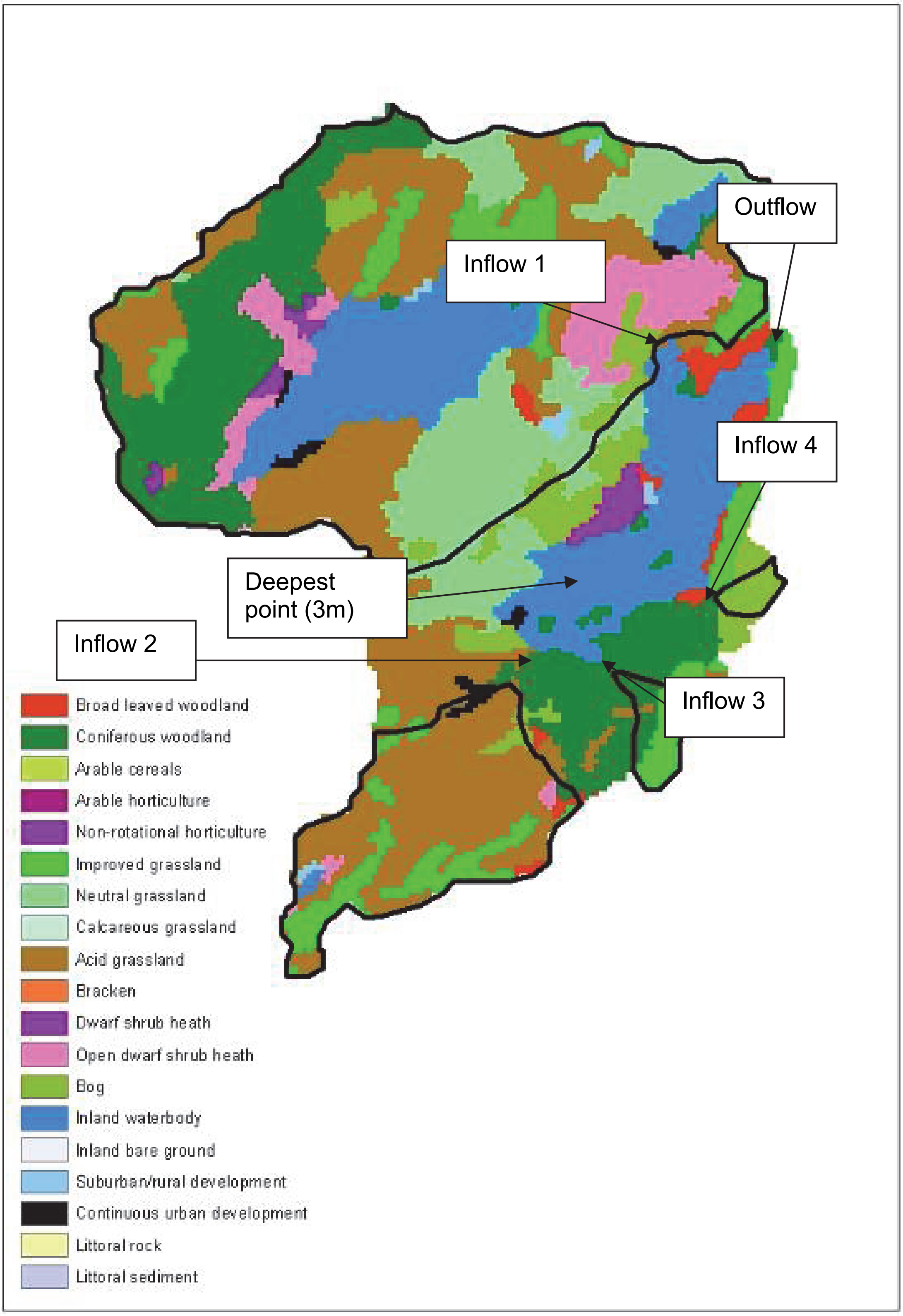


Figure 38. Mochrum Loch catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

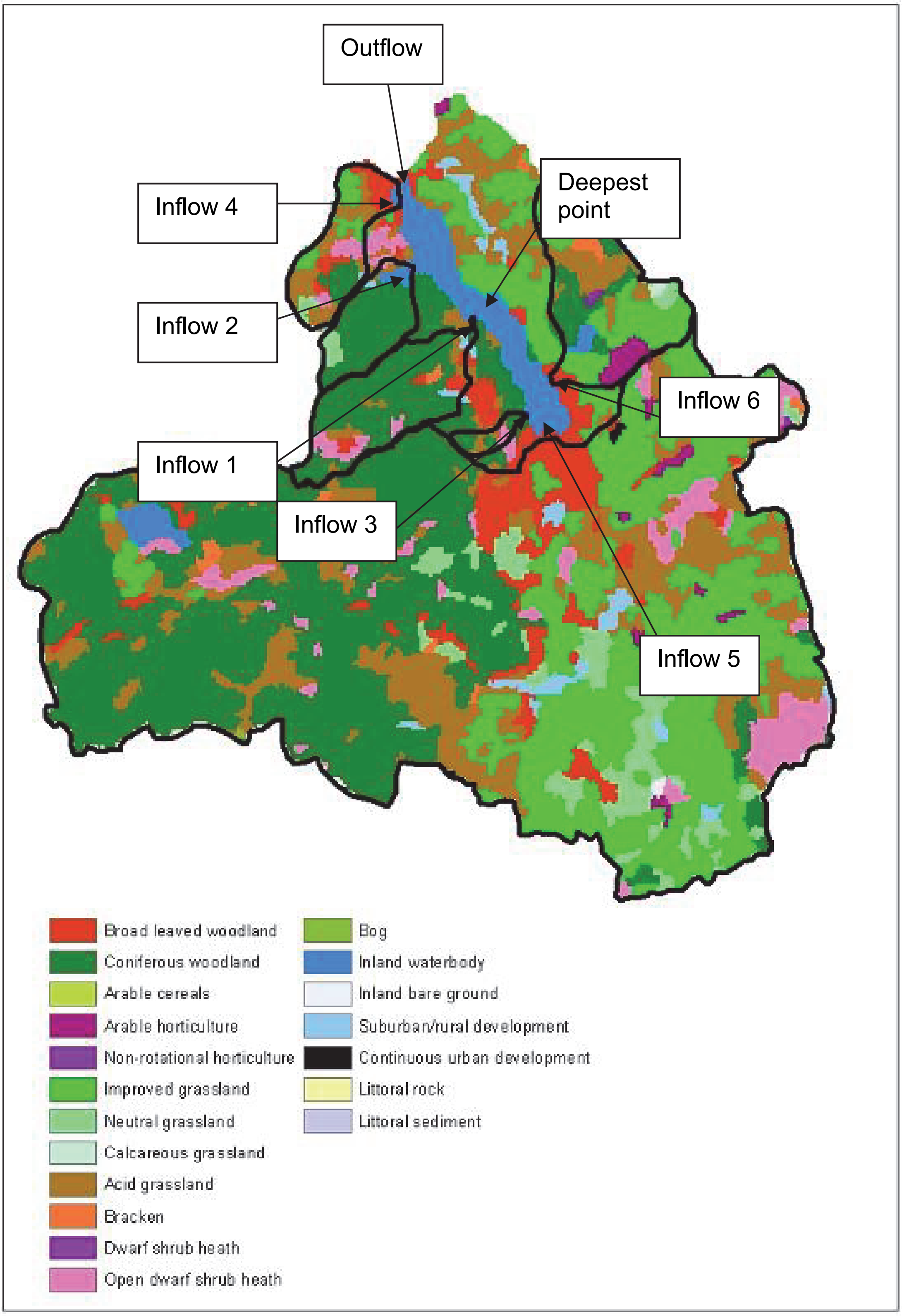


Figure 39. Woodhall Loch catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

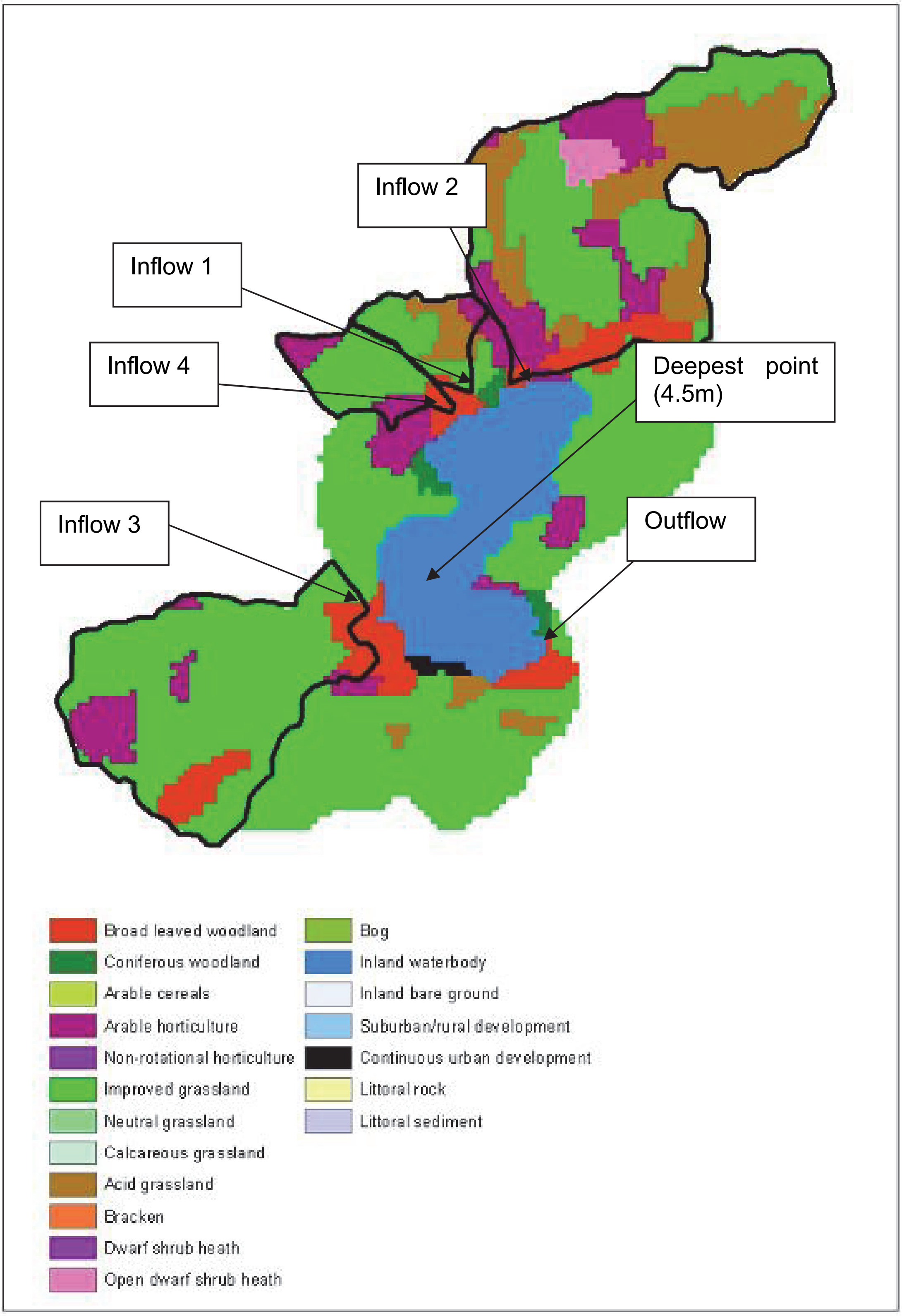


Figure 40. Milton Loch catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

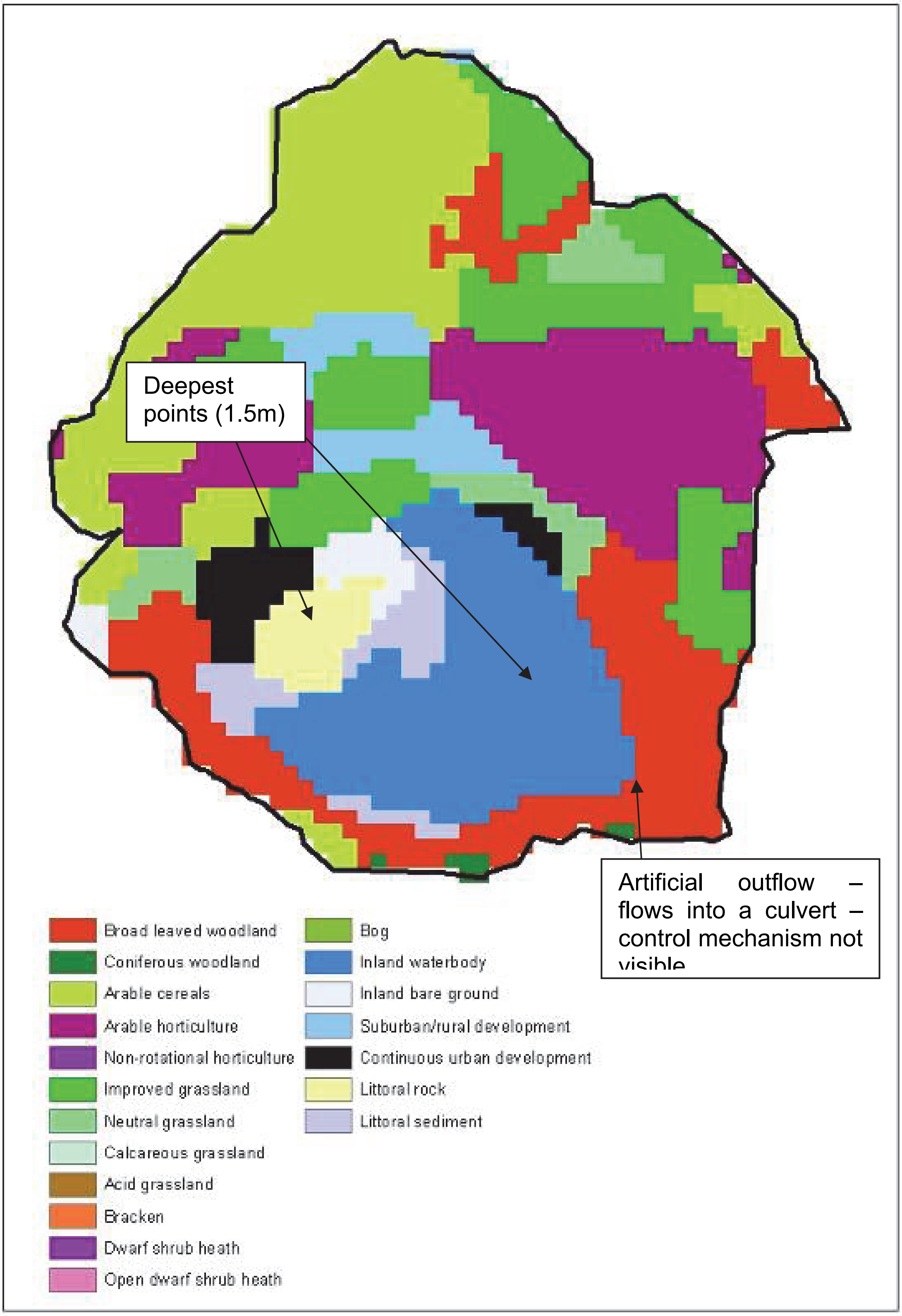


Figure 41. Kilconquhar Loch catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

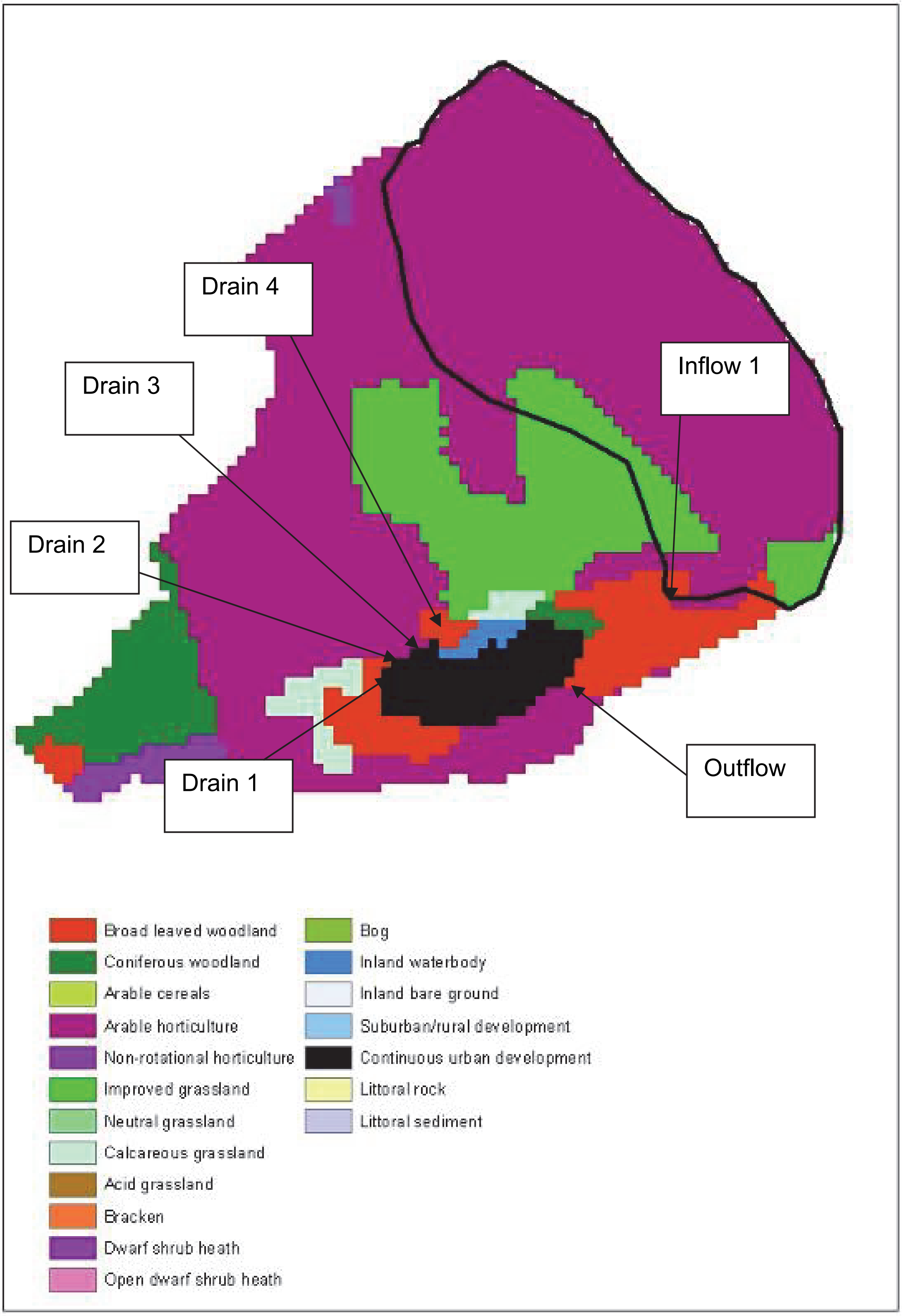


Figure 42. Dun's Dish catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

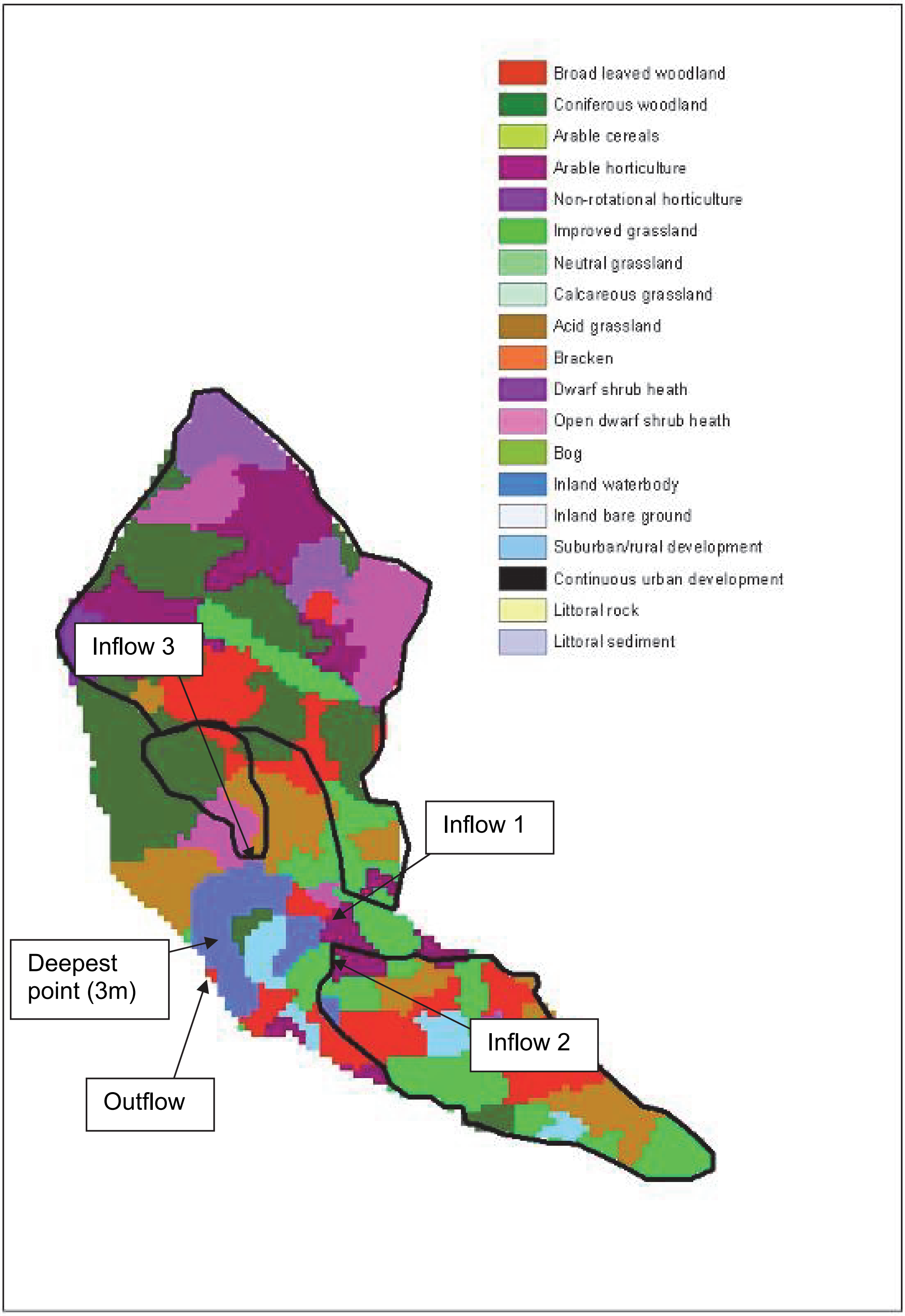


Figure 43. Loch of Aboyne catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

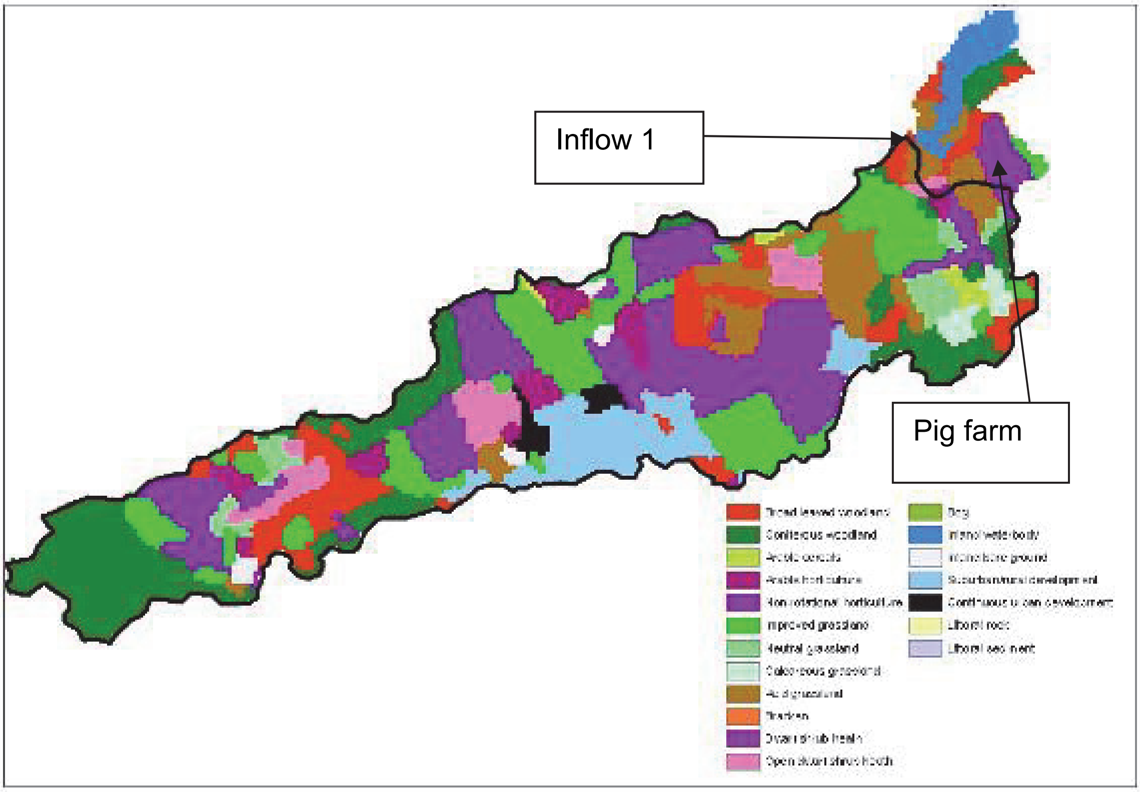


Figure 44. Loch Spynie catchment area and LCM land use parcels (LCM2000 © NERC (CEH) 2000)

Table 17. Broad Habitats and their distinction in LCM2000 (LCM2000 © NERC (CEH) 2000)

Land use type	Definition
Broad-leaved, mixed and yew woodland	Broad-leaved woodland in stands > 5 m high with tree-cover > 20%; or scrub < 5 m, with cover > 30%. Mixed woodland is included if broad-leaved trees in conifers cover > 20%. Stands ≥ 0.5 ha are mapped as separate blocks.
Coniferous woodland	Coniferous woodland, semi-natural and plantations, with cover > 20%, and recently felled forestry. Once felled areas are colonised by rough grass, heath or scrub they take one of these classes.
Arable and horticulture	Annual crops, recent leys, freshly ploughed land, rotational set-aside, and perennial crops such as berries and orchards. Once set-aside is substantially vegetated with weeds or rough grass, it is included in the Improved grassland Habitat.
Improved grassland	Improved grasslands in swards dominated by agriculturally 'preferred' species, generally 'improved' by reseeding and/or fertiliser treatment. May be used for agriculture or amenity. Fertile pastures with *J. effusus* are included. Set-aside grass is included, but where possible, distinguished at the subclass level; abandoned or little-managed Improved grasslands may be confused with semi-natural swards.
Neutral grassland, calcareous grassland and acid grassland	Acid, neutral and calcareous semi-natural swards are generally not reseeded or treated with fertilizer; they are dominated by lower productivity grasses, perhaps with many herbs. Grassland management may obscure distinctions from Improved grassland. Neutral, calcareous and acid components are distinguished at subclass level using a soil 'acid sensitivity' map. Pastures with *J. effusus* and with semi-natural spectral characteristics are included with acid swards.
Bracken	The bracken habitat is, at the height of the growing season, dominated by *Pteridium aquilinum.* Where images pre-date the late growing season, or where stands are dissected, bracken may be missed.
Dwarf shrub heath	Ericaceous species and gorse forming > 25% of plant cover; open and dense heaths are divided at subclass level. The Habitat includes wet and dry categories but ericaceous vegetation on peat ≥ 0.5 m deep is recorded as 'bog'. In contrast, LCMGB 1990 used a definition based on presence of seasonal standing water.
Bog	Bogs include ericaceous, herbaceous and mossy vegetation in areas with peat >0.5 m deep; ericaceous bogs are distinguished at subclass level. Inclusion of Ericaceous bogs contrasts with LCMGB 1990 where bogs were herbaceous or mossy in seasonal standing water.

Standing open water and canals, rivers and streams	Water bodies ≥ 0.5 ha are mapped, but only the wider canals and rivers (>50 m) are shown. LCM2000 does not distinguish standing from flowing water
Built-up areas and gardens	Urban land, rural development, roads, railways, waste and derelict ground, including vegetated wasteland, gardens and urban trees. In LCM200, all larger areas of vegetation (≥ 0.5 ha) are identified as the appropriate cover class. Continuous urban and discontinuous suburban cover are distinguished at subclass level.

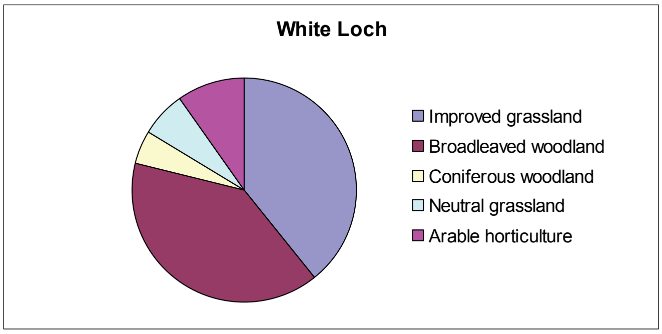


Figure 45. White Loch land use (68% of total catchment)

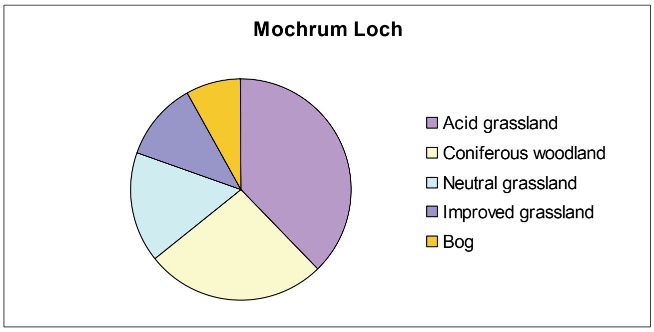


Figure 46. Mochrum Loch land use (73% of total catchment)

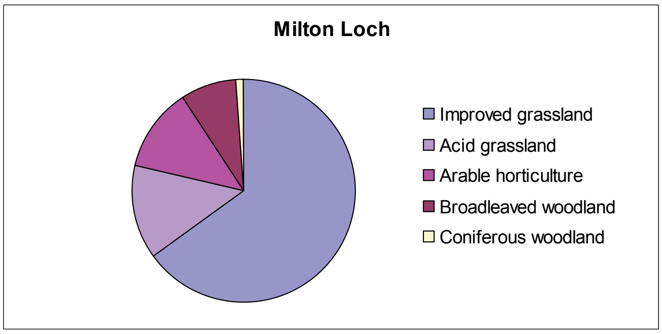


Figure 47. Milton Loch land use (86% of total catchment)

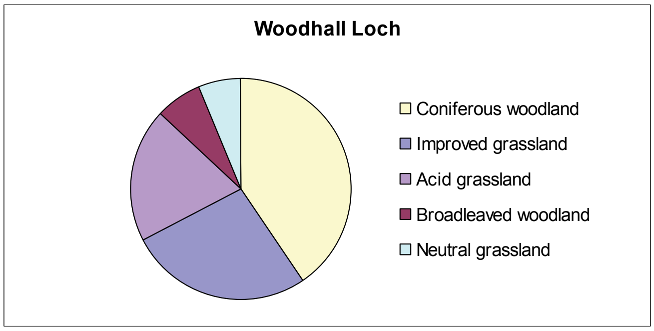


Figure 48. Woodhall Loch land use (89% of total catchment)

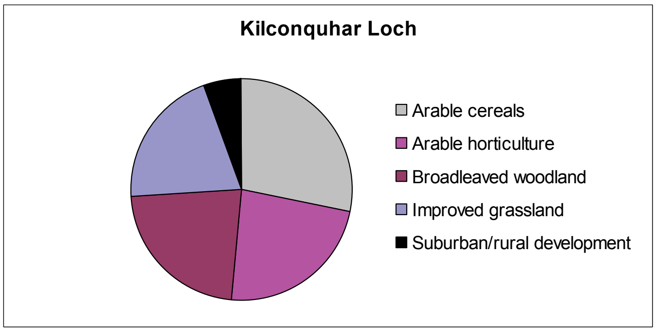


Figure 49. Kilconquhar Loch land use (71% of total catchment)

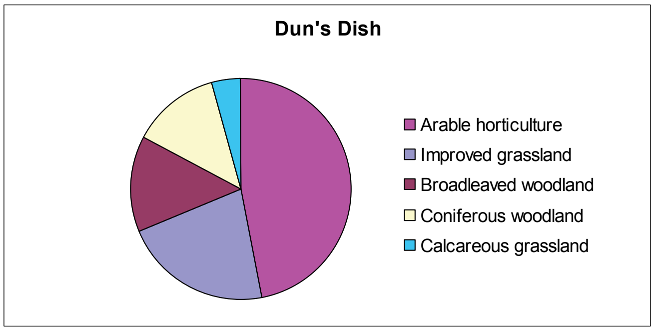


Figure 50. Dun's Dish land use (88% of total catchment)

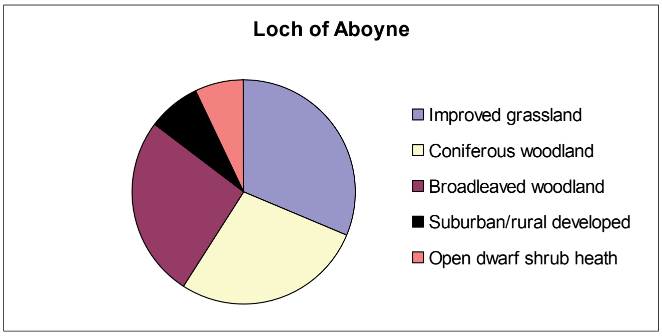


Figure 51. Loch of Aboyne land use (64% of total catchment)

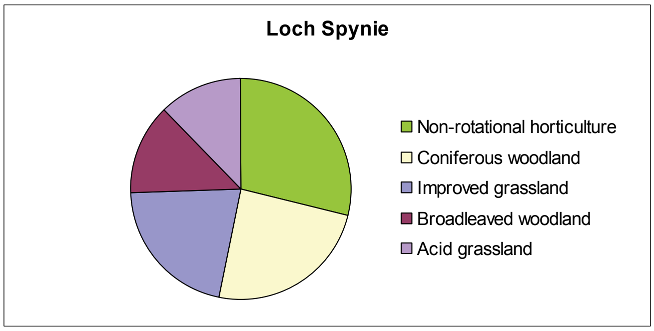


Figure 52. Loch Spynie land use (74% of total catchment)

Figures 45 to 52 show the top five land uses by area for each loch catchment (with percentage of catchment represented in the top five shown in brackets)

3.9.2 Nutrient loadings based on export coefficients

PLUS export coefficients for each type of land use were used to calculate the total theoretical loss rates of P from each land use type within each catchment. This was done by measuring the total area of each land use type within each catchment and sub-catchment using ArcGIS and LCM2000 data, and multiplying the total area by the associated export coefficient for that land use type. This produced the total amount of P export expected from each land use type in one year (expressed as tonnes). The resulting P loadings are shown in Table 18.

3.9.3 Nutrient loadings based on inflow concentrations

For comparison with P loadings modelled using export coefficients, data collected during the present project were also used to calculate P loadings from each catchment and sub-catchment. These were based on measured mean TP concentrations in the inflowing streams and estimates of flow based on gauged flows in similar catchments, but corrected for differences in catchment size and rainfall, as well as taking PET into account. This was the best method of flow estimation available in the absence of any gauged rivers in the target catchments.

The P loadings based on inflow concentrations could only be calculated for the areas of each loch catchment drained by inflowing streams. Across the eight target lochs, the proportions of the catchments drained by inflowing streams ranged from 52% to 92% (see Table 19). The remaining areas drain directly into the lochs via surface run-off. In order to produce P loadings that accounted for 100% of each catchment, each loading was scaled up to 100%; for example, if only 50% of the catchment was drained by surface inflows, the P loading would be multiplied by 2. The drawback of using this method is that it assumes equivalent P loadings for measured and unmeasured areas of the catchment which cannot be confirmed. However, it is the only method possible using the available data and so has been used despite this drawback.

Table 18. Total annual loadings (tonnes) of P from each land use type within each catchment (derived from PLUS model P export coefficients)

Land use	White Loch	Mochrum Loch	Woodhall Loch	Milton Loch	Kilconquhar Loch	Dun's Dish	Loch of Aboyne	Loch Spynie
Improved grassland	0.0242	0.0372	0.3373	0.0951	0.0087	0.0102	0.0117	0.0497
Inland waterbody	0.0076	0.0240	0.0119	0.0064	0.0029	0.0014	0.0019	0.0023
Broadleaved woodland	0.0113	0.0040	0.0413	0.0055	0.0044	0.0030	0.0045	0.0141
Coniferous woodland	0.0009	0.0261	0.1584	0.0005	0.0001	0.0019	0.0032	0.0171
Open dwarf shrub heath	0.0003	0.0030	0.0116	0.0003			0.0005	0.0026
Dwarf shrub heath		0.0012	0.0002				0.0001	0.0008
Neutral grassland	0.0008	0.0100	0.0145		0.0004			0.0015
Acid grassland	0.0000	0.0231	0.0471	0.0038			0.0021	0.0054
Calcareous grassland			0.0001			0.0004		0.0007
Non-rotational horticulture						0.0060		0.2226
Arable horticulture	0.0202		0.0391	0.0595	0.0330	0.0731	0.0080	0.0426
Arable cereals					0.0402			0.0089
Suburban/rural development	0.0024	0.0083	0.0816		0.0107		0.0132	0.1017
Continuous urban development	0.0001	0.0128	0.0028	0.0025	0.0076			0.0164
Bog		0.0016	0.0000					
Bracken			0.0028					
Inland bare ground			0.0001		0.0001			0.0004
Total export for entire catchment	**0.0678**	**0.1514**	**0.7489**	**0.1735**	**0.1081**	**0.0959**	**0.0453**	**0.4869**

Table 19. Annual loadings (tonnes) of P and N fractions from each sub-catchment based on annual mean measured inflow concentrations and rainfall corrected gauged flows

Sub-catchment	TP	TSP	SRP	NO_2-N	NH_4-N
Mochrum 1	0.502	0.348	0.158	0.093	1.561
2	0.105	0.041	0.022	0.022	0.319
3	0.036	0.018	0.011	0.002	0.041
4	0.006	0.004	0.002	0.001	0.018
Total sub-catchments (71%)	0.649				
Entire catchment	**0.914**				
Woodhall 1	0.021	0.016	0.008	0.007	0.146
2	0.020	0.017	0.008	0.005	0.078
3	0.004	0.003	0.001	0.001	0.004
4	0.040	0.031	0.025	0.008	0.034
5	0.890	0.593	0.326	0.266	1.118
6	0.091	0.069	0.050	0.024	0.349
Total sub-catchments (88%)	1.006				
Entire catchment	**1.211**				
Milton 1	0.013	0.011	0.008	0.002	0.021
2	0.053	0.030	0.016	0.045	0.197
3	0.030	0.014	0.010	0.009	0.058
4	0.002	0.002	0.002	0.004	0.029
Total sub-catchments (52%)	0.098				
Entire catchment	**0.189**				
Dun's Dish 1	0.038	0.030	0.020	0.007	0.056
Total sub-catchments (79%)	0.038				
Entire catchment	**0.048**				
Aboyne 1	0.012	0.007	0.004	0.003	0.012
2	0.013	0.005	0.002	0.007	0.084
3	0.002	0.001	0.001	0.000	0.002
Total sub-catchments (72%)	0.027				
Entire catchment	**0.038**				
Spynie 1	0.131	0.082	0.054	0.041	0.299
Total sub-catchments (92%)	0.131				
Entire catchment	**0.142**				

Table 20. Comparison of annual external P loadings derived from P export coefficients and from measured inflow P concentrations

	P loading derived from P export coefficients (tonnes)	P loading based on annual mean measured TP concentrations in the inflows (tonnes)
White Loch	0.068	No surface inflows to measure
Mochrum Loch	0.167	0.914
Woodhall Loch	0.738	1.212
Milton Loch	0.185	0.188
Kilconquhar Loch	0.108	No surface inflows to measure
Dun's Dish	0.162	0.048
Loch of Aboyne	0.124	0.038
Loch Spynie	0.508	0.142

3.10 Limnological modelling

3.10.1 Drainage ratio, loch hydraulic loading and water retention time

Drainage ratios, loch hydraulic loadings and water retention times required for P modelling were estimated from mean annual rainfall data using the statistics shown in Table 21.

Table 21. Limnological measures used to calculate hydraulic loading and water retention time for each water body

	Catchment area (m^2) (modelled)	Lake surface area (m^2) (modelled)	Lake volume (m^3) Murray and Pullar (1910)	Annual mean PET-corrected rainfall (m)	Annual inflow volume (m^3)
White Loch	1929800	565000	2605150	0.725	1399105
Mochrum Loch	9353900	1781000	1925546	1.35	12627765
Woodhall Loch	30066900	879000	4077626	1.35	40590315
Milton Loch	3631300	476000	1274258	0.975	3540518
Kilconquhar Loch	1280000	193000	453070	0.254	325120
Dun's Dish	1133500	104000	26000*	0.416	471536
Loch of Aboyne	1240000	144000	283169	0.416	515840
Loch Spynie	6688100	173000	198218	0.224	1498134

*Dun's Dish volume estimated from current modelled surface area and mean depth from Recorda Cos (2006)

Note that in Table 21, lake area has been modelled from current GIS data, whilst values for lake volume are those presented in Murray & Pullar (1910). Ideally, a bathymetric survey would have been carried out of each loch in the present study. This would have allowed calculation of volume. However, the additional time required to carry out bathymetric surveys was not available. In addition, it would not have been possible to survey several of the lochs in this way, due to their shallow nature, and lack of satellite coverage would have been an issue, satellite coverage being necessary for present-day bathymetric survey methods.

Loch areas given in Murray and Pullar (1910) were compared with those obtained from GIS modelling of current map data. Five of the lochs appear to have decreased in area, two have increased in area and no historical data were available for the eighth (Dun's Dish). White Loch now appears to be 6.3% smaller; Woodhall Loch, 29.3% larger; Mochrum Loch 91.5% larger; Milton Loch 23.1% smaller; Kilconquhar Loch, 49.9% smaller; Loch of Aboyne, 6.5%

smaller and Loch Spynie 28.8% smaller. In Woodhall Loch, Mochrum Loch, Kilconquhar Loch and Loch Spynie, the large apparent change in area may have been influenced to an appreciable extent by the thick fringes of reedswamp which fluctuate and may or may not have been included in the historical measurements. The result is a wide range of variation in areal change across the lochs (6.3% to 91.5%) that may reflect differences in current volume when compared with the volumes reported by Murray and Pullar (1910). However, since the fringes of the lochs are all very shallow, a change in area does not necessarily reflect a change in volume of the same magnitude. Indeed, the change in volume is likely to be much smaller than any change in area. The use of historical volumes in conjunction with current measured areas is undoubtedly not ideal; however, it is argued that in the absence of current measured volumes, it is acceptable to use the historical volumes, provided that the additional error this could introduce to the model is borne in mind.

3.10.2 Drainage ratio

The drainage ratio (DR) is the ratio of catchment area to lake surface area and gives an idea of the effect of catchment size on nutrient loading. A high DR indicates a catchment that is large compared to loch size and therefore likely to export a relatively large amount of terrestrial nutrients. The proportion of N and P obtained from land (as opposed to atmospheric inputs) increases with increasing drainage ratio. Lochs with a high DR may therefore be more sensitive to land use activities within the drainage basin. A small DR implies that there is a relatively small area of land in the catchment area to receive precipitation and nutrients, so a loch with a small DR may be subject to lower nutrient loadings. However, whether DR is high or low, the effects of nutrient loadings on the ecology of the receiving waters are dependent upon water retention time (WRT).

3.10.3 Water retention time

WRT is the average time required to completely fill the basin of a loch with water. The WRT, and its reciprocal measure, the flushing rate, are important variables in limnology. Water entering a loch contains nutrients, organic matter and contaminants, so WRT may be considered indicative of nutrient supply, nutrient retention, the productivity of a system and the time available for algae to grow before being removed from the system. Generally, the larger the basin of the loch, the longer it retains water, but the larger the catchment area, the more rapidly water is flushed from the loch.

Lochs with a long WRT are associated with lower water and nutrient loadings from the catchment area, which may lead to less allochthonous enrichment. Such water bodies receive relatively more of their water and nutrients from the atmosphere, so may be prone to acidification. However, a long WRT may exacerbate the effects of enrichment, as it allows more time for particulate matter to settle and for retention of nutrients in the sediment, in addition to oxidisation by microbes. Large lochs may have long WRTs. However, small lochs with small catchments may also have long WRTs. Where the latter is the case, the impact of lower nutrient loadings may be significant due to limited dilution capacity.

A short WRT indicates rapid flushing, which may result in higher organic and inorganic nutrient inputs in total over time. Lochs with short WRTs are also more sensitive to variation in run-off from their relatively large catchments. Although phytoplankton productivity would be expected to increase with increasing nutrient loadings, if flushing rate is high (and WRT low), there is a greater capacity for dilution of nutrient concentrations and for algal cells to be transported from the system. When flushing rate exceeds phytoplankton growth rate, diversity and biomass of phytoplankton decrease. In water bodies receiving high nutrient loadings, this process improves the carrying capacity of the loch. In conclusion, the effects of DR and WRT are site-specific.

WRT is calculated using the following equation:

$$T_W = Vol_{loch} / Vol_{inflow}$$

T_W - lake water retention time (y)
Vol_{loch} - volume of the loch (m^3)
Vol_{inflow} - volume of water flowing into the loch in a year (m^3)

3.10.4 Loch hydraulic loading

The hydraulic loading (q) is coupled to WRT, as it is a surrogate for the volume of water entering a loch annually and therefore affects the quantity of nutrients and organic matter being received. It is a conceptual measurement that can best be described as the depth of water that would be stacked evenly on the surface of a loch annually if the entire volume from inflows and direct precipitation could be placed in this way.

Loch hydraulic loading is calculated using the following equation:

$$q = Vol_{inflow} / A$$

q - hydraulic loading (m yr^{-1})
Vol_{inflow} - the volume of water flowing into the loch in a year (m^3)
A - surface area of the loch (m^2)

Table 22 shows the DR, hydraulic loading and WRT (Tw (Vollenweider, 1976)) for each loch. These measures are based on the rainfall estimates shown in Table 13, and take into account a standardized PET of 400 mm.

Table 22. Drainage ratio, hydraulic loading (q) and water retention time (T_W) for each loch

	Drainage ratio (CA:LA)	q (m yr^{-1})	T_W (y)
White Loch	3.42	4.61	1.86
Mochrum Loch	5.25	1.08	0.15
Woodhall Loch	34.21	4.64	0.10
Milton Loch	7.63	2.68	0.36
Kilconquhar Loch	6.63	2.35	1.39
Dun’s Dish	10.90	0.25	0.06
Loch of Aboyne	8.61	1.97	0.55
Loch Spynie	38.66	1.15	0.13

The two lochs with catchments so small that they did not contain surface inflows, i.e. White Loch and Kilconquhar Loch, had the longest WRTs and the lowest flushing rates, as they had water inputs from direct precipitation only. These hydrometric variables, together with measured inflow P concentrations were used to predict in-loch TP concentrations using the model shown in Plate 1 (equation 1). The resulting predicted TP concentrations for all of the lochs are shown in Table 23 which also shows the annual mean measured water column TP concentrations.

Table 23. Predicted water column TP concentrations based on the Vollenweider P loading model (Plate 1, equation 1) (Vollenweider, 1976) and annual mean measured water column TP concentrations

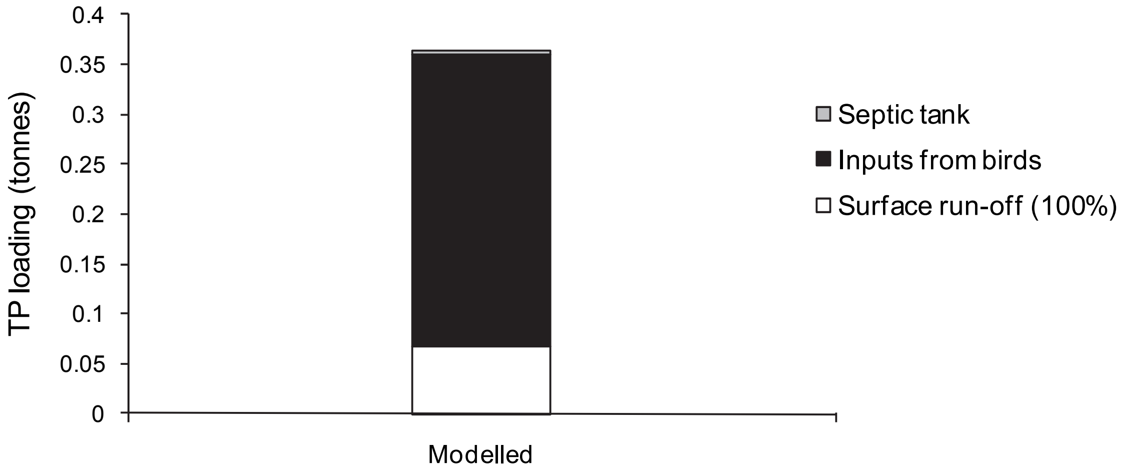
	Predicted loch TP concentration (µg P L^{-1})	Annual mean measured TP concentration (µg P L^{-1})
White Loch	42	62
Mochrum Loch	24	37
Woodhall Loch	5	25
Milton Loch	47	87
Kilconquhar Loch	143	169
Dun's Dish	1188	332
Loch of Aboyne	45	44
Loch Spynie	118	65

3.10.5 Nutrient Budgets

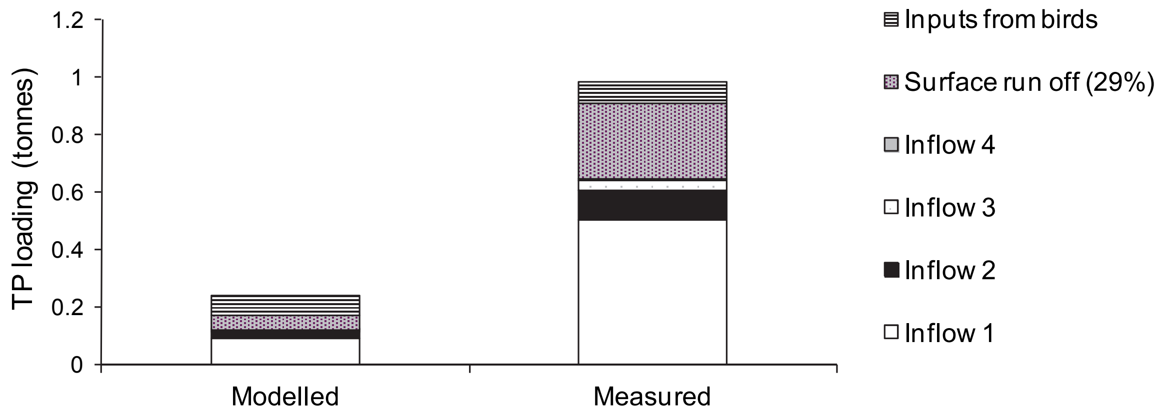
For comparison, budgets were modelled using land use information and export coefficients, as well as being estimated from measured concentrations of nutrients in inflows. The contributions of each sub-catchment and other direct nutrient sources to the total amount of P entering the lochs are shown in the budgets in Figure 53, as are those estimated from land use and nutrient export coefficients. For budgets calculated from results of monitoring of inflow waters, surface run-off and nutrient loading were derived by scaling the area covered by inflows up to 100% of the catchment. Bird inputs based on estimated number of birds (provided by SNH) were added to both the budgets modelled from loss coefficients and the budgets estimated from nutrient concentrations in the inflow waters. In the budgets estimated from nutrient concentrations, only two septic tanks were located that were not already accounted for by seeping into the inflowing streams. These were at White Loch, which does not have any surface inflows and at Dun's Dish, where a septic tank lies outside the area accounted for by the inflowing stream, and were added to the budgets estimated from nutrient concentrations. For the budgets modelled from loss coefficients, septic tanks within each inflowing sub-catchment had to be added as they were not already accounted for in the loss coefficients. It was estimated that there was one septic tank within the catchment area of Inflow 1 of Mochrum Loch; eight in Inflow 5 and two in Inflow 4 of Woodhall Loch; one in Inflow 3 and one in Inflow 2 of Milton Loch; two in Inflow 1 of Loch of Aboyne and 22 in Inflow 1 of Loch Spynie. These were all added to the loss coefficient budgets.

Nutrient budgets showing the contribution of each land use type in each catchment and based on the P export coefficients from the PLUS model are shown in Figures 54 (the southern lochs) and 55 (the northern lochs).

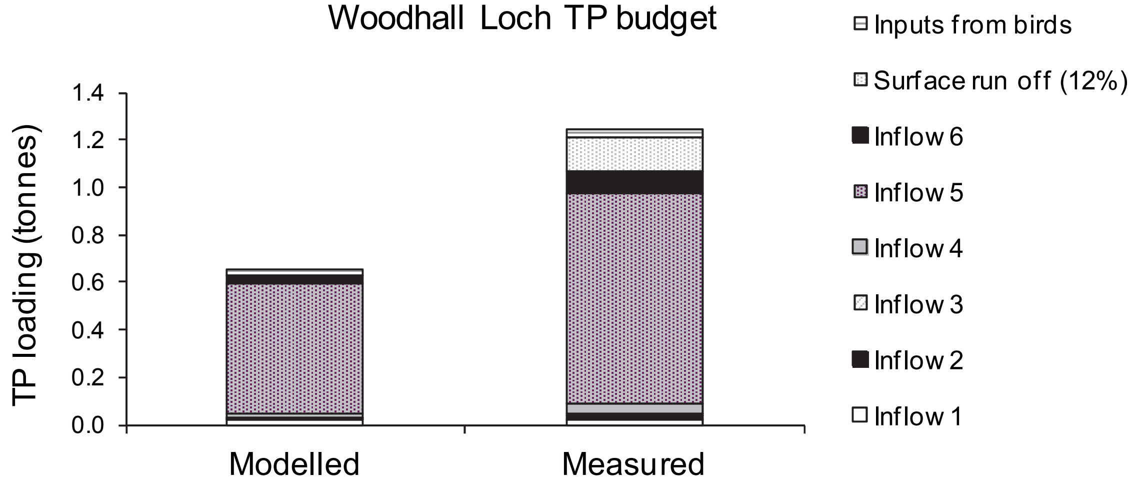
White Loch TP budget

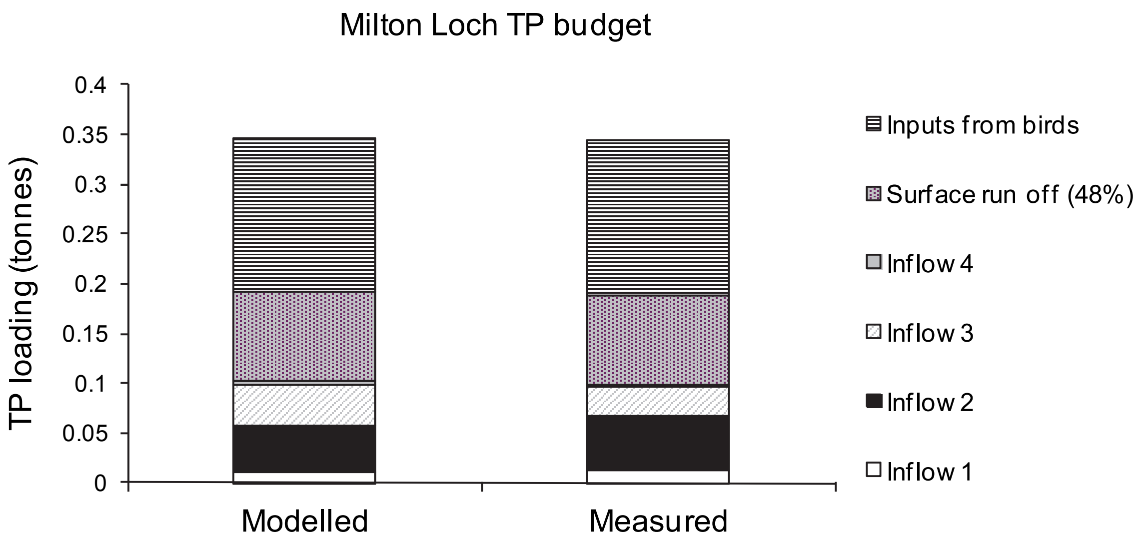


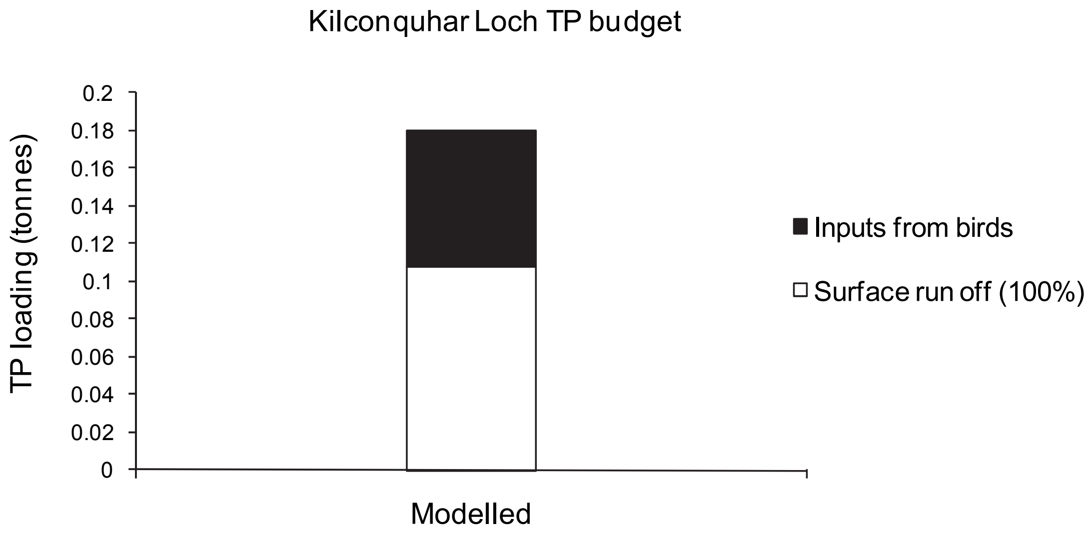
Mochrum Loch TP budget

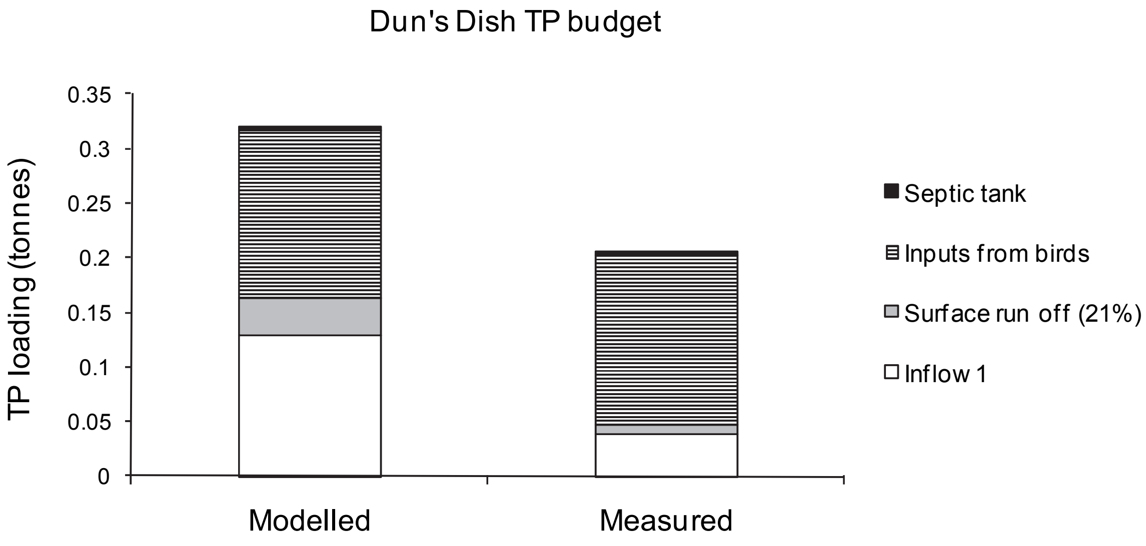


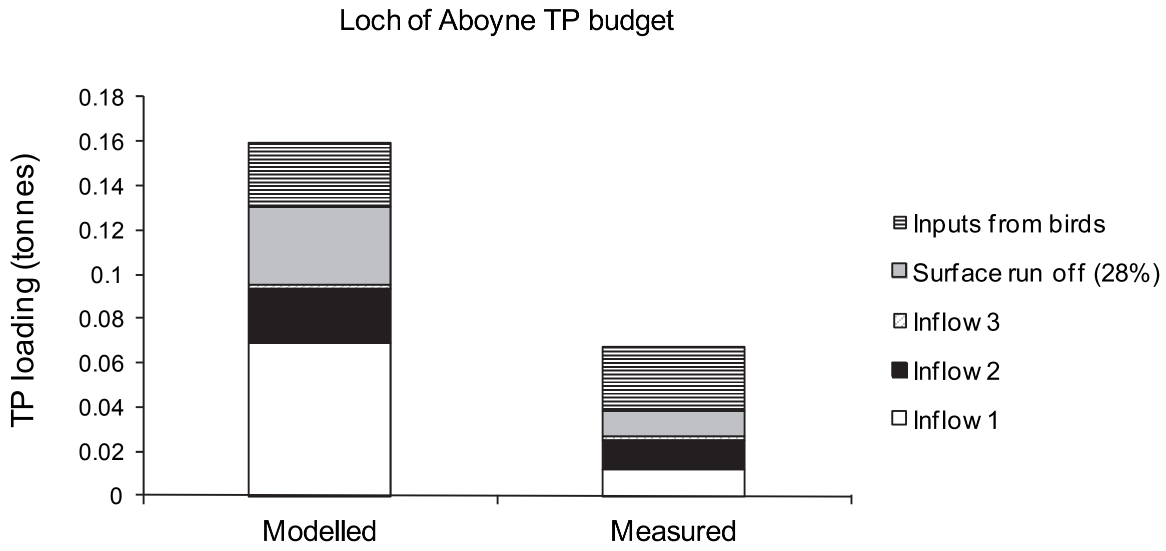
Woodhall Loch TP budget

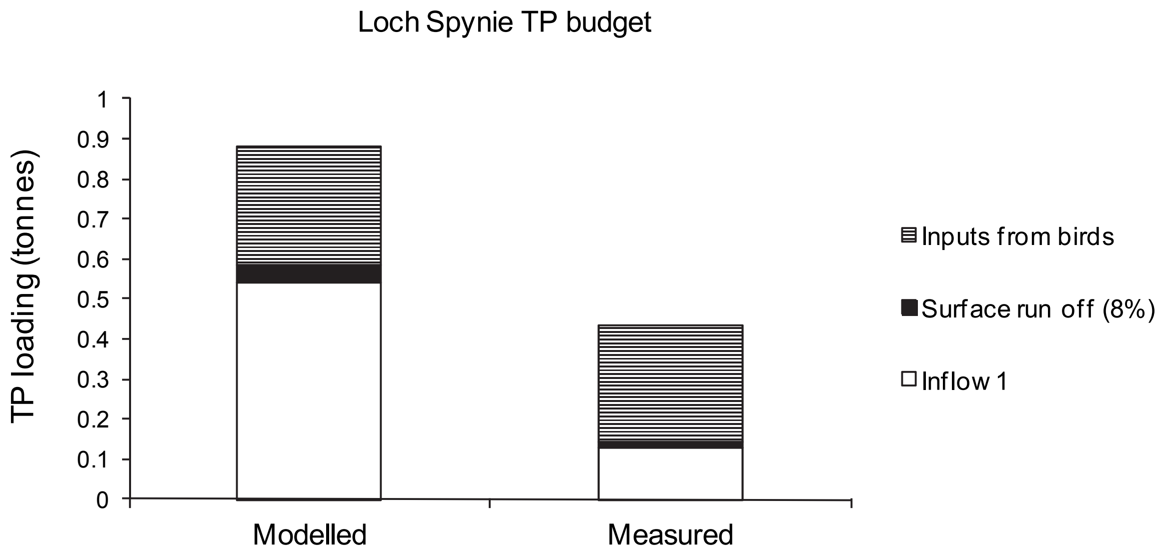



Milton Loch TP budget
TP loading (tonnes)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Modelled
Measured
Inputs from birds
Surface run off (48%)
Inflow 4
Inflow 3
Inflow 2
Inflow 1


Kilconquhar Loch TP budget
TP loading (tonnes)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Modelled
Inputs from birds
Surface run off (100%)


Dun's Dish TP budget
TP loading (tonnes)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Modelled
Measured
Septic tank
Inputs from birds
Surface run off (21%)
Inflow 1





Measured – estimated from P concentrations measured in samples of inflow water

Figure 53. TP nutrient budgets for the eight lochs

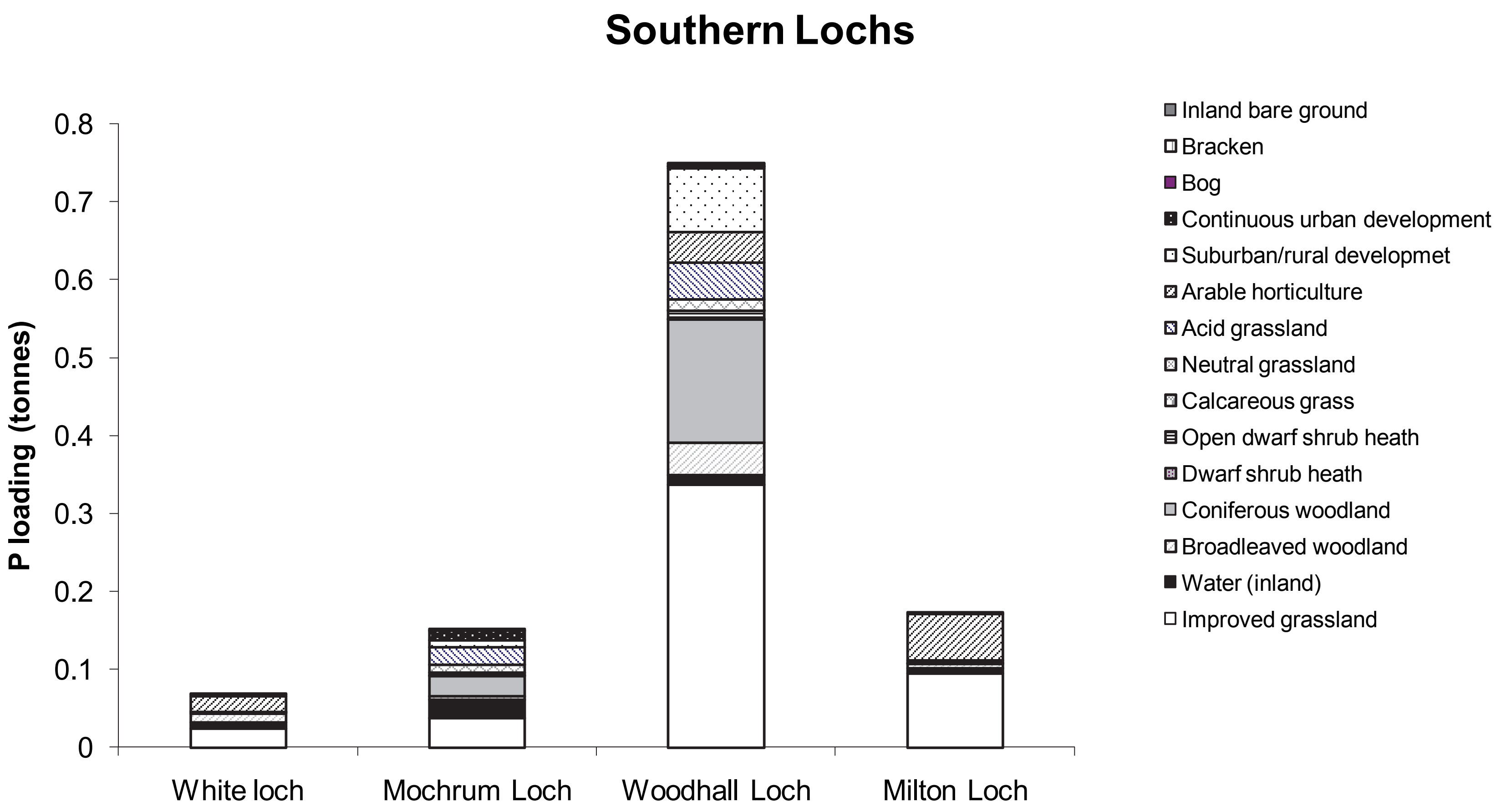


Figure 54. P budgets based on land use for each of the southern lochs, derived using PLUS P export coefficients

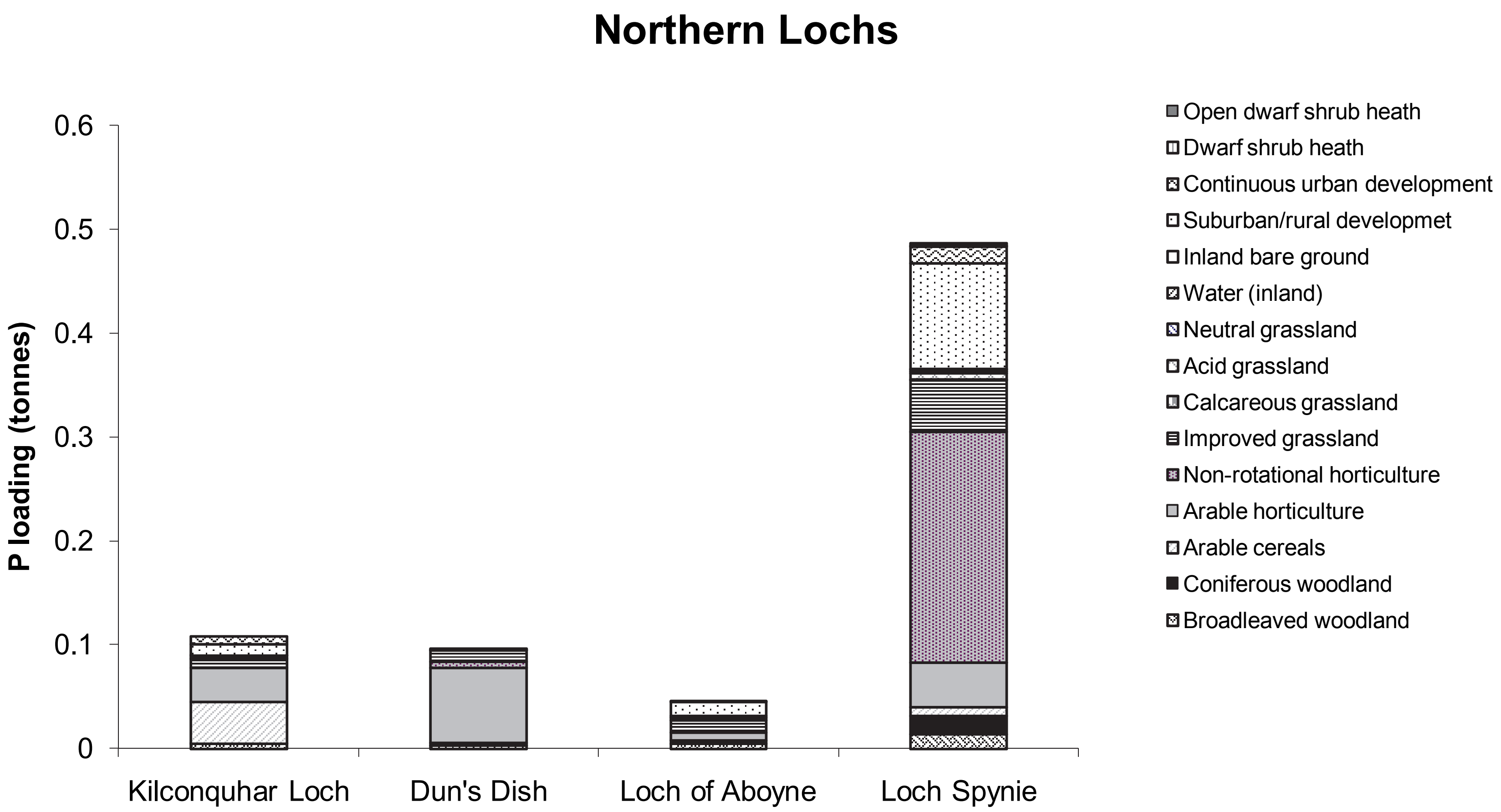
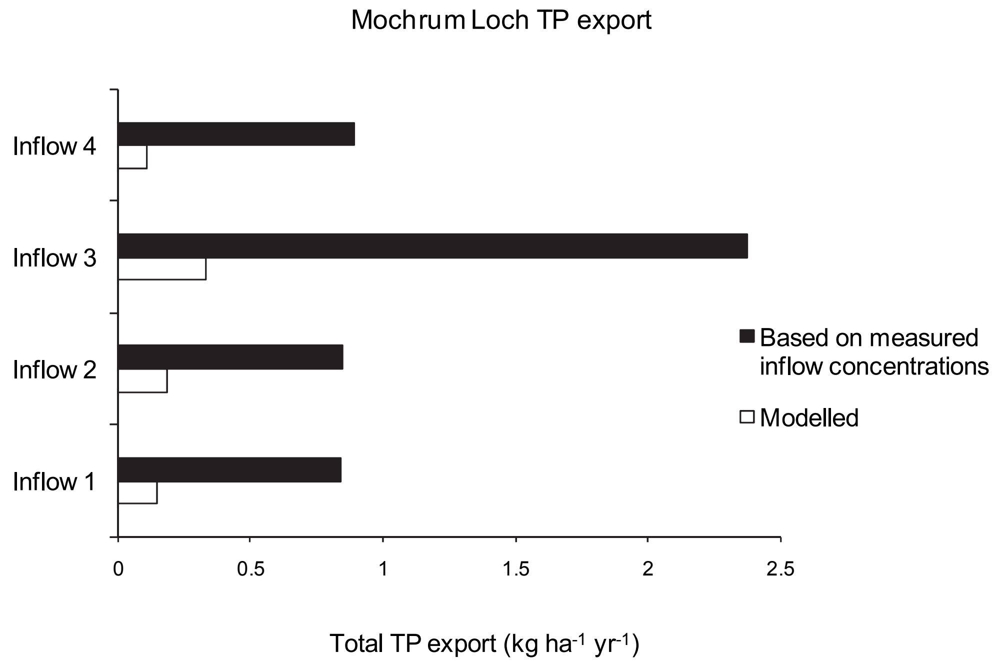
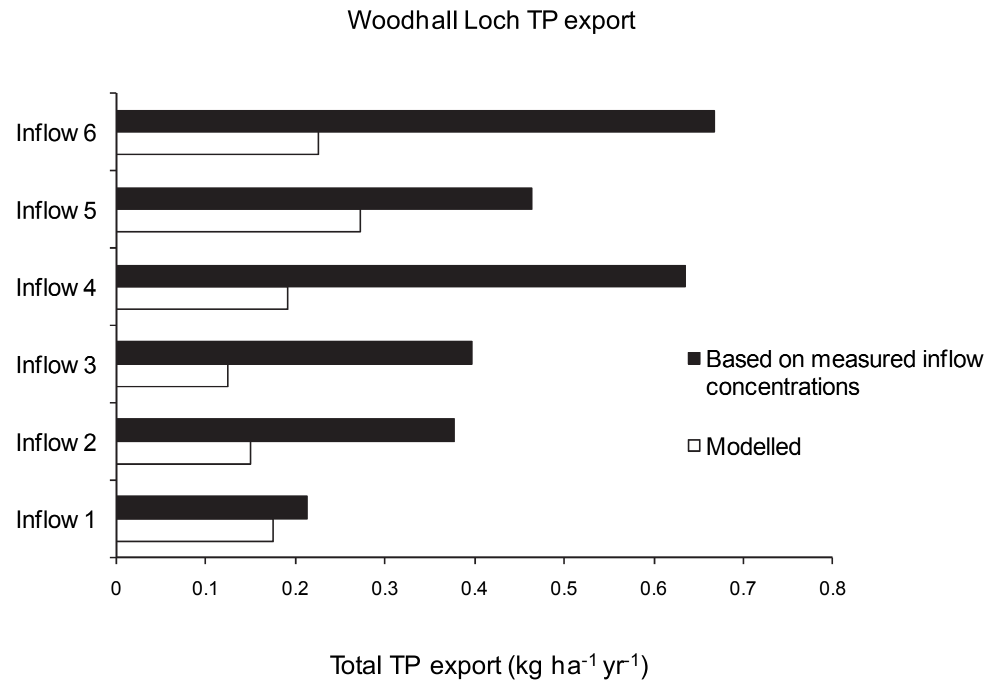


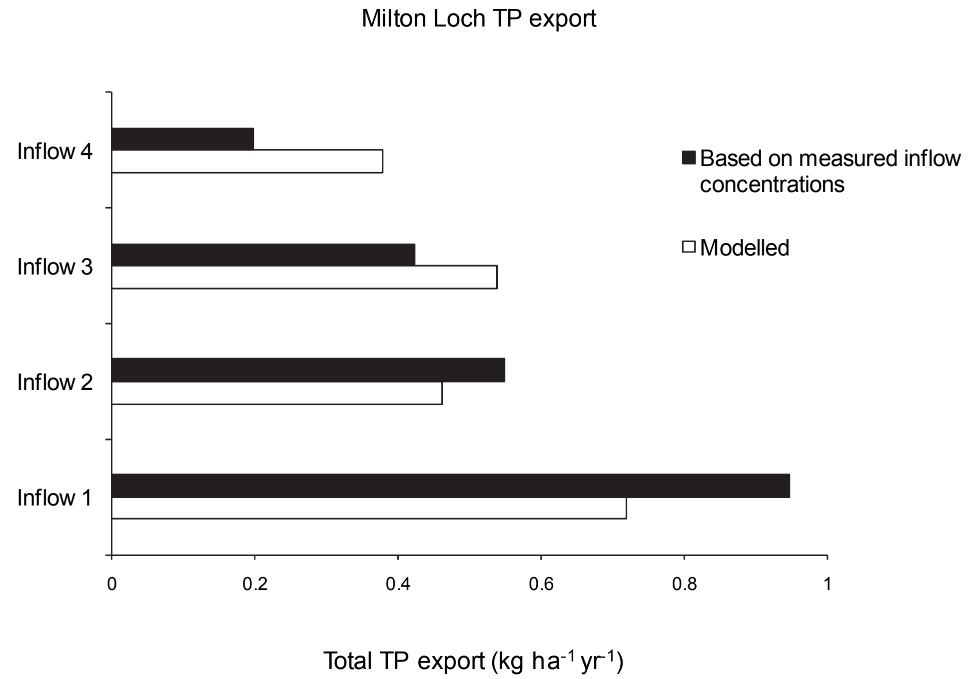
Figure 55. P budgets based on land use for each of the southern lochs, derived using PLUS P export coefficients

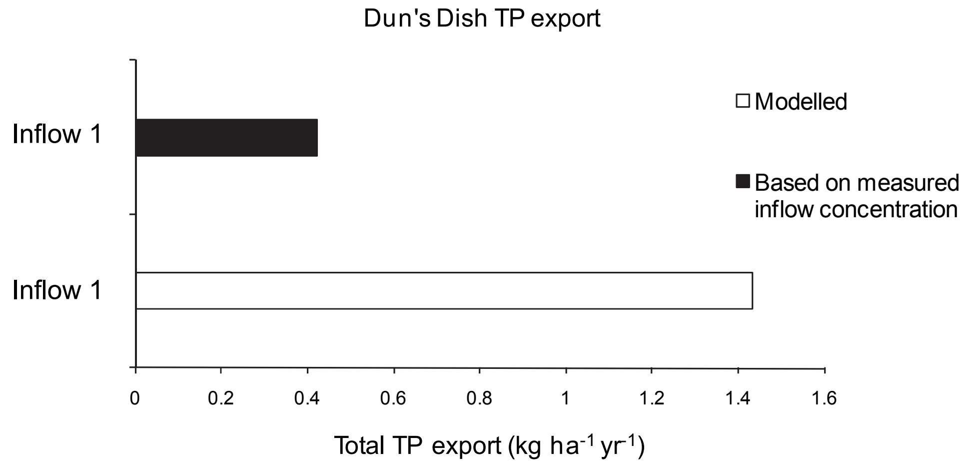
3.10.6 Export Rates

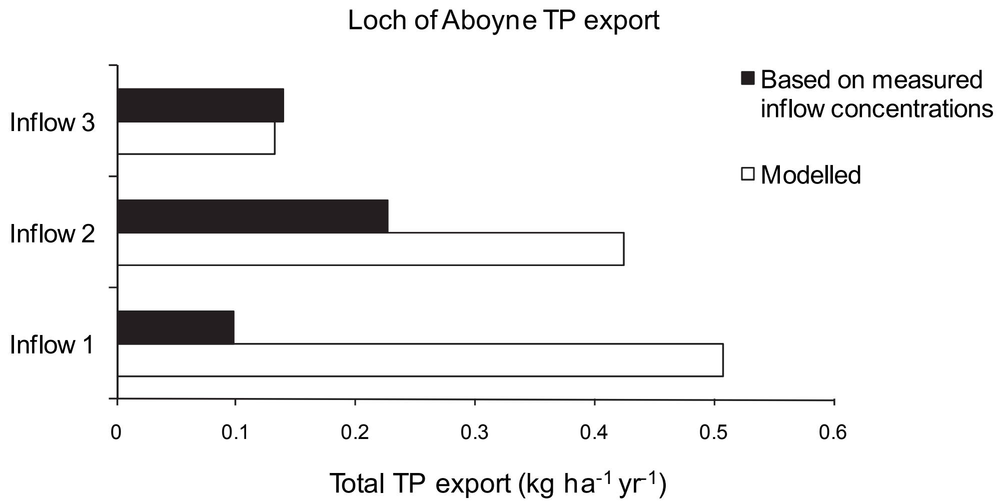
The size of the nutrient loading for each sub-catchment is largely determined by the size of the catchment area. Loadings can be converted into areal export rates to compare the intensity of P losses within each sub-catchment and hence identify where loss rates are greatest. Areal loss rates are shown in Figure 56 below. Note that two lochs – White Loch and Kilconquhar Loch – had no surface inflows and therefore could not have sub-catchment export rates calculated for them.






Milton Loch TP export
Inflow 4
Inflow 3
Inflow 2
Inflow 1
Based on measured inflow concentrations
Modelled
0
0.2
0.4
0.6
0.8
1
Total TP export (kg ha-1 yr-1)


Dun's Dish TP export
Inflow 1
Inflow 1
Modelled
Based on measured inflow concentration
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Total TP export (kg ha-1 yr-1)


Loch of Aboyne TP export
Inflow 3
Inflow 2
Inflow 1
Based on measured inflow concentrations
Modelled
0
0.1
0.2
0.3
0.4
0.5
0.6
Total TP export (kg ha-1 yr-1)

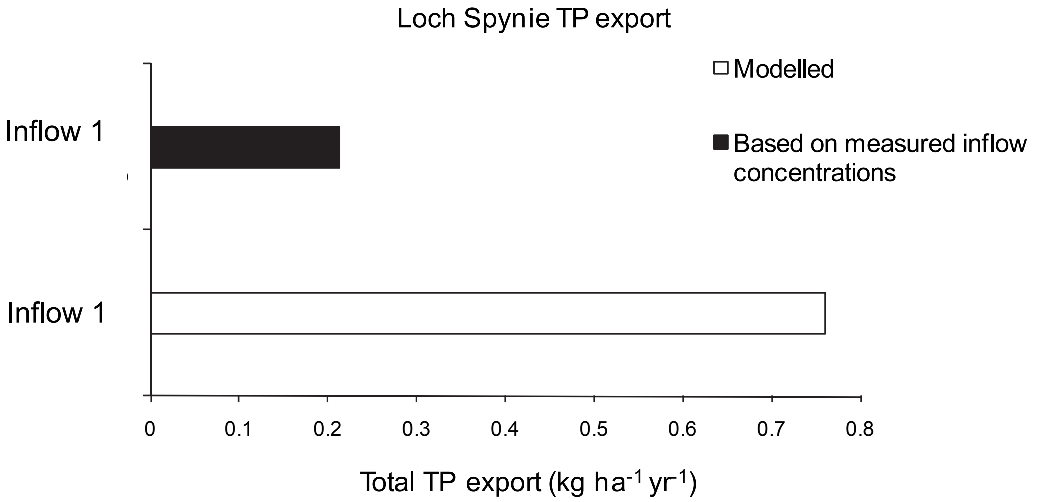


Figure 56. TP export rates for each sub-catchment based on measured inflow concentrations and modelled rates

The export rates based on measured data were higher than those calculated from loss coefficients for each sub-catchment for Mochrum Loch and Woodhall Loch, suggesting that changes in land use could be leading to an increase in nutrient export. For Dun's Dish, Loch of Aboyne and Loch Spynie, export rates based on measured data were lower than modelled rates, so it is possible that some improvements in land use or reduction in point sources may have occurred in these catchment areas. Export rates estimated by the two methods were similar for the sub-catchments of Milton Loch, suggesting that export is as expected for the recorded land use type present.

3.10.7 Chlorophyll modelling

P has been referred to as the common limiting nutrient, i.e. algal growth is ultimately limited by the amount of P available. The relationship between TP and Ch*a* can, however, be complex, as the upper limit of algal crop may not be reached due to grazing, wash-out, light attenuation or limitation by other nutrients, such as N or Si. As a result, there may be a great range of actual crop at any given P concentration, particularly at higher TP levels.

For the purposes of Water Framework Directive (WFD), models were developed to predict Ch*a* concentration from TP level (Phillips *et al*., 2008). Models were produced for different types of lake in the WFD lakes typology. In the typology, lakes are divided into types based on depth and alkalinity. The lochs studied in the present project represent four different lake types and the model associated with each type is presented in Table 24.

Table 24. Chlorophyll models for each lake type in the lake typology (Phillips et al., 2008)

Loch type	Chlorophyll model used
Shallow, high alkalinity	Log10 Chl = -0.306(±0.10) + 0.868(±0.07) Log10 TP
Very shallow, low alkalinity	Log10 Chl = (±0.03) + 1.108(±0.02) Log10 TP
Shallow, low alkalinity	Log10 Chl = (±0.03) + 1.108(±0.02) Log10 TP
Very shallow, high alkalinity	Log10 Chl = -0.306(±0.10) + 0.868(±0.07) Log10 TP

The Ch*a* concentrations predicted for each of the target lochs are shown in Table 25, along with measured growing season Ch*a* concentrations for comparison. Growing season measurements are the mean of the summer and late summer measurements.

Table 25. Mean measured growing season TP and Cha levels with Cha concentrations predicted from TP levels

	Measured mean growing season TP (µg P L^{-1}) (ranges in parentheses)	Mean depth	Alkalinity	Measured growing season chlorophyll *a* (µg L^{-1}) (ranges in parentheses)	Predicted Cha (µg L^{-1})	Measured Cha lower, similar or higher than predicted
White Loch	92 (85-99)	Shallow	High	22 (5-39)	25	Similar
Mochrum Loch	35 (30-39)	Very shallow	Low	4 (2-6)	15	Lower
Woodhall Loch	25 (22-28)	Shallow	Low	4 (3-5)	11	Lower
Milton Loch	105 (91-118)	Very shallow	High	23 (19-27)	28	Similar
Kilconquhar Loch	292 (48-536)	Very shallow	High	7 (3-10)	68	Lower
Dun's Dish	532 (439-625)	Very shallow	High	43 (6-80)	115	Lower
Loch of Aboyne	55 (52-57)	Very shallow	Low	20 (18-22)	25	Similar
Loch Spynie	70 (41-98)	Very shallow	High	19 (4-35)	19.8	Similar

4. DISCUSSION

4.1 Stakeholder consultations

SNH contacts for each of the lochs were established by SNH's nominated officer. These contacts provided an introduction and contact details for all the landowners around the loch sites. Landowners were contacted before each visit to confirm that access would be permitted and to inform them of work planned in and around the lochs. In addition, several landowners took an interest in the lochs and were able to provide some information on activities in catchment areas, potential stakeholders and historical aspects of the lochs. This information is summarized below, but it should be noted that the lochs are not well-used or well-known, and activities that might lend themselves to voluntary action are not widespread. In addition to discussions with landowners, SEPA was consulted in order to highlight any potential issues at the lochs, but the information available on the lochs involved was limited.

White Loch
White Loch is fully contained within the boundary of Loch Inch Estate. There was a great deal of stakeholder interest and concern regarding the wildfowl population on the Loch (especially the breeding component of the population) and therefore any proposition to control the bird population would be likely to be met with resistance. However, other methods of restoration may be well supported by the Estate, as there is also concern over a perceived marked increase in macrophyte growth, as well as the decline in water quality and occurrence of cyanobacterial blooms.

Mochrum Loch
Stakeholders with an interest in Mochrum Loch include Mochrum Estate, which controls the outflow by use of hatches, a fishing club (for trout and coarse fishing) and landowners on the southern shore, at Lochside Cottage. The degraded state of the Loch with regard to water quality and the presence of *C. helmsii*, however, may not be appreciated widely amongst stakeholders.

Woodhall Loch
Six landowners were consulted before each visit to Woodhall Loch, but there was limited knowledge and use of the Loch amongst stakeholders. There was an indication of interest in any developments arising from this project from one landowner, who reported observing surface algal blooms. There is an active angling club on the Loch and therefore there may be a group with an interest in water quality. As with Mochrum Loch, however, an appreciation of the degraded state of the Loch may be minimal.

Milton Loch
Three landowners were contacted before each visit to Milton Loch. Activity of stakeholders in the catchment focused on farming rather than any interest involving the Loch. There is some fishing on the Loch, but this is low-level.

Kilconquhar Loch
There are two estates surrounding Kilconquhar Loch, Ely Estate and Kilconquhar Estate. However, there was limited knowledge, use of and interest in the Loch itself, other than as wildfowl habitat. There was no fishing on the Loch during the period of study.

Dun's Dish
There are two owners of the land adjacent to Dun's Dish, both of whom are farmers. One farmer acquired the land recently and has little interest in or knowledge of the Loch, whilst the other has a strong interest in the Loch for wildfowling. The Loch itself is owned by the National Trust for Scotland (NTS), but NTS does not own any surrounding land or access track. NTS had limited data on the Loch, but provided a Masters thesis on the hydrology of

the site (Recorda Cos, 2006), which documented a number of useful physical measurements.

SEPA was able to provide limited information on the site. Historically, SEPA carried out water quality monitoring of the outflow. High BOD_5 and algal growth were noted. A more recent study, which looked at nutrient budgeting, attributed the majority of inputs to arable farming, with a small proportion coming from a septic tank. These findings were similar to the conclusions of the present project.

Loch of Aboyne
Loch of Aboyne is used for angling, but the most active group is likely to be the waterski club. The club has been involved in attempting to tackle water quality issues in the past, through the use of barley straw, and there was an anecdotal report of an improvement in water quality as a result. Membership of the water-skiing club includes one of the adjacent landowners, who takes a keen interest in the quality of the habitat. There are three adjacent landowners in total, all of whom rely on the Loch for various purposes (water-skiing, angling and abstraction for irrigation of the golf course).

Loch Spynie
There is one landowner adjacent to Loch Spynie and that is Pitgaveny Estate. The Estate has been involved in sensitive management practices in the past, in partnership with SNH and indicated an interest in the state of the Loch during the present project. However, information on the Loch itself was not available. There is a well-used bird hide on the southeastern shore of the Loch and it is likely that one of the most interested stakeholder groups, other than the Estate, is birdwatchers. Consequently, if management of the bird population for the purposes of loch restoration were to be considered, it is unlikely that it would be a straightforward option.

4.2 Temperature and dissolved oxygen profiles

Depth profiles of temperature and dissolved oxygen concentrations were obtained in late summer for each loch that had sufficient depth to allow profiling (Figure 11). Loch Spynie and Dun's Dish were found to be too shallow for depth profiles to be obtained. The situation in Loch Spynie was also exacerbated by thick macrophyte growth throughout. In Mochrum Loch, Kilconquhar Loch and Loch of Aboyne, the decrease in dissolved oxygen levels with increasing depth was small, as would be expected in water bodies of shallow maximum depth (1.8 to 4.0 m (Murray and Pullar, 1910)).

There was a small difference in dissolved oxygen concentration between surface and deeper water in White Loch, despite this water body having a greater maximum depth (11 m (Murray and Pullar, 1910)). In contrast, Woodhall Loch, with a maximum depth of 15 m, showed a considerable decrease in temperature and dissolved oxygen with depth. Dissolved oxygen saturation decreased from 100% at the surface to 34% near the substrate and there was also a gradual 1°C difference in temperature between the surface, which was at 16.9°C and the substrate which was at 15.9°C. There was no differentiated thermocline present, as the changes took place gradually with depth. The deep water being depleted of oxygen ties in with other observations such as high TP concentrations at depth and Mn being present, suggesting that sediment release of P may be happening to some extent in Woodhall Loch.

4.3 Nutrients and trophic status

4.3.1 In-loch nutrients

pH

The majority of the loch samples had pH values ranging from circumneutral (~7) to slightly alkaline (~8). However, some of the lochs had pH values that were above the broad optimal range of pH 6 - 8.5, and this was particularly pronounced for the summer samples (Figure 12). These elevated summer pH values can be explained by increased photosynthetic activity, which results in increased uptake of CO_2 and bicarbonate, secretion of OH^- ions and precipitation of calcium carbonate. The results of the surveys validate this explanation, as the four lochs with the highest summer pH values (Figure 12) are also those with very high TP values (Figure 25), the latter indicating high productivity (Milton, Kilconquhar, Dun's Dish and Aboyne).

Raised pH in lochs that experience algal blooms can contribute to fish kills. Changes in pH can also result in changes in the composition of biological communities. The form in which dissolved inorganic carbon (C) is present has considerable effects on the macrophyte community, as certain macrophytes may be suited to habitats of high availability of CO_2, others may be adapted to low CO_2 environments, whilst other species may be able to switch to bicarbonate as a C source.

Total Phosphorus

The highest concentrations of TP were found in Dun's Dish and the late summer sample from Kilconquhar Loch. The majority of lochs had TP levels in the OECD (1982) eutrophic category, with Dun's Dish, Milton Loch and Kilconquhar Loch having one to three samples with TP concentrations in the hypertrophic category (Figure 34). Woodhall Loch had the lowest TP levels, with these falling consistently within the mesotrophic category. Trophic status is discussed in more depth below along with comparisons with other classification methods.

In Kilconquhar Loch, TP concentrations in the first three samples taken from the water body were similar and fell just within the eutrophic category, but the water column TP level measured in late summer was extremely high, falling well above the hypertrophic boundary. Two surface samples were taken from two different points on the Loch, and the same result was found for both of them, suggesting that it is unlikely this was an anomaly due to contaminated sample bottles or equipment. Also, samples from other lochs that were analysed in the same batch did not show the same high P levels, again indicating that laboratory processes were not causing an anomaly. The extremely high TP level therefore suggests a sudden flushing of nutrients into the water column of Kilconquhar Loch.

The water body has no surface inflows and is fed by underground springs and surface run-off. Possible causes of such a flush of nutrients could include the following: flooding of underground aquifers containing accumulated nutrients from arable activities; surface run-off after a harvest or fertilization of land; significant release of nutrients from septic tanks; and release of P from sediments. The high P levels were not accompanied by elevated levels of other nutrients such as N, or SS, as might be expected if the source were e.g. a septic tank, polluted groundwater or the result of agricultural activity in the catchment. In addition, the surface catchment area is small, so it is less likely to be a source of such additional nutrients than if it covered a larger area. Groundwater does not usually replenish quickly, or in spates, so may be associated with consistently high nutrient levels if polluted. The cause of the particularly high nutrient levels measured in the water column of Kilconquhar Loch in late summer may therefore be release of P from sediment within the Loch. Sediment nutrient release may occur under anoxic conditions, but release of P is also possible when conditions are oxygenated at the sediment-water interface, particularly in fully-oxygenated, shallow lochs, with a large supply of organic matter to the sediments (Moss, 1998).

Phosphorus fractions

SRP is the fraction of P that is considered to be highly bio-available, i.e. in a form that can be used directly for algal growth. High concentrations of SRP suggest that most bio-available P has not been used by algae, and at the time of sampling, the phytoplankton are unlikely to be P-limited. A high proportion of SRP also points to pollution from organic waste products, including those from domestic animals, birds or domestic sewage.

Generally, SRP was found to represent a relatively small fraction of the TP levels in each loch (Figure 17). There were, however, three lochs where SRP constituted a substantial proportion of the TP present. These were Loch of Aboyne (range 6 - 29 µg P L^{-1}), Dun's Dish (range 8 -170 µg P L^{-1}) and Kilconquhar Loch (range 4 - 431 µg P L^{-1}). Dun's Dish and Kilconquhar Loch both have very large bird populations, and there is some livestock grazing in the Loch of Aboyne catchment. Surprisingly, the SRP fraction was not found to represent a high proportion of TP in samples from Milton Loch, the drainage basin of which supports the most intensive livestock grazing of all the loch catchments studied.

In stable, low nutrient systems, SRP would be expected to be present at < 1 µg P L^{-1}. The lowest concentration recorded during the present project was 5 µg P L^{-1} for the spring and summer samples in Woodhall Loch, which is expected to be an oligotrophic water body. The other water body which is expected to be oligotrophic, i.e. Mochrum Loch, had a minimum recorded SRP concentration of 6 µg P L^{-1}, which was also found in the spring and summer samples. These values were therefore higher than would be expected in oligotrophic systems.

Nitrogen

Notably, the highest TAN concentrations were observed during winter in all eight lochs. The rate of biological oxidation of NH_4 is at its lowest during the cold winter months, as higher temperatures are required for nitrification, which occurs during decomposition of organic matter. Nitrification results in conversion of NH_4 to oxidised nitrogen compounds. In addition, during the growing season, plants preferentially take up TAN rather than TON, which is also likely to contribute to the marked decrease in TAN concentrations in all of the lochs during the spring and summer (Figures 22 and 23).

In general, in nutrient enrichment studies of water bodies, high summer concentrations of TAN are attributable to input of wastewater from sewage or livestock. Milton Loch is the only water body to exhibit an increase in TAN in late summer, and this is consistent with the fact that this catchment area is the most heavily stocked with cattle.

NO_2 –N declined throughout the growing season, as might be expected due to denitrification (Figures 20 and 21). All eight lochs exhibited this trend, aside from Milton Loch, in which NO_2 –N declined from winter to summer before increasing substantially in late summer. As with the increase in TAN concentrations at that time, it is likely that the increase in NO_2 –N was related to inputs of livestock waste becoming nitrified rapidly at the higher temperatures at this time of year.

Measured NO_3-N levels decreased from winter to late summer in all lochs, though concentrations in Milton Loch increased from summer to late summer. Of the water bodies examined, Loch Spynie had the highest concentration of NO_3–N. The level measured in spring was significantly higher than any of the other concentrations determined across all lochs studied. In contrast, Kilconquhar Loch had the lowest concentrations throughout the period of study. However, the results for both of these water bodies are likely to be indicative of enrichment. Decreases in NO_3–N concentrations to very low levels in summer are generally indicative of systems which have received additional nutrient inputs, low levels of NO_3–N occurring as a result of uptake by plants or utilisation of NO_3–N as an oxygen donor at the sediment-water interface.

Silica

Towards the end of winter, when day length, temperature and light intensity start to increase, diatoms are typically the first group of phytoplankton to increase in numbers and biomass. They require silicate (SiO_2) to produce their cell walls, and continue growing until late spring or early summer, when nutrient limitation (including SiO_2 limitation) causes the diatom population to go into decline. In deep lochs, sinking contributes to the decline in diatom numbers, but this effect is less important in shallow lochs, as they are more easily resuspended by wind-induced turbulence. For six of the lochs, measured SiO_2 levels were high in the winter, and then decreased in the spring and summer (Figure 24), with increased diatom growth. In Dun's Dish, SiO_2 concentrations decreased from winter to spring, but increased in summer, before decreasing again in late summer. As this water body is extremely shallow, it would not necessarily be expected to exhibit typical patterns of limnological behaviour. The availability of data for Milton Loch was not sufficient to allow any definite patterns in SiO_2 cycling to be revealed.

TP and manganese

Samples were taken at depth from the deeper lochs, to determine if TP concentrations near the sediments were higher than at the surface. This would give some indication of P being released from the sediments. For White Loch, Woodhall Loch and Mochrum Loch, P concentrations near the sediments were lower than surface concentrations for the winter, spring and summer samples (Figure 25). For the samples taken in late summer, however, TP levels in deeper water were higher than those at the water's surface. It is therefore possible that the sediments in these three lochs were releasing P to the water column, possibly due to development of anoxic conditions in deep water in late summer. Nitrate concentrations were low for these three lochs during late summer, but the lowest concentrations were during the summer sampling (Figure 18). As discussed above, depletion of nitrate concentrations is suggestive of an elevated oxygen demand at the sediment-water interface, as a consequence of nutrient enrichment.

The same is not true for Loch of Aboyne. There was no increase in deep water TP concentrations, suggesting that sediment release of P is not as marked for this water body.

Manganese (Mn) concentrations were analysed in a number of the water samples taken at depth, as the release of P under anoxic conditions is accompanied by the release of Mn and Fe (Kalff, 2002). It is thought that concentrations of Mn in fresh waters typically range from 1 – 200 µg Mn L^{-1} (Barceloux, 1999). All the samples tested had concentrations < 1 µg Mn L^{-1} (Figure 25) and so there is no substantial evidence for elevated Mn concentrations in the samples taken at depth.

However, the highest Mn level was found in the water column of Woodhall Loch, where a Mn concentration of 0.58 µg Mn L^{-1} was recorded. This gives some indication (albeit relative to the other lochs) that anoxic P release may have occurred. A number of factors may encourage P release within this water body. It is the deepest of those surveyed, with mean and maximum depths of 6.1 m and 14.9 m, respectively (Table 5). It was found to have the greatest depletion of dissolved oxygen at depth in late summer (Figure 11). In addition, water column TP concentrations were higher than expected for an oligotrophic, low alkalinity water body. These factors may contribute to encouraging internal P loading (Niirnberg, 1994). However, it was noted that Ch*a* concentrations were not elevated.

In Kilconquhar Loch, higher P concentrations were measured in samples taken near to the substrate, but nutrient cycling is thought to be occurring in a different way in this water body, as it is believed that it is too shallow for anoxic P release, oxic P release occurring instead.

Chlorophyll *a*

For seven out of the eight lochs, there were two distinct peaks in Ch*a* concentrations, in the spring and late summer (Figures 26 and 27). In sites elsewhere, the spring phytoplankton community is often characterised by a bloom in diatoms, but by late summer, cyanobacteria typically become the dominant algal type. The result is a double peak in Ch*a* concentrations within the year. This double peak is not present in Loch of Aboyne, where algal growth appears to have steadily increased throughout the summer. Loch of Aboyne was found to have an unusual phytoplankton crop in that both the spring and summer blooms were dominated by chlorophyta or green algae, which far exceeded both diatoms and cyanobacteria. In nutrient-rich systems, chlorophyta may become the dominant algal group (Moss, 1998).

Suspended solids

The highest levels of suspended solids were observed in Dun's Dish (Figure 28). This may be attributed to the extreme shallowness of the water column. With even a slight wind and unsettled weather, particulates were resuspended from the substrate, so it was difficult to obtain a sediment-free water sample. Inorganic particles generally made up a small fraction of the suspended solids in each loch, but in Dun's Dish, inorganic particles accounted for a considerable proportion of the total solids present in the water column (Figure 29).

Secchi depth

Whilst Secchi depth cannot reliably predict light attenuation within the water column, it can be used broadly to characterize the clarity of water present. Measurements of Secchi depth may be examined over time within lochs, but may also provide a means of comparing lochs in terms of phytoplankton productivity, in systems where algal cells account for the majority of suspended solids within the water column (Kalff, 2002). Ranges of Secchi depth measurements associated with different trophic states are shown in Table 26. In some of the shallower lochs in the present study, Secchi depth was difficult to determine due to dense macrophyte growth, or insufficient loch depth, i.e. light penetrated the entire water column and trends could not be distinguished in the shallower lochs, because the water columns were so shallow that light penetrated to the substrate.

In Mochrum Loch Secchi depth was lower in winter and spring, whilst in Woodhall Loch, Secchi depth was lower in spring and late summer, coinciding with phytoplankton (Ch*a*) production peaks (Figure 30). In White Loch, Secchi depth decreased from winter to late summer. This is consistent with the lower levels of Ch*a* and SS measured in winter and higher levels determined in late summer, though lower levels of Ch*a* and SS were also measured in spring. Only one measurement was recorded in Milton Loch.

Loch of Aboyne, the deepest of the northern water bodies, did not show the typical pattern of highest turbidity in spring and late summer (Figure 31). In this Loch, water clarity was highest in spring, when Ch*a* and SS concentrations were at their lowest. Ch*a* and SS levels were higher in summer and late summer than in spring. There was no pronounced diatom bloom in this Loch, which was dominated by Chlorophyta (or green algae), rather than diatoms and cyanobacteria.

Biochemical Oxygen Demand

BOD_5 is a measure of the amount of dissolved oxygen used in chemical and biological processes in water samples, over five days at 20°C. In water bodies which have been polluted with organic matter, such as manure, sewage and vegetation, oxygen use increases, as it is used in the decomposition of the pollutants. Generally, the higher the concentration of waste material present in the sample, the higher the oxygen demand. In the field, increased temperature and concentrations of nutrients such as N and P can contribute to high BOD. As water temperature increases, the rates of chemical and biological processes increase, thereby requiring more oxygen, but increased productivity itself may lead to production of more waste. The BOD_5 of crude sewage is expected to be approximately 600 mg O_2 L^{-1}, whilst that for unpolluted river water should be less than 5 mg O_2 L^{-1} (Moss, 1998).

The BOD_5 measured in samples from the surface inflows of six lochs is shown in Figure 33. The remaining water bodies did not have surface water inflows which could be sampled. There is a strong trend for BOD_5 to be higher during late summer, which may be due to lower rates of dilution of organic pollutants, because of lower rainfall, as well as larger amounts of organic material contributed over the summer. However, note that summer BOD_5 measurements were not possible for four of the six lochs large enough to have surface inflows, as the inflowing rivers and drains were dry.

Generally speaking, BOD_5 results were similar in the inflows of the different lochs. BOD_5 measurements in the winter samples were in the region of 0 to 3 mg O_2 L^{-1}, indicating low levels of organic pollution. However, BOD_5 measured in late summer tended to be higher, in the region of 5 to 6 mg O_2 L^{-1}, which suggested moderate pollution.

One of the drains flowing into Dun's Dish deviated from this general trend. BOD_5 was measured as 12 mg O_2 L^{-1} in the sample taken in winter from Drain 4. This was the highest BOD_5 of all the samples taken during the present study. The TP level in the same sample was in excess of 700 µg P L^{-1}. Drain 4 also contained 'sewage fungus' and detrital evidence of sewage effluent. Together these observations indicated a high level of sewage pollution in this drain.

4.3.2 Trophic status

By convention, lochs fall into three main trophic classes. These are: oligotrophic (nutrient poor), naturally or enriched mesotrophic with a moderate nutrient status, and naturally or enriched eutrophic, with a high nutrient status. Hypertrophic may be considered to be an extreme subset of the eutrophic category and may describe lochs that are not only nutrient enriched but nutrient saturated. Ultra-oligotrophic lochs comprise a subset of the oligotrophic category. These are water bodies with extremely low nutrient concentrations (≤4.0 µg P L^{-1}). The main factors determining trophic categories are the geology and soils of the surrounding area, land use and loch hydromorphology (depth and water retention time).

Oligotrophic lochs are low in nutrients and are especially prevalent in the Scottish Highlands. According to the classification of OECD (1982), such lochs have water column TP levels of <10 µg P L^{-1}. At high altitude, the soil is thinner and the land is less suitable for agriculture. With low buffering capacity, oligotrophic lochs are particularly sensitive to acidification. Oligotrophic lochs are generally not particularly biodiverse, but support sensitive species of fish, such as salmonids and coregonids, and plants such as lobelia and quillworts.

Mesotrophic lochs have moderate nutrient levels (10-35 µg TP L^{-1}, according to the classification of OECD (1982)), and are home to a characteristic array of sensitive and often uncommon biota. These lochs are relatively rare in the UK, and are generally situated between upland and lowland areas. Many lochs that were once mesotrophic have become enriched with nutrients from human activities and as a result, have lost sensitive species.

Eutrophic lochs have higher nutrient concentrations (35-100 µg TP L^{-1}, according to the classification of OECD (1982)). Naturally occurring eutrophic lochs tend to have lower nutrient levels than artificially enriched eutrophic lochs. In general, in the UK, TP concentrations in naturally occurring eutrophic lakes would not be expected to be > 50 µg TP L^{-1} (JNCC, 2005). This eutrophic lake type is relatively common in the UK, particularly in the urbanised and agricultural lowlands. In cases where a water body has undergone anthropogenic enrichment, problems may include loss of biodiversity and the formation of toxic cyanobacterial blooms.

The impact of increased nutrient concentrations in the water column of a loch is dependent on the baseline or reference nutrient status of the receiving water. For example, only small increases in nutrients in the water column of an oligotrophic loch will shift it to into a mesotrophic state. However, in small lochs, the response of biota to nutrient enrichment is considered to be non-linear and proceeds in a step-wise fashion. The stable-state hypothesis in limnology argues that the ecological response of small lochs in particular to nutrient enrichment is not a gradual and progressive one, but rather lochs experience sudden and rapid regime changes that radically alter their ecological functioning and biodiversity (Scheffer *et al*., 2001).

Small lochs exhibit stable states, which enable them to resist, in terms of their ecology, changes in nutrient status. For example, for a clear-water, oligotrophic loch undergoing an initial phase of nutrient enrichment, there may be little change in lake typology. The macrophyte-dominated environment is a habitat that provides a refuge for large-bodied zooplankton, which exert efficient, top-down control on phytoplankton. The clear water and macrophytes also favour piscivorous fish which, if present, predate on planktivorous fish, again promoting the large-bodied zooplankton that control phytoplankton. Eventually, this stable state breaks down, with a rapid shift from a clear-water, macrophyte-dominated loch, to a turbid loch with high phytoplankton and low macrophyte abundance.

Enrichment of a water body may take place for a long time before such ecological impacts become apparent. It should also be noted that the changes in loch ecology that occur before any switch in state, such as loss of rare or sensitive macrophyte species, changes in macrophyte community structure or phytoplankton community composition can be of great significance, especially in lochs that are designated as features of conservation interest.

The stable state hypothesis also operates in reverse, so that reductions in nutrient inputs, unless they are very large, do not necessarily result in any obvious or immediate biological recovery in a lake. The turbid water conditions created by the phytoplankton-dominated system are inimical to sustaining large-bodied zooplankton, due to an absence of macrophytes and an environment that favours planktivorous fish over piscivorous fish. Despite a decrease in nutrient inputs, a phytoplankton-dominated system may persist. A switch to clear water conditions may require the reduction of nutrient loadings to levels considerably less than those occurring when the switch from the clear water system took place.

A factor which may contribute to limited responses of lochs, especially small, shallow lochs, to lower P loading, is release of P from loch sediments. This release reflects historical high loadings to the loch and sufficient reducing capacity to allow sediment P release (though as discussed, deoxygenation may not be necessary for P release, particularly if the P content of sediment is elevated). The reducing capacity is generated by high levels of primary productivity and oxygen depletion. Again, it is argued that definition of the scale of the internal P loading is important in planning loch recovery, as in some instances, an effective recovery plan may require in-loch techniques that will suppress sediment nutrient release.

4.3.3 Trophic status of the target lochs

The widely used system of lake classification produced by OECD (1982) recommends that several parameters are used to determine trophic status. These are annual mean TP level, mean and maximum Ch*a* concentrations, and mean and minimum Secchi depth. The ranges for each trophic category, as defined by OECD are shown in Table 26.

Table 26. Ranges of variables defining trophic status (OECD, 1982)

Trophic status category	Mean total phosphorus (μg P L^{-1})	Mean chlorophyll *a* (μg L^{-1})	Maximum chlorophyll *a* (μg L^{-1})	Mean Secchi depth (m)	Minimum Secchi depth (m)
Ultraoligotrophic	≤4	≤1	≤2.5	≥12	≥6
Oligotrophic	≤10	≤2.5	≤8	≥6	≥3
Mesotrophic	10-35	2.5-8	8-25	6-3	3-1.5
Eutrophic	35-100	8-25	25-75	3-1.5	1.5-0.7
Hypertophic	≥100	≥25	≥75	≤1.5	≤0.7

The corresponding measured parameters for the eight target lochs are shown in Table 7. TP is arguably the most commonly referred to of the parameters, as it is closely linked to productivity and less likely than Ch*a* and Secchi depth to show wide fluctuations that are weather and season dependent. For example, Ch*a* concentrations may show distinct spikes caused by short term algal blooms and Secchi depth may vary with water colour, rainfall and unsettled weather. For this reason, where the parameters give conflicting definitions of trophic status, TP is considered the most reliable.

Table 7 shows the expected trophic status of each loch, i.e. that defined by the feature's name, along with its observed trophic status, based on the variables measured and OECD (1982) definitions. On the basis of TP levels, Ch*a* concentrations and Secchi depth only three of the lochs were found to be of the expected trophic status (i.e. that defined by the feature's name). These were White Loch, Milton Loch and Loch Spynie, which were all confirmed as eutrophic. The remaining lochs were one category more enriched, or in the case of Mochrum Loch, two categories more enriched than expected. In several of the lochs, measured summer TP levels were in the hypertrophic category (Milton Loch, Kilconquhar Loch and Dun's Dish), whilst only the TP concentration in Woodhall Loch was within mesotrophic boundaries (Figure 34). TP level in the water column of Mochrum Loch fluctuated around the mesotrophic/eutrophic boundary, whilst concentrations in White Loch, Loch of Aboyne and Loch Spynie were well within the eutrophic category (Figure 34).

The classification of OECD (1982) was developed using data from both natural and enriched water bodies. However, the consideration of TP levels in lochs in Scotland is now normally examined in relation to site–specific natural or historical water column TP values. Alkalinity has long been used to characterise lakes and such characterisation is presently the basis for assigning lochs to types, with which target TP levels are associated. This is the case when considering both Ecological Status under Water Framework Directive (WFD) and condition of sites designated for their conservation value. In general, low, moderate and high alkalinity types correspond to oligotrophic, mesotrophic and eutrophic conditions, respectively. Target TP levels associated with these types have been set in relation to the values which would be expected naturally. Targets for the lochs in the present survey are discussed below.

4.3.4 Target TP concentrations

Generally speaking, for shallow lakes, macrophyte dominated systems are likely to persist if TP levels are below 25-50 µg P L^{-1} (Moss *et al*., 1996). Once water column TP concentration rises above about 50 µg P L^{-1}, then alternative states may exist and the lake is vulnerable to the forward switch to a phytoplankton-dominated system. The more TP concentrations increase above this level, the more vulnerable to a forward switch the lake becomes. None of the water bodies in the present study should therefore have TP targets greater than 50 µg P L^{-1}. The mean growing season (summer and late summer) TP concentrations measured for each loch are shown in Table 27 for comparison with this broad target, as well as refined targets described in the following section. From Table 27, it can be seen that six of the eight lochs - White Loch, Milton Loch, Kilconquhar Loch, Dun's Dish, Loch of Aboyne and Loch Spynie – are above the nutrient range where they are vulnerable to alternate states and a forward switch, i.e. above 50 µg P L^{-1}.

Other classification methods that are relevant to standing waters and that refine loch TP targets further include the "Common Standards Monitoring Guidance for Freshwater Lakes" (JNCC, 2015) (CSM Guidance) and the "Environmental Standards" defined for WFD purposes. TP levels in standing water features of SSSIs are expected to be within the limits set in the CSM Guidance. The CSM Guidance presents type-specific upper limits in TP concentrations for lochs of different trophic types. The upper limit for very shallow eutrophic lochs is 50 µg P L^{-1}, for very shallow mesotrophic lochs it is 20 µg P L^{-1} and for oligotrophic lochs it is 10 µg P L^{-1}. CSM type-specific limits are presented in Table 27, along with mean growing season TP level for each of the eight study lochs for comparison.

Under the WFD, all surface water bodies are expected to achieve good ecological status (GES) and good chemical status by 2015 (Council of the European Communities, 2000). Environmental Standards provide loch type-specific ranges for TP that would be considered to represent GES and High Ecological Status (HES). Loch type is based on depth (very shallow, mean depth <3 m; shallow, mean depth 3 – 15 m; deep, mean depth >15 m) and alkalinity (low, moderate and high). The most up-to-date version of Environmental Standards should be consulted for expected target TP ranges for each loch, based on the alkalinity types shown in Table 27. All of the relevant information on environmental standards and typology for TP in lakes is in ministerial directions and there is no separate method statement. The following link contains the directions published in 2014: http://www.wfduk.org/resources/lakes-phosphorus

Targets of the Environmental Standards and the CSM Guidance are necessarily type-specific, but targets for individual lochs are required. For designated sites, targets should be based on the lower of the WFD or CSM targets. There is also a principle of no deterioration for both WFD and CSM.

Table 27. Measured and target TP concentrations

Loch	Alkalinity type[T]	Upper limit of TP range (µg L^{-1}) for expected trophic status*	Measured mean growing season TP (µg L^{-1})
White Loch	High	35 – 50**	92
Mochrum Loch	Low	10	35
Woodhall Loch	Low	10	25
Milton Loch	High	50	105
Kilconquhar Loch	High	50	292
Dun's Dish	High	50	532
Loch of Aboyne	Moderate	15 – 20**	55
Loch Spynie	High	50	70

[T]From Phillips *et al*., 2008
** From Common Standards Monitoring Guidance for Freshwater Lakes (JNCC, 2015)*
**Depth dependent

4.4 Macrophytes

Macrophytes not only provide valuable habitat for fish and invertebrates, but also give a direct indication of the health of a water body, whether through the level of diversity in communities or the presence of sensitive or rare species. Of the six lochs for which historical SLSP macrophyte data were available (i.e. all except White Loch and Mochrum Loch), Woodhall Loch had by far the most diverse macrophyte community, with 64 species present. It is the second largest of the target lochs at approximately 88 ha in surface area, and size is likely to have some bearing on the number of species present. Note also that the species list was not restricted to submerged and floating-leaved species. However, Woodhall Loch is one of the water bodies in the study which is less affected by anthropogenic enrichment, having TP concentrations within the OECD mesotrophic category.

Dun's Dish had the lowest macrophyte diversity with 30 species recorded. Only seven of these were submerged or floating-leaved species. The majority were part of the diverse emergent wetland community. This agrees with observations made during the current project that submerged macrophytes were not abundant or widespread within Dun's Dish, and this was thought to be largely due to the extreme shallowness of the Loch (<0.5 m) and the constantly shifting sediments. It is possible that historically, Dun's Dish may have had greater macrophyte diversity and abundance before becoming so shallow due to infilling. It is also a characteristic of enriched water bodies that the open water does not support macrophytes in diversity and abundance. Poor diversity may therefore be linked to enrichment and loss of macrophytes leads to destabilisation of loch sediments.

Loch of Aboyne was found to contain a rich macrophyte community, with 44 species recorded. This compares to 43 species recorded in Mochrum Loch, which is 12 times larger than Loch of Aboyne. The macrophyte community of Loch of Aboyne was therefore very diverse for its size. Of particular note, *Potamogeton compressus* was recorded.

As loss of macrophyte diversity is indicative of enrichment and is an important consideration in assessing the condition of the designated sites, a comprehensive macrophyte survey is recommended to complement the findings of this project and to determine the impacts of changes in water quality upon the macrophyte communities since the historical SLSP data were collected.

4.5 Zooplankton and phytoplankton

4.5.1 Phytoplankton

The relationships between phytoplankton community structure and environmental factors have been well-documented, and it is possible to make some broad general statements at the species level. The types of phytoplankton and zooplankton that predominate throughout the year can give further insight into the productivity, control mechanisms and trophic state of a loch. Temperate zone lochs tend to have a recurring and characteristic assemblage of dominant groups at particular times of the year. However, it is not possible to predict species composition within individual systems.

Phytoplankton refers to several groups of algae and one large group of photosynthetic bacteria, the cyanobacteria or blue-green algae (phylum Cyanophyta). This latter group is functionally similar to the other phytoplankton groups and so is discussed as a component of the phytoplankton, rather than as bacteria. The main phyla of phytoplankton identified and considered here are as follows:

- Cyanophyta or blue-green algae
- Bacillariophyta or diatoms
- Chlorophyta or green algae, including the desmids
- Cryptophyta or cryptomonads
- Chrysophyta or golden algae
- Dinophyta or dinoflagellates.

The first three groups – diatoms, cyanobacteria and Chlorophyta - are the most important in terms of phytoplankton dominance.

Diatoms

Diatoms usually represent the highest fraction of the growing season biomass in mesotrophic systems, and contribute proportionately less in nutrient-rich systems. Most species are large and heavy with a silicon shell (frustule), and so are prone to sinking to the sediments, where they can remain viable for years. If resuspended whilst still viable, diatoms can start photosynthesising within hours of returning to the euphotic zone. Hence they have a tendency to bloom in the spring when they are likely to be returned to the phytoplankton through mixing of the water column, at a time when temperature and light conditions are favourable for growth. Their growth is also dependent on nutrient availability, including that of silicon, with which they construct their frustules.

Cyanobacteria

Nutrient-rich temperate lochs tend to be dominated by cyanobacteria in the form of large colonies, filaments or floating rafts, particularly in late summer. The importance of cyanobacteria in a system tends to rise with increasing nutrient concentrations and algal biomass, and this group experiences lower loss rates due to grazing, sinking or disease than other groups. The shift from diatom dominance early in the year to cyanobacteria later in the year is likely to be attributable to lower loss rates of cyanobacteria as much as a higher growth rate.

Chlorophyta

Chlorophyta often contribute a large proportion of species richness to temperate lakes. In lochs with lower nutrient levels in the water column, they tend not to contribute a large proportion of the biomass, but in nutrient-rich lochs, they provide a large proportion of the biomass. The Chlorophyta includes a suborder called the desmids – ornate, mainly single-celled algae, with cells almost divided into two semicells. A diverse flora of elaborate desmids can occur in low nutrient lochs.

Cryptophyta

Cryptophyta are a group of a limited number of small flagellates that tend to make their greatest proportional biomass contribution in oligotrophic and mesotrophic lochs.

Dinophyta

Dinophyta (motile dinoflagellates) usually contribute a small fraction of species number or biomass, but can occasionally dominate or co-dominate the summer biomass of stratified, eutrophic lochs.

Chrysophyta

Chrysophyta exist as small single-celled algae or flagellated colonies that usually contribute few species and little biomass of eutrophic lochs, but can co-dominate with the Cryptophyta in oligotrophic and humic lochs.

4.5.2 Zooplankton

Zooplankton play a very important role in structuring and suppressing the algal communities, as they graze upon phytoplankton. They fall into two main groups, crustaceans and rotifers. Rotifers are very small (generally < 200 µm) and contribute a tiny proportion to the total algal grazing, feeding also on bacteria and detritus. The Crustacea are very efficient at grazing on algae, in particular the water fleas or Cladocera, which are particularly common in shallow loch systems. Some types of water flea feed within the plant beds, on periphyton and phytoplankton, whilst others prefer feeding in open water. *Daphnia*, for example, prefer open water and can filter extremely large volumes of water, removing algae, bacteria and detrital particles as small as 1 µm from the water. *Daphnia* are such efficient filter feeders that they can prevent a phytoplankton community from developing, and depending on size of loch, a reasonably dense population of *Daphnia* has the ability to filter the entire volume of a water body in less than a day.

The other common group of crustaceans are the Copepoda, but they tend to be less prevalent in shallow lochs, instead playing a more important role in large, deep lochs.

4.5.3 Predation and top down control by fish

Zooplanktivorous fish feed preferentially on large, slow-moving Cladocera such as *Daphnia*. As a result, the opportunity for zooplankton to completely suppress phytoplankton is seldom realised, and a balance is found where the zooplankton population is composed of smaller Cladocera, fast moving copepods and large numbers of rotifers, which are too small to be heavily predated by fish. Fish can therefore promote algal growth by removing grazing zooplankton from the water. In addition, fish transport nutrients from the littoral zone into the open water through their excreta, thereby providing further support to algal growth.

Young coarse fish such as roach (*Rutilus rutilus*), rudd (*Scardinius erythrophthalmus*), bream (*Abramis brama*) and perch (*Perca fluviatilis*) feed heavily on zooplankton. Young trout feeding in still open water will also take zooplankton, but to a lesser extent, as they tend to prefer benthic invertebrates. Hence zooplankton are more likely to be depleted when a loch is managed as a coarse fishery. However, piscivorous fish such as large perch and pike

(*Esox lucius*), as well as birds such as kingfishers, cormorants and herons help suppress rates of zooplanktivory by removing zooplanktivorous fish from the system.

In order to avoid predation by fish, Cladocera take refuge in littoral plant beds, moving out to feed in open water at night when they cannot be seen easily by fish (which hunt primarily by sight). Aquatic plants therefore provide an important haven for zooplankton.

The shallow, northern lochs did not appear to contain copepods (Table 10), and were often totally dominated by the rotifers, indicating depletion of the large zooplankton through top-down control by zooplanktivorous fish.

The deeper, southern lochs were dominated by copepods and rotifers. Cladocera were seldom dominant, again, indicating top-down control by zooplanktivorous fish. Cladocera were only dominant in Woodhall Loch and Loch of Aboyne during the summer. Both lochs are used for angling, so it is evident that there are fish present, but it may be that these lochs are not managed as coarse fisheries, but rather as trout or pike fisheries, so that downward pressure on the large Cladocera is kept in check.

4.6 Macrophyte versus algal dominance

The addition of nutrients to a lake can shift its ecology to alternative states. By allowing more vigorous macrophyte species to shade out smaller plants such as charophytes, enrichment leads to dense macrophyte stands with low biodiversity. Whilst nutrient enrichment can have an impact on the composition of the macrophyte community, it may not displace such aquatic plants altogether (Moss *et al*., 1996). An additional mechanism may be required to cause the switch to an algal-dominated system, such as physical plant damage, or removal or depletion of grazing zooplankton such as Cladocera, through the feeding activities of zooplanktivorous fish.

Although some of the target lochs are vulnerable, all of the lochs except Dun's Dish had strong macrophyte growth, so did not appear to have switched from macrophyte-dominated to algal dominated-states. However, diversity, structure and conservation importance of the macrophyte species and communities present in the lochs were not examined in the present project, so it is possible that there have been impacts on the macrophyte communities. Dun's Dish did not have many submerged macrophytes present, but it is difficult to know whether the extreme shallowness and consequent shifting sediments make the water body unsuitable for macrophyte colonisation, or whether macrophytes were lost because of enrichment and this has led to shifting sediments.

Two lochs where the water was noticeably green and turbid, indicating strong algal growth, were White Loch and Loch of Aboyne. There is anecdotal evidence (from discussions with loch owners) that macrophyte stands in White Loch have become denser in recent years, and have started to become a nuisance to the Loch's owners. It may be that this has been caused by nutrient enrichment, which could eventually, given the right conditions, lead to algal dominance. Loch of Aboyne has an active waterski club on it, and this has the potential to curtail the macrophyte population through physical damage from extensive motor boat use. This represents a mechanism which could deplete macrophytes and encourage algal dominance, in the presence of elevated nutrient levels.

4.6.1 Seasonality in lakes

Sampling was carried out on four occasions throughout the year, to attempt to capture and model the limnological changes associated with seasonality. In lakes in temperate regions, it is generally accepted that in spring, increasing day length and temperature give rise to an increase in productivity and a characteristic spring bloom of planktonic diatoms (Moss, 1998)

- provided that silica, required to construct diatom frustules, is not limiting (Bailey-Watts, 1976). The increased productivity continues throughout the summer, with different groups of algae becoming dominant as time progresses. Typically, a bloom of cyanobacteria occurs in late summer. Cyanobacteria are able to dominate at this time, as unlike most other groups within the plankton, they are buoyant, conferring on them a much lower loss rate due to sinking, and many are able to fix nitrogen when this nutrient becomes limiting (Smith, 1983). In deep lakes, long periods of warm, stable weather in summer give rise to thermal stratification, and in richer systems, the lack of complete mixing at this time may allow oxygen to become depleted in the hypolimnion (the deep water layer). Accumulations of buoyant cyanobacteria may occur at the water's surface. These may be unsightly and toxic (Bell & Codd, 1994; Kalff, 2002). As summer gives way to autumn, air temperature decreases Surface waters cool and density gradients which are associated with the thermocline in the water column break down. In addition, more unsettled weather typically contributes to mixing of the water column. A state of low productivity remains throughout the winter, due to low light levels and temperatures.

4.7 Chlorophyll a modelling

Ch*a* is routinely used in limnology as an estimate of phytoplankton abundance. The OECD (1982) produced equations relating lake water column TP and Ch*a* concentrations. Since then, further equations relating TP and Ch*a* have been produced, including those which resulted from Water Framework Directive related research and monitoring (Table 24).

Ch*a* concentrations that are lower than predicted point to factors other than P influencing phytoplankton abundance. Such factors may include zooplankton grazing/top down control, limitation of phytoplankton growth by another nutrient such as nitrogen, or light limitation. The latter may be due to e.g. high concentrations of humic substances, elevated phytoplankton biomass, or increased levels of suspended solids.

Mochrum Loch and Woodhall Loch were observed to have much lower growing season Ch*a* concentrations than those predicted by the model used, suggesting that algal growth is limited by a factor other than water column TP level in these two lochs.

Dun's Dish also had Ch*a* levels which were much lower than predicted using water column TP concentration and lake type. The extreme shallowness of the loch (<0.5 m) meant that resuspended sediment was present in the water column, even during weather which was only slightly unsettled. The laboratory results for suspended solids were found to be extremely high in Dun's Dish on two of the four sampling visits. Light attenuation due to high suspended solid loading is therefore likely to be important in Dun's Dish and this may be limiting algal growth.

White Loch, Milton Loch, Loch of Aboyne and Loch Spynie all had Ch*a* concentrations similar to those predicted by the TP model, indicating that P availability is limiting algal growth. Reduction in water column TP concentration would therefore be expected to result in a decrease in Ch*a* concentrations.

In Kilconquhar Loch, the high TP concentration measured at the end of summer resulted in the predicted Cha level being high, but it was considerably higher than measured levels of Cha. The high TP concentration measured at the end of summer may have occurred as a result of oxic P release and may have been temporary, but there appears to have been a limiting factor other than TP concentration controlling algal growth in the Loch, e.g. zooplankton grazing or self-shading.

4.8 Eutrophication in shallow lochs

4.8.1 Sources of nutrients

Nutrients inputs to lochs are typically divided into those with point or diffuse sources. Point sources are normally end of pipe inputs, such as those from sewage treatment works and are often consented discharges that may be controlled. Diffuse source nutrient inputs are more difficult to define, identify and control. Whilst they originate from the landscape, some diffuse sources are effectively point sources, such as contaminated runoff from farm yards, cattle feeding areas, or even direct discharges from septic tanks serving single rural dwellings. Once such diffuse sources are identified, nutrient loadings from them may be limited through better management or mitigation.

True diffuse inputs from land to water are, however, highly diverse, both in form and quantity. For example, losses of P from grassland systems tend to be in soluble forms, but particulate forms predominate from arable systems (Catt *et al*., 1998). Land use has a major bearing on the quality and quantity of loss. Streams draining agricultural land were found to have up to nine times greater concentrations of nitrate and phosphate than streams draining upland non-agricultural areas, where water quality is generally very good (Binkley *et a*l., 1999). However, even a consistency of land use does not necessary imply a consistency of P loss. For example, where a field is under constant management, but accumulates P through regular manure applications in excess of P offtake, P builds up in the soil, leading to elevated P losses, although no change in nutrient management has occurred. Where losses arise from the soil, they are largely passive and transport depends on rainfall and runoff, but incidental losses arise directly from human activities, for example, high losses of P occurring when runoff follows soon after manure applications to land (Smith *et al*., 1998).

Whilst upland areas are normally characterised by low P losses, forest planting and fertilising organic upland soils leads to elevated P losses. Current experience is that elevated P losses are also associated with timber harvesting on these soils, with high losses of soluble P being recorded through release from the root mass (Cummins and Farrell, 2002).

The diversity of loss mechanisms and sources that make up the continuum of diffuse P losses is of relevance to the current project, as it implies that as the study lochs drain a variety of land use types, there is unlikely to be a commonality of approaches to lowering diffuse source nutrient inputs, but rather management recommendations will have to be individually tailored to land use in each catchment.

4.8.2 Alternative states

Increased nutrient inputs and concentrations lead, at first, to increased growth of macrophytes and phytoplankton. Eventually, if nutrient levels continue to rise, macrophytes disappear and algae become more dominant, increasing the turbidity of the water. Lower light levels and changes in water chemistry ultimately lead to a loss of diversity of macrophytes and sometimes cause regression of marginal reed swamps (Moss *et al*., 1996; Boar & Crook, 1985). Smaller or more sensitive submerged plants are least able to compete for light and tend to be the first groups of plants to be lost during the progression of eutrophication, e.g. charophytes (which are large algae) and smaller pondweeds (Kalff, 2002). Canopy-forming, submerged species are better able to compete, as their photosynthesising surfaces are nearer to the water's surface, although they may also become restricted by the presence of draping filamentous algae (Moss *et al*., 1996). Eventually, highly competitive, ubiquitous species that cope well with turbidity become dominant. Plants with floating leaves can often be the most tolerant to enrichment e.g. the water lilies and duckweeds, although at very high nutrient levels, such populations may be unstable and prone to disappearance.

However, nutrient enrichment alone may not cause the switch from macrophyte dominated to algal dominated systems (Moss *et al*., 1996). Plants associated with low nutrient waters, such as *Lobelia dortmanna* and *Subularia aquatica* are likely to be lost as a result of nutrient enrichment. However, certain macrophyte species may thrive under elevated nutrient conditions and instead of building up in the water column, the additional nutrients are sequestered into the sediments or the plants themselves. Other mechanisms are often required to result in the loss of plants, such as damage from propellers, deliberate removal for management purposes, or changes in water level. Removal of grazers can also promote the switch, as the balance between the different levels of the food web is disturbed and the buffering effects lost (Moss *et al*., 1996). The introduction of non-native grazers, such as the common carp that feed on macrophytes can also promote the switch (Crivelli, 1983). Nutrient elevation on its own may only push a loch system into a condition where alternative states may exist, given a further pressure (Moss, 1991).

However, whilst loss of macrophytes may not occur without an additional pressure on a standing water system, nutrient enrichment alone may lead to changes in frequency of occurrence of characteristic and uncharacteristic species, and in macrophyte community structure. Such alternations may occur through direct effects of increased nutrient availability, but also because of changes in pH and the availability of carbon dioxide, which may occur as a result of increased plant biomass (of algae and/or macrophyte species). In sites that have been designated as SSSIs for their standing water interest, preservation of a macrophyte community which is representative of a particular type of water body is important and enrichment may lead to changes in that community, or to deleterious effects on populations of rare species.

4.9 Shallow loch restoration

Before commencing a programme of restoration, it is necessary to identify the desired outcomes, i.e. the reasons for carrying out restoration measures. In the case of the eight target lochs, the main driver is the need to improve them as sites of nature conservation value, i.e. to move towards the appropriate nutrient status and protect biodiversity. Most of the lochs are also important for their bird populations, but with the correct management, it should be possible for the sites to support rich bird assemblages without the danger of becoming excessively enriched by them, e.g. as a consequence of large populations supported by artificial feeding. Uses of the water bodies, such as land drainage, flood prevention and irrigation represent pressures. Recreational and amenity uses, such as angling, water-skiing and walking, may be in conflict with nature conservation targets for the lochs. It is therefore desirable to investigate ways in which pressures on the water bodies could be reduced or their effects mitigated.

It is unlikely that any loch can be restored completely to its pre-industrial state, and in any case, it is not possible to know accurately what that state was. Rather, a process of rehabilitation[1] is more appropriate, whereby improvements are made that reduce the prevalence of algal blooms, and bring trophic status nearer to the desired level, as described in the names of the features, so that presence of appropriate biodiversity and characteristic species is encouraged. Macrophyte diversity appropriate to loch type is of paramount importance in loch conservation, not only in its own right, but because invertebrate, bird and fish communities are associated with the plant life present. Once nutrient levels have been restored and stabilised, then the reintroduction and/or promotion of rare or sensitive plant species may be implemented.

[1] For the purposes of this project, the term ‘restoration’ refers to a process of rehabilitation, i.e. an improvement rather than a return to historical, pre-industrial conditions.

In terms of setting nutrient reduction targets for each loch, the limits of 25-50 µg P L^{-1} should be attainable for most of the target lochs (or 10 µg P L^{-1} for Mochrum and Woodhall Lochs). The larger the nutrient reductions that can be made, the less vulnerable to phytoplankton dominance the loch will be and the more likely it will be that reductions and biodiversity improvements can be maintained. Note also that for lochs in Scotland, the limit of 50 µg P L^{-1} remains relatively high. In addition, where target lochs already appear to be in the correct trophic state, measures still need to be put in place to protect and conserve water quality, as it is likely to be easier and cheaper to preserve the lochs rather than to attempt to rehabilitate them later.

The steps involved in loch restoration can be summarized as follows:

- identification and remediation of disturbances promoting a switch to phytoplankton dominance or undesirable changes in the macrophyte community
- nutrient control and reduction
- restoration or establishment of the desirable fish and plant communities.

4.9.1 Removal of forward switches

Factors that promote phytoplankton dominance over plant dominance must be identified for each loch and where possible, ceased, reduced or amended, e.g. deliberate weed cutting, incidental damage from boat wash and propellers, grazing or trampling by domestic or exotic waterfowl, presence of carp, absence of piscivorous fish in relation to zooplanktivorous fish and leakage of pesticides or herbicides.

4.9.2 Nutrient reduction and control

The approaches to nutrient reduction may take two forms.

Catchment-based measures aim to reduce nutrient inputs at source, and essentially involve the removal of the causes of enrichment. This approach is therefore effective in the long-term, but it can take substantial inputs of time and resources to result in tangible improvements. The speed with which such measures may work depends on water residence time, background catchment inputs and the quantity of P stored in loch sediment. N and P are both required for increased algal production, and most often, P is the nutrient limiting production and therefore the nutrient for which control is normally required. Fortunately, P is more readily controlled than N, which can be sequestered in an uncontrollable manner from the atmosphere by nitrogen fixers. In cases where N is the limiting nutrient, it may appear counterintuitive to control P, but it should be noted that often N is only limiting because P has been artificially increased, and control of P inputs will ultimately restore the former state (Lewis and Wurtsbaugh, 2008). In addition, in lochs where P has been building up over many years, it can be stored in and released from the sediments. Nutrient control therefore tends to focus on P first, and external P loading should be addressed before internal P sediment release, as external loading is the cause of increased internal loads. For each loch in the present project, external loads have been identified and placed in order of importance, and it is in this order that they should be addressed.

Within-loch measures can achieve results quickly and can sometimes be relatively less expensive in the short term. The drawback is that the measures are short-lived and they are not sustainable, as they may require repetition for many years and do not address the underlying causes. If undertaking in-loch measures, they should be carried out in tandem with catchment controls for the best results; however, in some situations, in-loch measures may be the only options that are practicable.

Catchment based measures

1. Reduction of sewage-related impacts

   - **Phosphorus stripping and diversion of sewage effluents**
     Sewage treatment works (STWs), run by Scottish Water, process 90% of the sewage produced in Scotland. The treatment process removes P from sewage effluents and waste water before releasing it to the environment. The proportion of P removed is dependent on the treatment system in place. Where tertiary treatment or P stripping is implemented, up to 95% of P may be removed from solution by dosing with a precipitant such as aluminium or iron salts. However, end of pipe sewage effluents are not an issue for the target lochs of the current project, as they do not receive effluents from STWs.

   - **Septic tanks**
     90% of the Scottish population is connected to the mains sewage system. Sewage from the remaining 10% of mostly rural population is treated by septic tanks and if properly designed and linked to soil soakaways, these should theoretically remove P. Maintenance such as tank emptying or the replacement of saturated P absorbing materials must be carried out regularly. Impeded drainage and waterlogged soils, along with poor or absent maintenance are common factors leading to badly functioning septic tanks. Due to the widespread issue of poor maintenance, a large proportion of the nutrient load entering waterways comes from poorly functioning septic tanks. A single malfunctioning septic tank may be considered as a point source of nutrients, but as dwellings and therefore septic tanks tend to be spread throughout the countryside, and often several septic tanks could be having an impact on a waterway, they can be considered *en masse* as a diffuse source of nutrients. In addition, the pathways by which nutrients from septic tanks reach receiving waters may be diffuse, rather than end of pipe. Inspection of septic tanks to ensure their correct functioning, as well as provision of information for septic tank owners (who may not be aware that their system is malfunctioning) would go some way to reducing the impact from this source. The target lochs do not receive effluents from STWs, so septic tanks are the only sewage-related nutrient sources that could affect them.

2. Reduction of land use impacts

   - **Livestock grazing** takes place in the drainage basins of all of the target lochs to some extent. The intensity of grazing is generally low and focused on sheep grazing, aside from Milton Loch which has high intensity cattle grazing and several farmyards within its small catchment. Application of slurry and run-off from hard standings such as farmyards results in nutrient losses to water bodies. Mitigation measures can be put in place to reduce this impact. Application of slurry to wet ground or during heavy rain should be avoided, as losses of P are higher under these conditions. In addition, manure should not be stored on hard standings, as upon decomposition, it releases N and P compounds which can ultimately enter watercourses. The use of watercourses to rinse slurry tanks results in direct nutrient inputs to water and should be prevented by restricting vehicular access to the lochs. It appears that overstocking of cattle and livestock access to the water bodies are not major issues within the target catchments. Poaching was not observed to be severe or widespread.

   - **Coniferous plantation forestry** is a major land use in five of the target loch catchments. The forestation of peatlands (e.g. as occurs in the catchment of Mochrum Loch) and their fertilisation with P has been shown to lead to high P losses and eutrophication problems in small lochs with forested catchment areas (Cummins &

Farrell, 2003). As time passes, eutrophication caused by planting and fertilisation decreases, as the P has either leached from the soil and been flushed out of the loch systems, or has been taken up by trees. However, at present, many of the plantations within the target loch catchments are at or near marketable size and clear-felling could well take place in the foreseeable future. There is evidence that clear-felling leads to enhanced nutrient losses to receiving waters (Cummins & Farrell, 2003). Any replanting and fertilisation with P will present a risk to adjacent waterbodies. Impacts from forestry activities are reduced with the use of appropriate management strategies, such as restricting the area clear-felled at any one time or fertilising by hand rather than by machine. Maintenance of an unfertilised riparian buffer zone reduces fertiliser run-off to streams and helps to establish a more natural mosaic of light and shade that benefits macrophyte, invertebrate and fish populations. The Forests and Water Guidelines (Forestry Commission, 2011) provide information on judicious forest management near water, and should be adhered to during any forestry activities in the catchments of the eight target lochs.

- **Natural wetlands** act as a biofilter, removing sediments and nutrients from waste water, surface run off or agricultural and sewage effluents. The soil and the roots, leaves and shoots of wetland vegetation provide substrates upon which microorganisms can break down organic material. P and N are both removed from water by wetlands. Both can be bound into biomass, whilst P can also be precipitated by compounds found in wetland soils and N species can be denitrified and converted into gases that re-enter the atmosphere. Where wetlands do not occur naturally, or have been drained and removed for development or land management, or are of themselves of value, constructed wetlands can be introduced to perform the same biofiltration function that is provided by natural wetlands.

- **Riparian buffer strips** are small areas or strips of land between waterbodies and surrounding land use that are allowed to remain in permanent vegetation (trees, shrubs and native grasses), in order to intercept pollutants and sediments. It is thought that around 50% of nutrients and 75% of sediments may be removed by buffer strips, as they slow down run off and their root systems offer bank and soil stabilisation that reduce erosion (Lowrance, 1991). In addition, they confer considerable biodiversity value by supplying habitat and wildlife corridors, but also through the edge effect, which is the tendency for increased variety and diversity to occur at community junctions. Ground conditions tend to be remarkably better, in terms of waterlogging and surface run-off, in recently planted forest rather than grassland. Planting trees on the downslopes of fields is therefore likely to be beneficial in terms of water quality.

3. Reduction of impacts from bird populations

Birds can adversely affect waterbodies through nutrient inputs from excreta and grazing of macrophytes. The latter may lead to destabilisation of sediments and promotion of algal production. Bird populations may be controlled in several ways: directly by discouragement, removal or shooting, or indirectly through provision of suitable habitat elsewhere. Since the bird communities occupying the target lochs of the current project are protected by legislation, direct reduction or control of the bird populations (i.e. by shooting) is not a viable method for reducing nutrient inputs into the lochs. However, consideration may be given to provision of alternative habitat in order to encourage birds away from the target lochs and towards alternative catchment areas, or to existing or created habitat within the catchments, but further from and less directly hydrologically connected to the lochs. Where consideration of control of the bird population has been recommended for target lochs, the nearest potential alternative lochs have been identified (Section 4.10). In managing and promoting alternative habitats for birds, several management measures can be utilized. These include the following:

- construction or restoration of reedbeds, marginal swamp, meadows and other nesting sites
- provision of shingle beds or muddy margins for foraging
- floodplain lowering or management of water levels (sluices, culverts, breaching embankments) to increase floodplain wetness
- maintenance of open water and nursery habitat for fish and fry
- provision of shallow water areas suitable for submerged, floating-leaved and emergent macrophytes
- control of predators including mink trapping if required
- fencing out cattle and other grazers
- control of invasive plant species.

Within-loch measures

1. Removal of biomass

Aquatic plants are the most practical fraction of the biomass to remove, but plants accumulate relatively little of the total P load. In addition, the process must be repeated for many years, and is only likely to result in a reduction in nutrients if carried out in tandem with external reductions in supply, as plants obtain their P mostly from the sediments, which are ultimately supplied by external loadings. Extreme care should be taken with this method, as removal of macrophytes can allow phytoplankton to become dominant in nutrient enriched conditions. In addition, macrophytes form an important component of the designation of the target lochs and so it unlikely that this method could be viewed as beneficial for the present project.

2. Sediment sealing

Chemical sealing to isolate the sediments from the water column can be achieved using alum or iron sulphate. These substances bind P at the interface of sediment and water. Chemical sealing may be suitable for reservoirs, boating lochs or water bodies supplying industry, but is not suitable for nature conservation purposes, as the chemicals can be toxic to biota or otherwise restrict ecological diversity.

An alternative method of sediment sealing is the Riplox method, which aims to oxidise the sediment surface using nitrate to promote the formation of ferric phosphate. This technique is more favourable as nitrate functions naturally in the sediments and it is not persistent, as denitrification takes place, promoting organic matter decomposition. The technique has been used successfully in Sweden (Moss, 1998), but it is expensive, requiring specialist operators and chemicals, and its success cannot be assured. Like other in-loch measures, it is only temporary and curbing external loading remains necessary.

3. Sediment removal

The removal of the sediments, or the P-enriched surface layers by suction through piping can have longer-lasting effects, but it is very disturbing to sediments, and plant and invertebrate life. In addition, the waste is bulky and disposal is expensive and difficult. As with chemical sealing, success is not guaranteed and external nutrient reduction is still required. Sediment removal should be used only as a last resort, if other methods have failed.

4. Increasing flushing rate

Flushing a loch with water with a low P concentration requires a suitable supply, and this would only be potentially achievable in the Loch of Aboyne, as it is thought that the main inflow is presently largely abstracted out of the catchment area. Increased flushing should theoretically speed up the removal of P stored in the lake, but the process is likely to be very slow.

The abstraction of water from natural lochs for the purposes of irrigation or potable supply can have significant impacts on the flushing rate and functioning of the waterbody. Abstraction of inflows can reduce the diluting effect of water on nutrient concentrations in a loch. It can also reduce the flushing rate, i.e. increase the water retention time, so nutrients remain in the water column for longer and are more likely to be bound up in the sediments or to support algal growth. Water levels in the loch can be lowered, thereby having an impact on littoral vegetation, habitats and buffering capacity, as well as reducing flows in the outflowing stream. Measures to reduce or adjust the amount of water abstracted may therefore help to reduce eutrophication by increasing the flushing rate. It should, however, be noted that adjustments to increase water levels could have a negative impact on submerged macrophytes. As water depth increases, the intensity of light penetrating to the bed of the loch decreases.

Establishment and stabilisation of communities

Once nutrient control has been acheived, it is possible to stabilise lake communities and establish fish and plant communities that will help maintain a balanced, lower nutrient system. Various techniques can be employed as discussed below.

1. Biomanipulation

Biomanipulation in terms of loch restoration commonly refers to the alteration of the fish community to promote grazing zooplankton to help control algal growth. This can be achieved by removing zooplanktivorous fish, such as roach and bream, or by adding piscivorous fish, such as pike and is less expensive compared with other loch restoration techniques (Jeppesen *et al*., 1991). Removal of the entire fish community has been successful in the past (Moss *et al*., 1996), but is difficult to achieve, requiring exhaustive netting and electrofishing. The addition of piscivores is more straightforward, but if pike are added, the lake should have sufficient macrophyte growth to provide cover for hunting. However, the addition of piscivores has a drawback in that they can quickly reduce abundance of prey species and die out, allowing the prey species to recover. Repeated stocking is therefore required.

For the current project, in target lochs where the natural fish community has been preserved, this represents part of the local distinctiveness of the site, and should not be disturbed for the purposes of biomanipulation. In lochs that are artificially stocked for fisheries purposes, further manipulation of the fish community is not a favoured option, as such action could cause further problems within the ecosystem (C. Adams pers. comm.). In addition, anglers may object to any potential reduction in their target species.

2. Promotion of diverse plant communities

Once lower nutrient levels have been stabilised and a lake is no longer vulnerable to a switch from macrophyte to algal dominance, selective weed cutting and planting can be carried out to encourage the re-establishment of rare macrophyte species that thrive at the earlier stages of succession and a diversity of species characteristic of the feature type.

4.10 Legislation

In addition to the legislation under which SSSIs are designated, the following European Directives are relevant to the target lochs:

- Water Framework Directive
- Nitrates Directive.

4.10.1 Water Framework Directive and CAR Regulations

The Water Framework Directive (WFD) 2000 has been translated into Scottish law by the Water Environment and Water Services (Scotland) Act 2003 (WEWS), which gives Scottish ministers powers to regulate activities relating to the water environment. The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended) (CAR) provide an instrument under WEWS whereby application for authorisation may be made to discharge to water, abstract water, impound water and carry out engineering work in and around a waterbody. Some of the target lochs of the current project have activities being carried out on them that require a CAR licence, e.g. abstraction from Loch of Aboyne and water level management in Mochrum Loch and Loch Spynie. In addition, some of the recommendations resulting from this project may require a CAR licence or review by SEPA. Where this is the case, this is noted in Table 28, which summarises the recommendations. The CAR are discussed further, with regard to diffuse pollution, in section 2.13.

4.10.2 Nitrates Directive and Nitrate Vulnerable Zones

The Nitrates Directive 1991 aims to control and prevent contamination of groundwater with nitrates sourced primarily from agricultural activities, such as slurry storage and spreading. Areas that drain to groundwater that is thought to be at risk from nitrate contamination or where groundwater nitrate concentrations exceed 50 mg L^{-1} must be designated as Nitrate Vulnerable Zones (NVZs), with suitable Action Programmes that aim to reduce and prevent further contamination.

In Scotland, there are four designated NVZs, and three of the target lochs lie within two of them. These are Kilconquhar Loch and Dun's Dish in Strathmore and Fife NVZ, and Loch Spynie in Moray and Aberdeenshire NVZ. The other two NVZs in Scotland are Lower Nithsdale and Lothian and Borders NVZs.

The key Action Programme requirement of farmers operating within NVZs is to prepare and implement a fertiliser and manure management plan that contains a risk assessment and map for manures and slurries, a calculation of the capacity of the necessary slurry storage facilities and a calculation of the loading limit for livestock manure. The number of livestock and movement of livestock manure and chemical fertiliser on or off the farm must also be recorded.

4.11 Loch discussions and recommendations

4.11.1 White Loch

White Loch is designated as a eutrophic water body, which means it would be expected to have a mean water column TP concentration within the range 35-100 µg P L^{-1} according to the OECD (1982), or a concentration < 50 µg P L^{-1} according to CSM Guidance. The mean measured TP concentration for White Loch in 2010 was 62 µg P L^{-1} and the mean growing season concentration (for summer and late summer samples) was 92 µg P L^{-1}. This indicates that White Loch has TP concentrations that are typical of eutrophic lochs. In addition, the Ch*a* concentration in a eutrophic loch would be expected to be in the range 8-

25 μg L^{-1}. The mean measured Ch*a* concentration for White Loch was found to be 19 μg L^{-1}, which again is a typical concentration for a eutrophic water body.

However, the OECD (1982) classification includes enriched eutrophic lakes, whereas the CSM Guidance is concerned with naturally eutrophic standing waters. Despite the measured TP and Cha concentrations falling within the expected ranges according to OECD (1982), the Loch has been judged to be in unfavourable condition due to poor water quality and the occurrence of cyanobacterial blooms. If cyanobacterial blooms were not present historically, this suggests that there has been a rise in nutrient concentrations above historic levels. The growing season TP concentration is very high within the eutrophic range; high enough to allow cyanobacterial blooms. The results of chemical analysis of water samples taken at depth may suggest that in late summer, P was released from the sediments, though the Mn concentration measured was low.

Shallow areas of the Loch were observed during survey to support dense macrophyte growth, and anecdotal evidence suggests vigorous growth is becoming a nuisance to the Loch owners. The latter may reflect either an increase in the growth of macrophytes as a response to an increase in the availability of nutrients, or a change in the perception of the Loch users as a result of changing activities or expectations. Further investigation of the macrophyte community would be useful.

The Loch is small (surface area 57 ha) with a very small catchment area (193 ha), but it has a surprisingly deep basin in the north east quadrant, with a maximum depth of 11 m. The water residence time is long at 1.86 y. The catchment is part of the Loch Inch Estate and is covered by parkland (including improved grassland) and woodland. There are no surface inflows to the Loch, which is fed by rainfall, surface run-off and possibly also by groundwater. Recharge and flushing rate are expected to be slow, but nutrient losses from the catchment appear to be small.

There is a large population of wildfowl overwintering and breeding on the Loch, estimated to be in the region of 930 birds in summer and 5000 in winter. In the P budget it was estimated that birds provide around 80% of the TP input to the Loch. Discussions with the Loch owner have indicated that the wildfowl population is of particular interest and importance to the Estate, and therefore reducing the number of birds would be difficult to implement. In addition, greylag geese constitute part of the designation and so cannot readily be interfered with. Selective shooting to control the bird population is unlikely to be an option, but it may be possible to reduce bird numbers at the Loch by providing suitable alternative habitat areas. Potential sites include Black Loch, which lies < 0.5 km to the northeast and is slightly larger than White Loch, and Cutts Loch, which is smaller and lies 1 km to the east of White Loch.

There is no fishing or shooting on the Loch. The south shore has a tarmac road within the estate linking the main public road to the visitor centre, and this is heavily used by dog walkers. The main amenity value of the Loch in this case is in the attractive landscape and rural walking. During survey, several dog walkers expressed concern regarding the presence of cyanobacterial blooms in recent years, algal growth detracting from the attractiveness of the site, as well as being a potential hazard for their dogs.

The evidence of cyanobacterial blooms and vigorous macrophyte growth gives cause for concern that nutrient levels in the Loch are on a slowly rising trajectory. If left unchecked, it is likely that enrichment will continue, and the Loch could switch to an alternate state where algae are dominant and macrophyte growth is inhibited. TP levels are already high enough for an alternative algal dominant state to exist (i.e. >50 μg P L^{-1}). The water of White Loch was observed to be green and turbid, with a very low Secchi depth and high Ch*a* concentration in late summer, indicating strong algal growth. The algae were dominated by diatoms in spring and cyanobacteria in late summer, and the zooplankton appeared to be missing the efficient grazing daphnid fraction. Ch*a* modelling showed that phytoplankton growth is likely to be controlled primarily by P in White Loch, so a reduction in P loading would be expected to lead to a concomitant decrease in algal production. Nutrient reduction is therefore important in the management of the Loch.

Action is necessary to prevent the onset of algal dominance, which is unfortunately likely to be inevitable if no management is undertaken. Recommendations on management actions are given below.

- According to the SSSI designation, land management practices have already been agreed with the landowner to minimise the loss of nutrients to water. This should be revisited and checked for potential improvements, e.g. avoidance of the use of fertilisers on parkland and/or a moratorium on grazing.
- Open sections of shoreline could be planted with riparian buffer strips to intercept nutrients in surface run-off.
- Checks should be carried out on the septic tank for the estate house which lies within the Loch catchment.
- Grazing zooplankton could be promoted through the removal of all fish from the Loch. However, this is not likely to be an option due to concerns over the potential for this to have other deleterious effects on the Loch's ecosystem.
- Loch sediment could be sealed using the Riplox method to reduce internal P loading
- Bird numbers could be controlled and maintained at a sustainable level by encouraging the use of alternative habitat.

Control of bird numbers would be expected to be an effective method for reducing nutrient inputs to the Loch, as the bird population is by far the most important source of external loading to the water body. Serious consideration should be given to any acceptable controls that could be placed on the bird population, although it is recognised that the wildfowl population is of importance to the land owner and that graylag geese are protected under the designation. Inputs from land use are proportionally small, but improvements in this area should still be considered as they are likely to be achievable and acceptable to stakeholders. If all other methods fail to achieve improvements in the Loch, the Riplox method could be considered.

4.11.2 Mochrum Loch

Mochrum Loch is expected to be an oligotrophic loch, and is described as such on the citation for the SSSI. This means that nutrient levels should be very low, and the OECD and CSM Guidance define the TP range for oligotrophic lochs as being <10 µg P L^{-1}. The measured mean annual TP concentration for Mochrum Loch, based on four samples taken throughout 2010 (winter, spring, summer and late summer) was 37 µg P L^{-1}, and the growing season mean (for summer and late summer) was 35 µg P L^{-1}. This means that TP concentrations are much higher than they should be in an oligotrophic water body, lying now on the boundary between mesotrophic and eutrophic status, according to OECD (1982).

Annual and growing season mean Ch*a* concentrations were 5 and 4 µg L^{-1} respectively. These values are higher than the OECD (1982) defined range of ≤2.5 µg L^{-1} for Cha level in oligotrophic water bodies. Ch*a* levels are therefore within the mesotrophic category. These nutrient levels are not likely to be sufficiently high to promote a switch from a macrophyte dominated state to an algal dominated state, but cyanobacterial blooms have been reported through SCM. *Nuphar*, *Equisetum* and *Littorella* were observed during sampling for the present project. Macrophyte growth appeared healthy and not overly vigorous or dense. The invasive species *Crassula helmsii* is present in the Loch, but control measures have been implemented.

Mochrum Loch has the largest surface area of the eight target water bodies (178 ha). The catchment area is also large (935 ha) and the residence time is only 0.15 y. The vast majority of the Loch is shallow, with large areas ≤1 m deep, though there is one very small deep area with a maximum depth of 6 m.

In spring, diatoms dominate the phytoplankton, whilst in late summer, cyanobacteria take over. No surface bloom was observed during any of the sampling visits, but this is not surprising as surface blooms can be short-lived and are dependent on continued calm weather. Rotifers dominated the zooplankton in spring, and large grazing *Daphnia* were lacking.

Land use and management within the catchment will be an important factor in nutrient control and reduction. Land use is currently dominated by sheep and cattle grazing at a reasonably low intensity, as well as a large area of coniferous forestry plantation. Large areas of heath, smaller areas of bog and flush, along with willow carr and reedbeds indicate that some areas of the catchment are not improved or drained and consist of good quality, low nutrient export habitat.

Despite the presence of good quality habitat, the P budget for Mochrum Loch showed that export rates are considerably higher than expected for the type of land use present, indicating that changes in management may have caused elevated losses. This is equally true for all four sub-catchments and there is a need to address the issues through land management agreements. Whilst there are SNH management agreements already in place for this area, these should be revisited and expanded if possible. Inflow 3 shows a particularly elevated P export rate. The inflow is a very small stream, less than 1 m across at the mouth and with a depth of <10 cm (although it did not run dry in summer). It contained extremely high levels of TP (upwards of 150 µg P L^{-1} in summer) and 'sewage fungus' was observed within the channel. This strongly suggests that there is a malfunctioning septic tank draining into this small sub-catchment, and the property of The May located upstream should be audited in this regard. Although the dwelling appears to lie just outside the watershed of the sub-catchment, the septic tank could be within the sub-catchment and this should be looked into.

It is evident from GoogleEarth that there has been blanket clear-felling of forest, partly within the small sub-catchment of inflow 3. It is possible that this has caused deterioration of the stream and elevated nutrients within the Loch. There remains a large parcel of forest at this end of the Loch, and any future clear-felling should comply with the Forests and Water Guidelines if it cannot be avoided completely. There are further areas of forestry upstream of Castle Loch, which drains into Mochrum Loch through inflow 1. It would appear from GoogleEarth that clear-felling has also taken place within the catchment of Castle Loch in the recent past. It is possible that this could have a knock on effect of elevating nutrient levels in Mochrum Loch, although the magnitude of this impact is unclear, as Castle Loch could act as a buffer. Nevertheless, the management of the forestry areas upstream of Castle Loch should be examined.

Angling takes place at a low level, but other than this, the Loch is not used for recreation. During summer sampling, one of the inflows was observed to contain large numbers of coarse fish fry, indicating that the Loch is or was stocked as a coarse fishery (although anecdotal evidence suggests that trout and pike are also present). The outflow is managed for the purpose of generating power. The Loch level is dependent on the position of hatches on the outflow and was observed to fluctuate between sampling visits. The differing positions of the hatches indicated that the level was manipulated on a fairly regular basis. This means that the flushing rate of the Loch may be controlled to some extent.

There is a rich breeding bird assemblage at the Loch, as well as a notable breeding population of cormorants, and these are both included within the SSSI designation. Population estimates suggest that there are around 700 birds using the Loch throughout the year. The nutrient budget for the Loch showed that inputs from birds accounted for a very small proportion of the total inputs (<0.1% of the total measured budget).

A decrease in water column nutrient concentrations is necessary in order to reduce cyanobacterial blooms, create conditions suitable for plant species that are suited to habitats with low nutrient levels and return the Loch to favourable condition. Management recommendations are set out below.

- Existing land management agreements need to be revisited and updated.
- There should be a moratorium on any further forestry operations within the catchment, or at the very least, management agreements should be drawn up to observe the Forest and Water Guidelines.
- Stocking densities and slurry management within the catchment need to be reviewed and reduced.
- The septic tank arrangements at The May require to be checked and maintained, and the installation of a more modern system considered if necessary.
- The only in-loch control mechanism recommended is a change in the fisheries policy in the Loch. It is suggested that there should be no further stocking with coarse fish, as many coarse species are zooplanktivorous and can reduce top-down control of algae. Trout and pike (if present) could be encouraged by introducing a catch and return policy for these species, whilst coarse fish could be removed from the Loch when caught.

It appears that chronic nutrient enrichment is taking place, with exports coming from all parts of the catchment area, due to changes in land management. Whilst the Loch does not currently have nutrient levels that could encourage a switch to phytoplankton dominance, cyanobacterial blooms are occurring which prevent the Loch from being considered to be in favourable condition. Therefore the primary management action required is to control and reduce nutrient export throughout the entire drainage basin, through use of extensive land management agreements. Export rates are elevated both in forested and agricultural sub-catchments, indicating that both major land uses are contributing to elevated export rates and need to be managed more sensitively.

4.11.3 Woodhall Loch

Woodhall Loch is designated as an SSSI and is expected to be of oligotrophic status. The OECD (1982) and CSM guidance define the TP concentration range for oligotrophic lochs as <10 µg P L^{-1}. The annual mean measured TP level, based on four samples (winter, spring, summer and late summer) and the growing season mean TP concentration (for summer and late summer) were both 25 µg P L^{-1}, placing the Loch well into the mesotrophic (moderate nutrient) category. The defined range for Ch*a* in oligotrophic lochs is ≤2.5 µg L^{-1} (OECD, 1982). The annual and growing season means were found to be 5.3 and 3.7 µg L^{-1} respectively, again placing the Loch within the mesotrophic category. The indication is therefore that TP has risen from historical levels. Although current nutrient concentrations are unlikely to be high enough to promote a switch from macrophyte to algal dominance, there have been occurrences of cyanobacterial blooms at the Loch, indicating sensitivity to small increases in nutrients. In addition, it is likely that there has been some change in biodiversity as a response to nutrient increases, particularly to the macrophyte community which can become more diverse at first, as plants tolerant of higher nutrient levels become established in the Loch. In order to return to favourable condition, it is necessary that the rise in nutrients is curtailed and if possible, reversed.

Woodhall Loch has a surface area of 88 ha and a very large catchment area of 3007 ha, indicating a rapid turnover of water. The Loch has one of the highest drainage ratios of the eight target water bodies, at 34.2. The water retention time is short at only 0.1 y and the deepest basin, located at the north end of the Loch, has a maximum depth of 11 m. Angling, shooting, pest control and motorised boating all take place at the Loch.

The TP budget based on measured inflow data was twice the size of the modelled budget based on land use export coefficients, indicating that changes in land management have resulted in a rise in P export. The highest areal loss rates were found for Inflows 4, 5 and 6. Land use in the catchment is largely devoted to coniferous plantation forestry in the western half of the catchment and improved grassland for livestock grazing in the eastern half. It is immediately obvious from GoogleEarth that large tracts of plantation in the catchment (perhaps more than half of the forested area in the west of the catchment) have been felled in recent years. This type of forestry activity is likely to have resulted in a large export of nutrients to the Loch and may have contributed to the elevated TP levels in the water column. The largest contribution to the P budget was provided by Inflow 5, which is by far the largest sub-catchment and contains much of the clear-felled land. It should be noted, however, that nearly half of this sub-catchment is agricultural in nature, comprising improved and unimproved pasture for grazing. It is possible that stocking densities are too high for the soil type, and this could also contribute to the high export rate from this sub-catchment.

Two small sub-catchments had export rates comparable to those of Inflow 5. These were Inflow 4 in the northwest of the catchment and Inflow 6 on the eastern shore. It is not clear why Inflow 6 should contribute such high export rates. The sub-catchment consists of a mixture of coniferous woodland and pasture. Inflow 4 contains a dwelling and may receive effluents related to sewage disposal and septic tanks.

Lower export rates were observed for Inflows 1, 2 and 3, which are forested, but clear-felling has not been carried out in recent years.

There is evidence for P release from the sediments in late summer, as P concentrations at depth were higher than those in surface water at that time, with an accompanying increase in Mn in deeper water, though Mn level was not high. Woodhall Loch was the only one of the target water bodies to show any real oxygen depletion with depth (most of the lochs were too shallow to expect to see a thermocline), although this was gradual and accompanied by only a 2 °C drop in water temperature.

Birds are not protected as part of the SSSI or any other designation at the site. The bird population is small with an estimated 300 birds occupying the Loch throughout the year. The contribution of birds to the P nutrient budget was estimated to be negligible.

Cyanobacteria were not found to be dominant in the spring and late summer phytoplankton samples, despite the occurrence of cyanobacterial blooms in previous years. Green algae were found to dominate the spring sample, whilst diatoms were important in the late summer sample. Rotifers dominated the spring zooplankton whilst both Copepoda and Cladocera were found later in the year. The indication is therefore that large grazing *Daphnia* are present in the Loch, and not predated to negligible levels by zooplanktivorous fish. The composition of the fish community is not known.

Nutrient levels must be reduced in order to prevent cyanobacterial blooms, create conditions suitable for nutrient intolerant plant species and return the Loch to favourable condition. Management recommendations are set out below.

- The management of Laurieston Forest, which covers most of the western half of the catchment, should be reviewed. Management activities such as replanting, fertilising and clear-felling remaining mature areas should be carried out very sensitively. Ideally, forestry operations would cease altogether.

- Existing land management agreements should be reviewed and improved and extended where possible.
- Stocking densities and slurry management practices need reviewing and more sensitive measures put in place.
- Septic tank functioning at the dwellings of Inflow 4 should be checked. Any repairs and maintenance required should be carried out.
- The slipway in the car park at the southeast end of the Loch should be blocked, to prevent vehicular access to the Loch, as farm vehicles were observed at the water's edge. Odours and sludge at this location were suggestive of slurry contamination.
- The only suggested potential in-loch measure relates to fisheries. Care should be taken to ensure no stocking with coarse fish takes place in the Loch, and trout and pike caught should be returned (assuming there are pike in the Loch).

Management of Woodhall Loch focuses on land use practices in the catchment area, as there is a requirement to prevent and reverse the chronic nutrient losses that appear to have occurred throughout the whole catchment area, but particularly in the plantation forest in the west of the catchment.

4.11.4 Milton Loch

Milton Loch is designated as a SSSI. The eutrophic water body is a feature of interest. The OECD (1982) defines the TP boundaries of eutrophic status as 35-100 μg P L^{-1} and the Ch*a* boundaries as 8-25 μg L^{-1}. As a feature of interest, the water column TP level should be <50 μg P L^{-1}. The annual mean and growing season mean of TP levels measured in Milton Loch were 87 and 105 μg P L^{-1} respectively, whilst annual and growing season mean Ch*a* concentrations were 27 and 23 μg L^{-1} respectively. These values put Milton Loch at the boundary between eutrophic and hypertrophic status, and indicate that the ecosystem is extremely vulnerable to a switch from macrophyte to phytoplankton domination. Should this switch occur, it would result in a substantial loss in the biodiversity of the Loch, affecting macrophyte, invertebrate, bird and fish communities.

Milton Loch has a surface area of 48 ha and a small catchment area of 363 ha, suggesting it has a slow turnover of water. The Loch has a low drainage ratio of 7.6. Water retention time is 0.4 y and the deepest part of the basin, located near the centre of the Loch, is only 1.5 m deep. Coarse fishing, shooting and pest control all take place at the Loch.

The catchment of Milton Loch is the most agricultural of the eight target water bodies, with between a half and three quarters of the catchment given over to improved grassland and fairly intensive cattle grazing. Small areas of broadleaved woodland and arable land are also present. In addition, there are a number of farmyards and hard standings in the catchment which may act as intense nutrient sources. As a result, this catchment would benefit greatly from the implementation of a nutrient management plan.

There are three regular surface inflows within the watershed, and one seasonal inflow (Inflow 4) draining around 50% of the catchment area. Areal export rates are highest for Inflow 1 in the northwest of the drainage basin, but all areas of the catchment area would benefit from nutrient management planning and review of stocking densities. There are between five and 10 farm houses and other residential dwellings within the watershed, and these should all be audited with regard to septic tank functioning.

Macrophyte growth was observed to be extremely vigorous, to the extent that an outboard engine could not be used. Elevated nutrient levels can cause an increase in macrophyte growth, but this is accompanied by a loss of diversity within the plant community and therefore within the invertebrate community. The spring phytoplankton population was dominated by Cryptophyta. The late summer sample was destroyed and could not be analysed. The zooplankton community appeared to be dominated by rotifers and to lack large-bodied, grazing *Daphnia*, thereby suggesting the presence of zooplanktivorous fish. No cyanobacterial blooms were observed during sampling visits, but the summer sampling visit was marked by the appearance of significant biomass of an unknown plant species. The plants involved were tiny (<10 mm across), green and single-leaved, not unlike *Lemna* or *Wolfia*, but were distributed throughout the water column and were widespread throughout the Loch. Although these plants could not be identified, the presence of high biomass of a single taxon that was surviving within the water column was indicative of nutrient enrichment.

A large population of breeding and overwintering waterfowl is present at Milton Loch, with an estimated 550 birds occupying the Loch in summer and 2,600 in winter. The SSSI designation does not include the bird assemblage, but recommends measures to avoid their disturbance. Nutrient budgeting has shown that nearly 50% of the P entering the Loch is likely to come from the bird assemblage. Control and maintenance of the bird population at more sustainable levels is therefore desirable. There are several water bodies close to Milton Loch that potentially could be managed to provide suitable alternative habitat. These are Auchenreoch Loch, which is a similar size to Milton Loch and lies around 1 km to the west, and Lochrutton Loch, Lochaber Loch and Loch Arthur, which are all slightly smaller than Milton Loch and are located around 5 km to the east and northeast. Although the bird population does not form part of the site designation, selective shooting is nevertheless unlikely to be an acceptable approach to management of bird numbers.

The modelled nutrient budget based on land use export coefficients and the budget based on measured inflow TP concentrations were almost identical, indicating that export rates are as expected for the land use types in the catchment. Improved grassland used for reasonably high intensity grazing is by far the most extensive land use type in the catchment area, and produces a high P export coefficient.

Management to reduce nutrient inputs from agriculture should be carried out in tandem with some potential within-loch strategies. Recommendations are given below.

- As the bird population contributes a large proportion of nutrient inputs to the Loch (~50%), its sustainable control at lower levels could potentially reduce export and in-loch nutrient concentrations. This may be achievable through the provision of alternative habitat at several nearby sites, but selective shooting is unlikely to be acceptable.
- A substantial proportion of the nutrients entering the Loch come from improved grassland used for grazing and so a far-reaching land management agreement to control stocking densities and manage slurry and fertiliser is required to curtail and reduce nutrient export from this source.
- The septic tanks in the five to 10 farmhouses and dwellings within the catchment area should be audited, repaired, improved where necessary, and maintained in the long term.
- In order to encourage large-bodied grazing zooplankton, a scheme to remove all fish from the Loch could be put in place. However, this option is unlikely to be considered owing to the possibility of unforeseen deleterious effects.
- The shoreline is mainly open, with cattle having unfettered access to the shore. The Loch would benefit from riparian buffer strips, as these would serve the dual function of intercepting some of the nutrients contained in surface run-off, and acting to keep cattle away from the shoreline, thereby reducing erosion and sediment/nutrient release. Fencing to restrict access of cattle to specific areas of shoreline would also be beneficial.

4.11.5 Kilconquhar Loch

Kilconquhar Loch is designated as an SSSI. The standing water feature is a eutrophic waterbody. The OECD defines the TP boundaries of eutrophic status as 35-100 µg P L^{-1} and the Ch*a* boundaries as 8-25 µg L^{-1}. As a feature of interest, the water column TP level should be <50 µg P L^{-1}. The annual mean and growing season mean values for TP measured in Kilconquhar Loch were 169 and 292 µg P L^{-1} respectively, whilst annual and growing season mean Ch*a* concentrations were 8 and 7 µg L^{-1} respectively. The mean TP values were very high and would put Kilconquhar Loch well into the hypertrophic category, but it should be noted that three of the four samples had TP values <50 µg P L^{-1}. The late summer sample had a TP concentration of 536 µg P L^{-1} and it is this that has raised the mean value to such a high level. It is likely that this high value was caused by a short-lived event, and is not representative of the long-term TP concentration in the Loch. Given the small size of the catchment, it is highly unlikely that the high late summer concentration was caused by massive sudden export from the land surface. Equally, groundwater recharge is generally slow and unlikely to cause such an event. The shallow depth of the Loch (< 1.5 m) means that the water column will remain well-mixed throughout the year. The surface sediments are therefore unlikely to become oxygen depleted, so anoxic release of P from this source would be unlikely. It is, however, possible that oxic P release from the sediments took place as a result of unsettled or stormy weather resuspending the sediments into the water column. Such an event could be viewed as ephemeral in nature, and as three of the samples had TP concentrations <50 µg P L^{-1}, the Loch can generally be regarded as eutrophic rather than hypertrophic. Whilst the Loch appears to have (largely) the nutrient range for a eutrophic loch, as defined by OECD (1982), the occurrence of algal blooms has been noted. This suggests an increase in water column TP concentration compared with historic levels. The elevated nutrient levels in the Loch are also thought to be having a negative impact on the bird assemblage at the site.

Normally, TP concentrations around 50 µg P L^{-1} represent a level that would make a water body vulnerable to a switch from macrophyte to algal dominance. However, Ch*a* concentrations in Kilconquhar Loch are lower than expected, lying around the boundary between mesotrophic and eutrophic status. The Loch does not appear to have responded to elevated nutrient levels with an increase in phytoplankton production of the expected magnitude, and Kilconquhar Loch was the only water body not to show any change in Secchi depth throughout the year. Phytoplankton growth may be constrained by peat-stained water or self-shading, or inhibited by the vigorous macrophyte growth present throughout the Loch. Otherwise, Kilconquhar shows typical seasonal phytoplankton dynamics, with diatoms dominating in spring and cyanobacteria in the late summer. The zooplankton population was dominated by rotifers in both spring and summer, and large grazing *Daphnia* were lacking. Normally, this would indicate the presence of zooplanktivorous fish, but there is no current information on the nature of the fish community in the Loch, so this cannot be confirmed. It is thought that the plant community is impoverished in the Loch, but thick fringes of reedswamp are still in good condition. The Loch is completely surrounded by reedbed and woodland.

Kilconquhar Loch has a surface area of 19 ha and a small catchment area of 128 ha indicating a slow turnover of water. There are no surface inflows to the Loch which is fed by surface run-off, direct rainfall and by underground springs, although an assessment of the exact nature of any groundwater dynamics is beyond the scope of this project. As there are no inflows, there is no measured P budget to compare with the modelled budget. The Loch has the lowest drainage ratio at 6.6. The water retention time is 1.4 y and the Loch has a maximum depth less than 1.5 m. Shooting and boating take place at a low level. Land use in the catchment is mixed, with roughly half of the catchment devoted to arable farming, which generally results in high P export rates. A large area of broadleaved woodland and the small village of Kilconquhar also fall within the surface water catchment.

Kilconquhar Loch lies within Strathmore and Fife NVZ which was designated in 2002. A legally binding Action Programme is therefore already in place on farms within the catchment, controlling the movement, storage and application of manures and chemical fertilisers in order to reduce the amount of nitrate entering groundwaters. However, there may be additional measures that would be recommended for limiting P loss.

The breeding bird assemblage is included as part of the SSSI designation, and there are concerns that a decline in diversity and abundance of the bird population is taking place. Estimates suggest that there could be several thousand birds occupying the Loch during winter. As a conservative estimate, nutrient inputs from birds account for just below 50% of the P export into the Loch. It may be possible to encourage the bird population to use alternative habitat, although the nearest waterbody is Gillingshill Reservoir, which is around 6 km away from Kilconquhar Loch and may already sustain a large bird population.

There are therefore two main sources of nutrient export to the Loch, those being arable horticulture and the large bird population. The latter could also contribute towards a decline in plant diversity.

Recommendations for management are as follows.

- A reduction in the number of birds occupying the Loch, through encouragement to use other habitat, would go some way towards reducing the nutrient load to the Loch, as birds represent such a large proportion of the nutrient export to the water body and may be degrading the macrophyte community by direct feeding. Direct control is unlikely to be an option, given that birds constitute part of the designation.
- Land use management agreements could be drawn up to encourage a shift away from high nutrient export horticulture, or the introduction of more sensitive management practices.

Within-loch measures are not as desirable in this case, as phytoplankton levels appear to be lower than expected, considering the elevated TP concentrations present. Management should focus instead on reducing nutrient inputs from the two main sources mentioned above.

4.11.6 Dun's Dish

Dun's Dish is an SSSI designated for its breeding bird assemblage and eutrophic water body. It is very shallow with a mean depth of <0.5 m and was too shallow to survey by boat. Shore samples were obtained instead. The substrate of the Loch was firm underfoot, but constant mixing by even light winds meant that the sediments were continuously whipped up into the water column. TP levels were very high (with an annual mean of 332 µg P L^{-1} and a growing season mean of 532 µg P L^{-1}), but TP concentrations were likely to have been increased by resuspension of sediments into the water column. The nutrient dynamics of Dun's Dish are therefore different to those of other target lochs. However, due to the extreme levels of TP measured, the Loch can be classified as hypertrophic. As a feature of interest, the water column TP level should be <50 µg P L^{-1}.

Ch*a* concentrations were also in the hypertrophic category, with annual and growing season means of 31 and 43 µg L^{-1} respectively. Therefore despite the constant mixing and resuspension of sediments, the Loch has responded to elevated nutrients with elevated phytoplankton growth, and it exhibited a remarkably predictable seasonal pattern of diatom dominance in the spring, with cyanobacteria prevalent in the late summer. Zooplankton samples could not be obtained as net trawling was not practicable in such shallow water. The bed of the loch was lacking in submerged macrophyte coverage. This may have been attributable to the instability of the substrate preventing macrophytes from taking root.

However, it is possible that the substrate is unstable as a result of loss of macrophytes. Of the eight target lochs, Dun's Dish was found to be the least diverse in terms of submerged and emergent macrophytes (Table 8).

The surface area of Dun's Dish is 10 ha and the catchment area is 113 ha. As a result of the large catchment relative to loch area, in addition to the shallow depth, the water residence time in the loch was calculated at 0.055 y.

The breeding bird assemblage is protected under the SSSI designation, as well as the Montrose Basin SPA. Figures for the size of the bird population were not available, so a conservative estimate was made in comparison to the medium to large population present on Milton Loch. Surprisingly, even this conservative estimate suggested that nutrient inputs from birds were up to five times greater than those entering via Inflow 1.

There is evidence that the basin of Dun's Dish is filling in very rapidly as a result of substantial erosion from the mainly horticultural catchment (Recorda Cos, 2006). It is likely that without intervention, the water body will succeed to the reedswamp and wet woodland that surrounds it in a relatively short space of time. The loss of open water habitat would have a negative impact on the breeding bird assemblage, and a loss of diversity and magnitude of the bird population would be expected.

The first management decision that must be made is whether to permit the process of infilling and succession to continue at the present rate. Infilling of standing waters is a natural process, but it normally occurs slowly, even in shallow water bodies. However, in the drainage basin of Dun's Dish, land use appears to be of a highly erosive nature. If the basin were to fill in, it might be possible to create alternative habitat elsewhere – Dun's Dish itself was artificially created.

Alternatively, management could aim to improve the sensitivity of land use in the catchment in order to slow the process of infilling to a more natural rate and to decrease the loading of nutrients entering the system from the catchment. Eventually, succession would still occur, but a less enriched and higher quality wetland may be produced than if there were no management intervention.

A third option is to preserve and deepen the open water. There is a defunct sluice gate at the outflow, which may be used to raise water levels, but this would only be a temporary fix, as infilling would rapidly undo any gains in depth. Dredging might be considered as a more direct method of guaranteeing increased depth, but should be carried out in tandem with land management improvements, to avoid the continuance of rapid infilling.

Dun's Dish lies within Strathmore and Fife NVZ which was designated in 2002. A legally binding Action Programme is therefore already in place on farms within the catchment, controlling the movement, storage and application of manures and chemical fertilisers in order to reduce the amount of nitrate entering groundwaters.

The Loch is surrounded by a dense layer of reedswamp and wet woodland and many (but not all) of the ditches flow through wetland before entering the loch. Unfortunately, the one inflow flows directly into the water body without flowing through wetland first. This is also the case for the field drain which flows directly downhill from the farmhouse and which was found to contain 'sewage fungus' as well as vastly elevated TP concentrations. Extension of the wetlands into these areas would go some way to acting as a silt and nutrient trap, but would not be sufficient on its own to have a large impact. A general reduction of silt and nutrient export throughout the entire catchment would also be required.

The potential management interventions for Dun's Dish are summarized as follows.

- Repair and maintain the septic tank arrangements at the farmyard and farmhouse directly up the hill to the north of the loch.
- Extend wetland habitat and riparian buffer vegetation to include inflow and ditch areas and the steep downslope to the north of the loch.
- Change land use from arable horticulture to more environmentally sensitive and less erosive land use practices through land management agreements.
- Manage the water level with a sluice, to increase depth and encourage the macrophyte community.
- Mitigate the negative effects of infilling and succession on the bird population by creating alternative habitat elsewhere or encouraging use of Montrose Basin instead.
- Dredge sediments to increase depth and provide a substrate less prone to resuspension for colonisation by macrophytes.

Dredging of sediments is a management measure which is normally undertaken only when other possibilities have been excluded. It may be less effective than expected in terms of reducing TP concentrations in the water column and eliminating easily disturbed sediment, but would result in removal of elements of the biological community. There are also issues over disposal of waste.

4.11.7 Loch of Aboyne

Under the Loch of Aboyne SSSI citation, this site is described as a mesotrophic loch and so a moderate level of nutrients is expected at this site. The OECD (1982) defined the water column TP range for mesotrophic status as 10-35 µg P L^{-1}, and for Ch*a* the corresponding range is 2.5-8 µg L^{-1}. The water column TP limit recommended in the CSM Guidance for a mesotrophic feature of interest is <20 µg P L^{-1}. The annual mean TP for Loch of Aboyne was found to be 44 µg P L^{-1} whilst growing season mean was 55 µg P L^{-1}. The annual mean Ch*a* concentration was 15 µg L^{-1} and the growing season mean was 20 µg L^{-1}. All of these measurements put Loch of Aboyne within the eutrophic category, hence it may be concluded that the nutrient loading to the Loch has exceeded the carrying capacity of the system.

The Loch is small, with a surface area of 14 ha. The catchment is also small, with an area of 124 ha. Three small surface inflows feed the Loch and the water retention time is 0.6 y. The catchment is heavily wooded, especially to the northwest of the water body, with approximately half of the catchment under tree cover – both coniferous plantation and broadleaved woodland. There is a large amount of improved grassland within the watershed, which includes the golf courses, as well as farmland to the east of the Loch.

Loch of Aboyne is very important for leisure and amenity. There are golf courses on two sides and a caravan site on a third side. There is a waterski club operating on the Loch in the summer. Physical disturbance and damage from motorised boating is likely to be having a negative impact on the macrophyte community at the Loch, and this could act as a switching mechanism, should nutrient levels continue to rise and make the water body vulnerable to loss of macrophytes.

It is unlikely that fertilisers from the western golf course could make their way into the Loch, as most of the course lies downstream of the outflow. However, water is abstracted from the Loch to water the greens of this golf course. A large chunk of the eastern golf course, which uses only organic fertilisers, lies within the catchment. A newly-built holiday lodge is associated with this course. The lodge is not connected to the sewerage system, but uses a SEPA-approved soakaway system located 200 m away from the Loch, but within the catchment area. Whilst every effort has been made to reduce the impact this will have on water quality, there will inevitably be some influence on nutrient loading. It is thought that the main inflow to Loch of Aboyne (Inflow 1) has, for a long time, been abstracted from the catchment to farmland lying to the east.

Management measures to reduce nutrient loadings entering the Loch from the drainage basin would be of benefit, though it is difficult to determine where these should be put in place. Each of the three sub-catchments showed similar areal export rates estimated from measured data, and these were lower than the export rates modelled from estimated loss coefficients. The loading from Inflow 2 was marginally higher than those calculated for each of the other two inflows. A large proportion of this sub-catchment includes woodland, but the remainder is agricultural in nature, incorporating improved grassland for livestock grazing.

The Loch is artificial and was created in Victorian times for a water supply as well as recreation. A dam on the western golf course allows the Loch to exist. The outflow is not controlled, and it is thought that due to the level of abstraction from the Loch and Inflow 1, there is only flow in the outflow for three quarters of the year. During dry periods, the water level in the Loch is not sufficient to overtop the entrance to the outflow. Flushing rate is likely to be lowered by this situation, allowing nutrients to remain within the Loch for a longer time and therefore making build-up in the sediments more likely. It should be noted, however, that no evidence was found to suggest that P was being released from the sediments during the summer, and there was no evidence of oxygen depletion in the water column. Whilst abstraction from an inflow would be expected to reduce the flushing rate of the water body, abstraction directly from the Loch could be viewed as an artificial outflow and may have less impact on flushing, depending on circumstances.

The phytoplankton of the Loch was unusual in that cyanobacteria dominated in the spring, with Chlorophyta predominating later in the summer. There is likely to be top-down control of the phytoplankton by grazing zooplankton, as Loch of Aboyne was one of the few target waterbodies with summer Cladocera appearing dominant (although the genus present was *Bosmina* spp., rather than the efficiently grazing *Daphnia* spp.). Angling takes place at the Loch at a low level, but it is not clear what fish species are present or targeted by anglers. Macrophyte growth was observed to be strong in the Loch, with a range of emergent species visible in summer. Birds are not mentioned in the SSSI designation, and it is thought that there is not a significant population occupying the Loch. The water body is likely to be too small and subject to disturbance to be attractive to a large number of birds.

Recommendations for management action

- In-loch measures, such as sediment sealing and biomanipulation are unlikely to be effective in Loch of Aboyne, as there was no evidence for major P release from the sediment, and phytoplankton levels were as expected for the amount of P present.
- Nutrient management in the agricultural section of Inflow 2 may prove worthwhile in reducing overall nutrient export from the drainage basin.
- A reduction in the amount of abstraction both directly from the Loch and from Inflow 1 would improve flushing of nutrients and algae through the Loch's outflow. This would be expected to help to reduce the amount of nutrients being stored in the sediments and the biomass of phytoplankton developing in the water column.
- The coniferous plantation occupying the sub-catchments of Inflows 1 and 2 is on very steep ground, and it is important that clear-felling of this plantation does not take place, as this would be likely to result in a very large release of P directly into the Loch
- It is considered that use of power boats for water-skiing is likely to be detrimental to the macrophyte community in the Loch and represents a danger to its macrophyte-dominated state, as nutrient levels are high enough to support an alternative phytoplankton-dominated state. Consideration should be given to ways of reducing this risk.

4.11.8 Loch Spynie

Loch Spynie is small, with an area of 17 ha, but has a large catchment area of 669 ha. The water retention time is short at 0.13 y. The Loch is surrounded by reedswamp, with a vast area of swamp at its western end. The hydrology of the area is modified and complex, as the Loch was historically part of a much larger wetland system, and was originally reclaimed from the sea. The Loch is now maintained by artificial banks, with the Spynie Canal running along the western shore and an impermeable embankment on the northern shore. There is only one surface inflow feeding the Loch. It drains an extremely large and varied catchment in terms of land use, which is mainly rural with a small amount of urban development in the City of Elgin.

The nutrient budget for Inflow 1, which was estimated based on a number of P concentrations and estimated flows, was approximately 35% of the budget modelled from loss coefficients. This indicated that export rates are considerably lower than expected, judging by the type of land use present in the sub-catchment, despite more than half of the sub-catchment being taken up by improved grassland and horticulture, land uses with characteristically high export rates. Nutrient budgeting has also indicated that twice as much P may come from the large bird assemblage as from Inflow 1.

Loch Spynie is described as a eutrophic loch in its SSSI citation. The OECD (1982) defined the water column TP concentration range for eutrophic status as 35-100 µg P L^{-1}, and for Ch*a* as 8-25 µg L^{-1}. The annual mean TP level for Loch Spynie was 65 µg P L^{-1} whilst the growing season mean was 70 µg L^{-1}. The annual mean Ch*a* concentration was 17 µg L^{-1} and the growing season mean was 19 µg L^{-1}. With these concentrations, the Loch is within the expected range for its eutrophic designation, according to OECD (1982).

However, OECD (1982) included enriched water bodies. In relation to a standing water feature in Scotland, TP levels would not be expected to be higher than 50 µg P L^{-1} and site-specific targets would be more likely to be set below this level. The range of TP values in the water column of the Loch was 41 to 98 µg P L^{-1}. The variability in TP levels suggests an unstable system, i.e. one which is enriched. Ch*a* values were elevated and the concentration of dissolved inorganic nitrogen measured in water from the Loch was also very high for a Scottish water body.

With regard to work undertaken in relation to the BAP Mesotrophic Lakes and Eutrophic Standing Waters habitats, hindcasting of water column TP concentration in Loch Spynie produced an estimate of an 'original' TP level of 28.8 µg P L^{-1}. This was calculated using a model involving alkalinity and depth. There are errors associated with the model. However, this figure may be used for illustrative purposes. Alkalinity data confirm that the water body is naturally eutrophic, but comparing the hindcast and present measured TP values indicates the Loch is also artificially enriched.

Although methods used in SCM involve only a partial survey, SCM results in 2009 indicated that open water vegetation is dominated by *Ceratophyllum demersum* and *Potamogeton pectinatus*. *C. demersum* is rootless and associated with high levels of available nutrients in the water column. Although *P. pectinatus* is associated with high alkalinity water bodies, dominance of this species may also indicate enrichment. Characteristic macrophyte species were present at only 43% frequency of occurrence, rather than the target of 60%, also indicating that there has been an adverse impact on the Loch.

Analysis showed the spring phytoplankton community to be dominated by Chlorophyta and by diatoms and cryptophyta in late summer. Cyanobacteria may therefore not be at nuisance levels in the Loch, and certainly there did not seem to be the same anecdotal evidence of cyanobacterial blooms as there was for the other target lochs. However, note that dominance of green algae may be indicative of a greater degree of enrichment than cyanobacterial blooms.

TP concentrations are high enough to support a switch from macrophyte to phytoplankton dominance, and so the Loch may be in a vulnerable state. The presence of a large population of grazing birds gives cause for concern, as they provide a potential switching mechanism. The recommendation is therefore that as the Loch is enriched and may be vulnerable to further adverse impacts, it should be monitored closely over the coming years. Potential measures for reducing nutrient loadings to the Loch should be investigated.

The SSSI designation includes the breeding bird assemblage, and there is also an SPA and Ramsar designation for birds at the site. There is a well-maintained and well-used bird hide on the southern shore, so the bird population is clearly valued by the local population as well as being of high conservation importance. Measures related to the bird population may not be possible. Loch Spynie lies within Moray, Aberdeenshire / Bank and Buchan NVZ which was designated in 2002. A legally binding Action Programme is therefore already in place on farms within the catchment, controlling the movement, storage and application of manures and chemical fertilisers in order to reduce the amount of nitrate entering groundwaters. However, consideration should be given to whether the management measures in the catchment are sufficient to reduce loadings of P in addition to those of N. As nutrient loadings from improved grassland and horticulture have been found to be high elsewhere, the present efficacy of control measures associated with these land uses should be examined.

4.12 Recommendations summary table

Table 28 provides a summary of the recommended measures for each loch. Individual loch summary sheets are also presented in Appendix 1. Any difficulties associated with the measures are given along with the type of mechanism by which measures may be achieved (i.e. regulatory, voluntary or economic), the stakeholders involved and the importance of the measure. The level of importance is not the result of a cost-benefit analysis, but simply reflects the magnitude of the potential reduction in nutrient export that could be expected.

4.13 Diffuse pollution regulation

Regulation of diffuse pollution in Scotland has become a priority for achieving the aims of the WFD. Several processes have been put in place under the auspices of the WEWS (Scotland) Act 2003, including the Diffuse Pollution General Binding Rules, the Rural Diffuse Pollution Plan and the establishment of Diffuse Pollution Priority Catchments. These are introduced briefly below and further information is available through the following links:

http://www.sepa.org.uk/media/34761/car_a_practical_guide.pdf
http://www.sepa.org.uk/regulations/water/diffuse-pollution/diffuse-pollution-in-the-rural-environment/
http://www.farmingandwaterscotland.org/farmingwaterscot/info/2/know_the_rules.

4.13.1 Diffuse Pollution General Binding Rules

Activities likely to cause diffuse pollution are regulated by the Water Environment (Controlled Activities) (Scotland) Regulations 2011 as amended (CAR). The present version of the guide to CAR (7.2, March 2015) includes revisions brought in by the Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2013. There are three levels of authorisation of activities under CAR: General Binding Rules (GBRs), registration and simple/complex licensing. The level of authorisation necessary for individual activities depends on the degree of risk to the water environment.

GBRs are mandatory requirements covering activities that constitute a lower risk than those requiring registration or licensing. They are based on good management practices that focus on controlling run-off from land to water. GBRs set a statutory level of good practice for implementation across Scotland. Compliance with the diffuse pollution (DP) GBRs is assessed by a partnership that includes SEPA and farmers' organisations. Better compliance with the DPGBRs is integral to reducing the majority of diffuse pollution problems in Scotland. DPGBRs address a number of aspects of rural land use. These include:

- storage and application of fertilisers
- keeping of livestock
- cultivation of land
- application of pesticide
- operation of sheep dipping facilities
- forestry.

4.13.2 Rural Diffuse Pollution Plan

The Rural Diffuse Pollution Plan for Scotland (RDPPS) was developed by the Diffuse Pollution Management Advisory Group (DPMAG). It aims to coordinate the work of key stakeholders, promote the effectiveness of diffuse pollution reducing measures and facilitate the delivery of the River Basin Planning programme. The national RDPPS involves awareness-raising, as well as targeting efforts to particular catchments with extensive diffuse pollution problems, through a Priority Catchment (PC) approach. Information on delivery at area and catchment level is found within Area Management Plans. The RDPPS is reviewed through the River Basin Management Plan (RBMP) cycle.

4.13.3 Diffuse Pollution Priority Catchments

As part of the RBMP process, initiated to fulfil the requirements of the WFD, a programme of work aimed at reducing and preventing rural diffuse pollution commenced in 2010. The programme involves the identification of Diffuse Pollution Priority Catchments (DPPCs) that fail to meet environmental quality standards. Each DPPC is investigated by SEPA, so that issues can be identified and contact made with the local land managers who will be implementing measures to reduce and control diffuse pollution. DPPCs are reviewed for each RBMP cycle. Work undertaken also depends on SEPA's PC operational areas.

The PC approach involves catchment walks and farm visits in areas of intensive agriculture, but this strategy does not cover requirements in all catchment areas, so SEPA is also outlining DP Focus Areas (FAs). FAs involve locations with more varied land uses, isolated impacts, or more diverse or less well-understood pressures, where additional investigation of pressures and possibly the development of new strategies and measures may be undertaken.

Considering the water bodies included in the current project, White Loch and Mochrum Loch are not presently being dealt with in a DPPC or FA. Milton Loch was included in the Stewartry Coastal PC in the first cycle of RBMP. Similarly, Loch of Aboyne was included in the River Dee PC for cycle 1. Dun's Dish was included within Kincardine and Angus Coastal PC for the second cycle. Woodhall Loch is in the River Dee (Solway) PC for the second cycle, but it is only partially in SEPA's operational area. Loch Spynie is within Moray Coastal PC for the third cycle, but is not in the operation area. Kilconquhar Loch is in South Fife Coastal PC, which is a candidate catchment for 2021. It would be expected that measures to address diffuse pollution would be implemented in catchment areas of lochs that are included in the operational areas of PCs.

4.14 Potential funding sources

4.14.1 Common Agricultural Policy

The Common Agricultural Policy (CAP) is the agricultural policy of the European Union (EU). CAP implements a system of agricultural assistance and funding to target support at environmental, economic and community development across rural Scotland (https://www.ruralpayments.org/publicsite/futures/).

The present CAP involves two 'pillars': Direct Payments (Pillar 1) and the Scottish Rural Development Programme (Pillar 2). The first pillar is support to farmers' incomes. The majority of farming businesses will be allocated a new payment entitlement in 2015. Most of a farmer's payments will be made up of the Basic Payment, given on an area basis, and its associated environmental payment, known as Greening.

Under the Crop Diversification measure, farmers will be allowed to choose between Europe's standard Greening requirement and an equivalent 'winter soil cover' requirement or an equivalent 'catch crops' requirement. Regarding the Permanent Grassland measure, there is a requirement to designate important grasslands in Natura 2000 sites. A mandatory equivalent measure for farmers on permanent grasslands will require them to produce a nutrient management plan, but the aim is to target this to the most intensive farms.

Standard measures will be implemented under the Ecological Focus Area (EFA) requirement and features such as fallow, buffer strips along watercourses and field margins, catch crops and nitrogen-fixing crops (with management prescriptions) will count towards the requirement.

4.14.2 Scottish Rural Development Programme

The Scottish Rural Development Programme (SRDP) 2014 - 2020 delivers Pillar 2, which funds economic, environmental and social measures for the benefit of rural Scotland (http://www.gov.scot/Topics/farmingrural/SRDP/SRDP20142020Schemes). SRDP is funded by the European Commission and the Scottish Government and its main priorities are as follows:

- sustainable economic growth
- protecting and improving the natural environment
- addressing the impact of climate change
- supporting rural communities.

A number of schemes will operate under SRDP, including those described below.

Forestry Grant Scheme

The Forest Grant Scheme involves a range of grants for woodland creation, agroforestry, tree health, woodland improvement, processing and marketing and sustainable management of forests.

Environmental Co-operation Action Fund

The Environmental Co-operation Fund is for facilitation of projects to drive forward improvements at an ecosystem scale, in order to achieve environmental obligations more effectively.

LEADER

LEADER will provide opportunities for individuals, businesses and communities to come together and support rural development, and provide long-lasting benefits to the local area. This will include support for non-agricultural small businesses, including farm diversification.

Agri-Environment Climate Scheme

The Agri-Environment Climate Scheme (AECS) is designed to support land management practices for the protection and enhancement of natural heritage and water quality, management of flood risk, and adaptation to climate change. The Rural Payments and Inspections Division (RPID) of the Scottish Government and Scottish Natural Heritage (SNH) have responsibility for the delivery of AECS, which will run from 2015 to 2020.

A wide range of management options and capital items are available under AECS, but it is targeted to individual farms. Applicants can check which options are available to them through the following link: http://targeting.ruralpayments.org/, before applying for funding.

A Farm Environment Assessment (FEA) will normally be required for applications to the AECS. The FEA involves a summary of important environmental features, so helps in the consideration of what to include in the application.

Funding is available to protect and enhance the natural environment in a number of ways, including the following:

- delivery of the 2020 Challenge for Scotland's Biodiversity by supporting appropriate management for vulnerable and iconic species and habitats, strengthening ecological networks, controlling invasive non-native species and enhancing the condition of protected nature sites
- contribution to Scotland's world-leading climate change targets by reducing greenhouse gas emissions from agriculture and securing carbon stores in peatlands and other organic soils
- meeting obligations to improve water quality under the EU WFD by reducing diffuse pollution
- controlling flooding through natural flood risk management
- supporting organic farming.

Funding for slurry storage specifically will become available in 2016.

Where there is strong justification for applying for management options that are not targeted on a holding, depending on the options concerned, applicants should contact Forestry Commission Scotland, SEPA or SNH, to discuss whether these organisations would provide an endorsement.

Management options available for designated sites

If intending to carry out management to benefit a designated site (SSSI, Special Protection Area or Special Area of Conservation), it is possible to apply for any management options which will benefit the special features of the site, but advice should be sought from SNH before completing any application.

Managing water quality and flood risk may include the following:

- converting arable land at risk of erosion or flooding to low-input grassland

- management of floodplains
- rural Sustainable Drainage Systems – sediment traps and bunds
- rural Sustainable Drainage Systems – swales
- Rural Sustainable Drainage Systems – retention Pond
- managing steading drainage and Rural Sustainable Drainage Systems
- alternative watering
- hard standings for troughs and gateways
- livestock tracks
- livestock crossing
- rural Sustainable Drainage Systems – wetland
- river embankment breaching, lowering or removal
- restore (protect) river banks.

4.14.3 SEPA Water Environment Fund

Previously known as the Restoration Fund, the Water Environment Fund (WEF) provides funding to projects designed to preserve and improve the water environment. The fund aims to restore Scotland's catchment areas, where activities have left them damaged, thereby contributing to RBMPs. One mechanism by which SEPA aims to improve the water environment is through the Controlled Activities Regulations (CAR). However, work that falls within normal duties or regulatory responsibilities will not be funded through the WEF.

WEF funding is aimed at external stakeholders, partnership working and projects that contribute to WFD objectives. Applications for projects tackling physical pressures affecting the water environment and projects delivering wider environmental, social and economic benefits are welcomed. Projects covered by this fund must address one or more of the following:

a) restoration of the morphology of the water environment
b) removal of barriers to migration of fish
c) control of invasive non-native species (INNS).

Projects on morphology may relate to restoration of the banks, bed and shore of water bodies.

The WEF is now closed to applications for funding to control INNS, as all funds for that purpose have been committed.

4.14.4 Scottish Natural Heritage grants

At the time of writing (June 2015), SNH is not receiving new funding requests. When this position changes, information will be provided on SNH's internet site (http://www.snh.gov.uk/).

SRDP is now the main source of Government funding for rural land management, including management to benefit nature and landscapes, and people's enjoyment of these assets. For projects that are eligible for funding from SRDP, applications should be made directly to SRDP.

SNH would offer grant support for projects not covered by SRDP and would also consider match funding LEADER external site projects. However, a decision on whether to fund these projects would be based on the availability of funding and how well the project matches SNH's priorities. SNH would give grants to support projects that increase the public benefits delivered through Scotland's nature and landscapes, and to improve the health of these natural assets. In funding projects, SNH would expect contributions to the following outcomes:

1. a wider range of people experiencing, valuing and helping to look after nature and landscapes
2. better places in which to live, work and visit
3. improvements in the health of Scotland's nature and landscapes
4. sustainable management of nature and landscapes as a key asset for
5. sustainable economic growth.

Funding would be more likely to be given to projects having particular attributes. Assessors would look for strong contributions to a limited number of priorities, though projects with the potential to deliver multiple benefits would be considered. Projects that would have a large impact on delivering SNH's outcomes and priorities, help to prevent problems in future, or result in the development of good practice that can be used elsewhere, would all be more likely to be funded.

4.14.5 Voluntary actions

Voluntary actions must be governed by a wide-ranging set of codes and guidance to ensure they are carried out in the most judicious manner. A description of the relevant guidance is given below.

Prevention of Environmental Pollution from Agricultural Activity

Any voluntary actions undertaken by landowners should comply with the "Prevention of Environmental Pollution from Agricultural Activity Code of Good Practice" (PEPFAA Code). The Code provides guidance for farmers on minimising the risk of causing environmental pollution, particularly to water, through farming activities. The Code reflects the provisions of GAEC and gives advice regarding mandatory and voluntary measures. Diffuse pollution, N and P and waste management are all covered by the Code.

The Four Point Plan

"The Four Point Plan" (FPP) aims to improve farm waste management and thereby reduce diffuse pollution for the purposes of compliance with the Nitrates Directive and WFD. Practices included in the plan were identified by the Scottish Agricultural College (SAC) and include the following:

- management of dirty water around the steading
- better nutrient use
- risk assessments for manure and slurry
- managing water margins.

It is intended that measures connected with the FPP should have no cost, be voluntary in nature and give rise to benefits for both the farmer, by cutting costs and assisting in grant aid application, and the environment, by improving water quality. The FPP complements the PEPFAA Code and is a step towards producing a Farm Waste Management Plan (FWMP).

BMP handbook

The FPP and PEPFAA code are complemented by Best Management Practices (BMPs) for the control of diffuse pollution from farming activities (http://apps.sepa.org.uk/bmp/). The "Handbook of BMPs for the Reduction of Pollutants Emanating from Diffuse Sources into Surface Waters" describes a range of BMPs addressing a variety of diffuse pollution problems associated with agriculture. The Handbook is part of the Farm Scale Diffuse Pollution Audit process developed by SEPA and partners. The measures described in the Handbook address diffuse pollution problems arising in the field or in and around the steading and affecting riparian habitats, e.g. storage and application of fertilisers, keeping of livestock and cultivation of land. They range from low or no cost changes, to routine practices, to the installation of treatment facilities.

Table 28. Recommendations summary

Loch	Recommended measure	Mechanism	Stakeholders	Importance*
White loch	Improvements in sensitive land management practices throughout the catchment. Awareness raising of diffuse pollution issues	Economic	SNH, landowner	High
White loch	Planting of open sections of shoreline with riparian buffer strips to intercept nutrients in surface run-off	Voluntary/ economic	Landowner	Medium
White loch	Audit and/or replacement of septic tank serving the estate house and potentially the visitors' centre	Regulatory	Landowner, SEPA	High
White loch	If other methods fail, consider use of Riplox method to seal sediments and reduce internal P loading		Landowner, SNH	Low
White loch	Control of bird numbers and maintenance at a sustainable level by encouraging the use of alternative habitat (this option is likely to be difficult to implement due to the protection afforded to birds, as well as their conservation importance)	Voluntary/ economic	SNH, landowner, RSPB	High
Mochrum Loch	There should be a moratorium on any further forestry operations within the catchment. As a minimum, management agreements to observe the Forest and Water Guidelines	Voluntary/ economic	Forest managers, Forestry Commission Scotland (FCS), landowners	High
Mochrum Loch	Existing land management should be reviewed and funding for measures obtained where possible. Awareness raising of diffuse pollution issues	Voluntary/ economic	Landowners	High
Mochrum Loch	Livestock stocking densities and slurry management practices should be reviewed and improved as appropriate	Voluntary/ economic	Landowners, SNH, SEPA	High

Loch	Recommended measure	Mechanism	Stakeholders	Importance*
Mochrum Loch	Audit and/or replacement of septic tank serving The May on the southeast shore	Regulatory	Landowner, SEPA	High
Mochrum Loch	No further stocking with coarse fish, as many coarse species are zooplanktivorous and can reduce top-down control of algae. Trout and pike should be encouraged by introducing a catch and return policy for these species, while coarse fish should be removed from the Loch when caught. This recommendation could be unpopular with anglers and Loch managers and wide consultation would be necessary in its consideration	Voluntary	Angling club, GFT	Medium
Mochrum Loch	Review of hatch operation on the outflow to control water levels in the Loch (CAR)	Regulatory	SEPA, landowner	Medium
Woodhall Loch	Land management should be reviewed and improved	Voluntary/ economic	Landowners, SNH	High
Woodhall Loch	Livestock stocking densities and slurry management practices need to be reviewed and more sensitive measures put in place. Awareness raising of diffuse pollution issues	Voluntary/ economic	Landowners, SNH, SEPA	High
Woodhall Loch	Audit and/or replacement of septic tanks of the houses in Inflow 4	Regulatory	Home owners, SEPA	High
Woodhall Loch	The slipway in the car park at the southeast end of the Loch should be blocked to prevent vehicular access to the water	Voluntary	Landowner, SNH, angling club	Medium
Woodhall Loch	Stocking with coarse fish should not take place in the Loch, and any trout and pike caught should be returned. This action could be unpopular with anglers, so the local club should be closely involved and consulted in considering this recommendation	Voluntary	Angling Club, GFT	High
Woodhall Loch	The management of Laurieston Forest, which covers most of the western part of the catchment, should be reviewed. Management activities such as	Voluntary/ economic	Forest managers, FCS, landowners, SNH	High

Loch	Recommended measure	Mechanism	Stakeholders	Importance*
	replanting, fertilising and clear-felling remaining mature areas should be carried out very sensitively. Ideally, forestry operations would cease altogether			
Milton Loch	Planting of open sections of shoreline with riparian buffer strips to intercept nutrients in surface run-off and fencing to prevent unrestricted access of cattle to shoreline	Voluntary	Landowners, SNH	Medium
Milton Loch	Control of livestock stocking densities and appropriate management of slurry and fertiliser is required to curtail and reduce nutrient export from these sources. Awareness raising of diffuse pollution issues	Economic	SEPA, SNH, landowners	High
Milton Loch	Control of bird numbers and maintenance at a sustainable level by encouraging the use of alternative habitat at several nearby sites	Voluntary/ economic	RSPB, SNH	High
Milton Loch	Audit and/or replacement of septic tank functioning at all houses in the catchment	Regulatory	SEPA, landowners	High
Kilconquhar Loch	Encourage a shift away from high nutrient export horticulture. Introduction of more sensitive management practices. Awareness raising of diffuse pollution issues	Voluntary/ economic	SEPA, SNH, landowners	High
Kilconquhar Loch	Control of bird numbers and maintenance at a sustainable level by encouraging the use of alternative habitat (this option is likely to be very difficult to implement due to the protection afforded to the birds)	Voluntary/ economic	RSPB, SNH, landowners	High
Dun's Dish	Repair, replacement and maintenance of the septic tank arrangements at the dwelling directly to the north of the Loch (Damside Farm)	Regulatory	Landowner, SEPA	High
Dun's Dish	Extension of wetland habitat and riparian buffer vegetation to include inflow and ditch areas and the steep downslope to the north of the Loch	Voluntary	SEPA, landowners	High

Loch	Recommended measure	Mechanism	Stakeholders	Importance*
Dun's Dish	Water level management to increase depth may help to restore macrophyte community. Further consideration would be required	Regulatory	SNH, landowners, SEPA	-
Dun's Dish	Changes in land use away from arable horticulture to more environmentally sensitive and less erosive land use practices. Awareness raising of diffuse pollution issues	Voluntary/ economic	SEPA, Landowners, SNH	High
Dun's Dish	Create alternative habitat elsewhere for birds. Wide consultation would be necessary if this option were to be considered.	Voluntary	RSPB, landowners, SNH	-
Dun's Dish	If other methods fail, consider dredging of sediments to increase depth and restore macrophyte community. Such an action would require careful consideration and wide consultation, as it is extremely invasive, may be of limited effectiveness in reducing turbidity and nutrient levels, and it would remove seedbank	-	SNH, landowners, SEPA	-
Loch of Aboyne	Sensitive land use practices and nutrient management in the sub-catchment of Inflow 2. Awareness raising of diffuse pollution issues	Voluntary/ economic	SEPA, landowners, SNH	High
Loch of Aboyne	Reduction in abstraction to increase flushing rate	Regulatory	SEPA, RSPB, landowners and water users	High
Loch of Aboyne	Sensitive management of coniferous forestry plantation	Voluntary/ economic	Forest managers, FCS, landowners, SNH	High
Loch of Aboyne	Consideration should be given to ways of reducing the risk to macrophytes from water-skiing on the Loch	Voluntary	Waterski club, landowners, SNH	Medium
Loch Spynie	Further monitoring of the water body and investigation of the catchment area	Economic	SNH, RSPB, landowner	Medium

*Importance is not the result of a cost-benefit analysis but simply a reflection of the scale of reduction in nutrient export that might reasonably be expected as a result of the measure

Note that removal of fish has not been included as a recommendation for these sites, owing to the possibility of problems arising through this approach to management.

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APPENDIX 1: LOCH SUMMARY SHEETS

Loch Summary Sheet – White Loch

Loch and catchment information

- SSSI feature: eutrophic loch
- Large bird population protected under SSSI designation
- Subject to cyanobacterial blooms, therefore considered to be in unfavourable condition
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 62 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 92 µg P L^{-1}
- 2010 mean chlorophyll *a* 19 µg L^{-1}
- TP levels within expected range for eutrophic status according to OECD (1982), but in excess of levels expected in SSSI feature and likely to be considerably higher than historic levels
- Evidence for P release from sediments in late summer
- NGR NX107608
- Loch area 58 ha
- Catchment area 235 ha
- Maximum depth 11 m
- Loch volume 2,605,150 m^3
- Water retention time 1.8 y

Nutrient budget

- No surface inflows
- Land use primarily parkland (including improved grassland) and mature broadleaved woodland
- No shooting, angling or motorised boating
- Large bird population estimated at 930 birds in summer and 5000 in winter (including greylag and white fronted goose)
- Loadings from catchment land use relatively small at approximately 20% of the total loading
- Loading from bird population accounts for around 80% of the total loading

Issues

- Nutrient enrichment has made the Loch extremely vulnerable to a switch from macrophyte dominated to algae dominated state
- Bird population highly valued by Loch owners, as well as being of nature conservation value
- Grazing by birds represents a potential forward switch to algal dominance

Biomass

- Vigorous macrophyte growth – Loch currently in a macrophyte dominated state
- Phytoplankton growth very strong, particularly in late summer when water appeared turbid and green (Secchi depth 1 m). Chlorophyll *a* concentration was very high. Algae dominated by diatoms in the spring and cyanobacteria in late summer
- Zooplankton dominated by rotifers and lacking large grazing *Daphnia* indicating presence of zooplanktivorous fish

Recommendations

- Encourage bird population to use alternative habitats.
- Audit sewage disposal facilities at gate lodge, estate house and visitor centre to ensure no effluents are entering the Loch.
- Consider riparian planting along open sections of shoreline to intercept nutrients in surface run off.
- Reduce nutrient exports from land to water through appropriate land management.
- If all other methods fail, consideration could be given to using Riplox to seal sediments and reduce internal loading.


A751
A75
Aird
© 2010 Tele Atlas
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Image © 2010 Getmapping plc
©2010 Google
Imagery Date: 1/1/2003
54°54'27.34" N 4°56'58.71" W elev 39 m
Eye alt 3.36 km

Loch Summary Sheet – Mochrum Loch

Loch and catchment information

- SSSI feature: oligotrophic loch
- Significant breeding bird assemblage protected under SSSI designation
- Subject to cyanobacterial blooms, therefore considered to be in unfavourable condition
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 37 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 35 µg P L^{-1}
- 2010 mean chlorophyll *a* 5 µg L^{-1}, growing season chlorophyll 4 µg L^{-1}
- In-loch TP and chlorophyll concentrations much higher than expected for an oligotrophic loch (eutrophic and mesotrophic levels respectively, according to OECD (1982), so in excess of levels expected in an SSSI feature) and presumably much higher than historical levels
- Evidence that P may be released from the sediments in late summer
- NGR NX302529
- Loch area 91 ha
- Catchment area 530 ha
- Maximum depth 6 m
- Loch volume 1,925,546 m^3
- Water retention time 0.15 y

Nutrient budget

- Four surface inflows draining 70% of catchment
- Nutrient budget based on measured inflow data approximately four times larger than budget modelled from loss coefficients, indicating that changes in land use are leading to increased nutrient export throughout catchment
- Land use primarily low intensity grazing on unimproved grassland and coniferous forestry plantation
- Angling takes place on the Loch, but there is no motorised boating
- Rich bird assemblage with estimates of 700 birds occupying the Loch throughout the year
- Estimates indicate P loading from bird population accounts for less than 0.1% of the total loading
- Highest P export found in Inflow 3 which is polluted by sewage (from septic tanks) and recent clear-felling

Issues

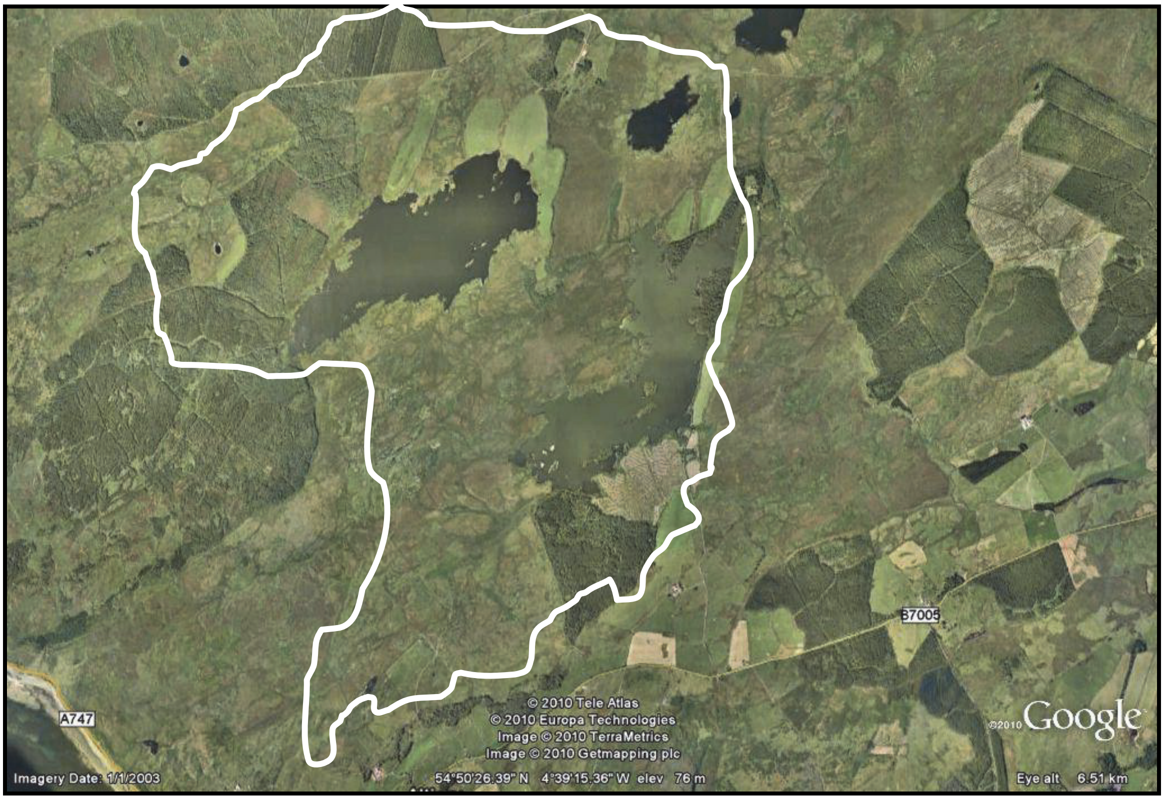
- Chronic increase in nutrient export rates throughout entire catchment due to changes in land use practices
- Clear-felling has taken place in reasonably large areas of the catchment, and there is more mature plantation that could be felled in the near future
- Possible increase in livestock grazing intensity and/or problems with slurry management
- Presence of coarse fish could reduce top-down control of phytoplankton
- Possible malfunctioning septic tank at Inflow 3

Biomass

- Healthy macrophyte growth, but with lower nutrient and higher nutrient tolerant plants present – Loch currently in a macrophyte dominated state
- Algae dominated by diatoms in the spring and cyanobacteria in late summer
- Zooplankton dominated by rotifers and lacking large grazing *Daphnia* indicating presence of zooplanktivorous fish
- Angling for trout, pike and coarse fish

Recommendations

- Improve land management practices to reduce chronic increase in nutrient export throughout the entire catchment.
- There should be a moratorium on clear-felling in the catchment, or at the very least, the *Forests and Water Guidelines* should be followed.
- Livestock stocking densities and slurry management practices should be reviewed and improved as appropriate.
- Septic tank functioning at Inflow 3 needs to be checked, improved and maintained as ‘sewage fungus’ was present in the inflow.
- Examine outflow hatch operation for potential ways of improving conditions in Loch.
- Fisheries policy could focus on reducing coarse fish in the Loch whilst encouraging trout and pike, in order to promote top-down control of phytoplankton.



© 2010 Tele Atlas
© 2010 Europa Technologies
Image © 2010 TerraMetrics
Image © 2010 Getmapping plc
A747
B7005
Imagery Date: 1/1/2003
54°50'26.39" N 4°39'15.36" W elev 76 m
Eye alt 6.51 km
©2010 Google

Loch Summary Sheet – Woodhall Loch

Loch and catchment statistics

- SSSI designation: oligotrophic water body
- Considered to be in unfavourable condition, as subject to cyanobacterial blooms
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 25 μg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 25 μg P L^{-1}
- 2010 mean chlorophyll *a* 5.3 μg L^{-1}, growing season chlorophyll 3.7 μg L^{-1}
- In-loch TP concentrations much higher than expected for an oligotrophic loch and likely to be much higher than historical levels
- Evidence that there may be P release from the sediments in late summer
- NGR NX671674
- Loch area 88 ha
- Catchment area 3007 ha
- Maximum depth 15 m
- Loch volume 4,077,626 m^3
- Water retention time 0.1 y

Nutrient budget

- Six surface inflows draining 90% of catchment
- Nutrient budget based on measured inflow data approximately twice as large as modelled budget indicating changes in land use leading to increased nutrient export throughout catchment
- Land use primarily coniferous plantation and grazing on improved grassland
- Angling, shooting and motorised boating take place on the Loch
- Small, undesignated bird assemblage with estimates of 300 birds occupying the Loch throughout the year
- Loading from bird population negligible
- Highest export rates found in Inflows 4, 5 and 6 due to clearfelling (Inflow 5), probable malfunctioning septic tanks (Inflow 4) and unknown causes (Inflow 6)

Issues

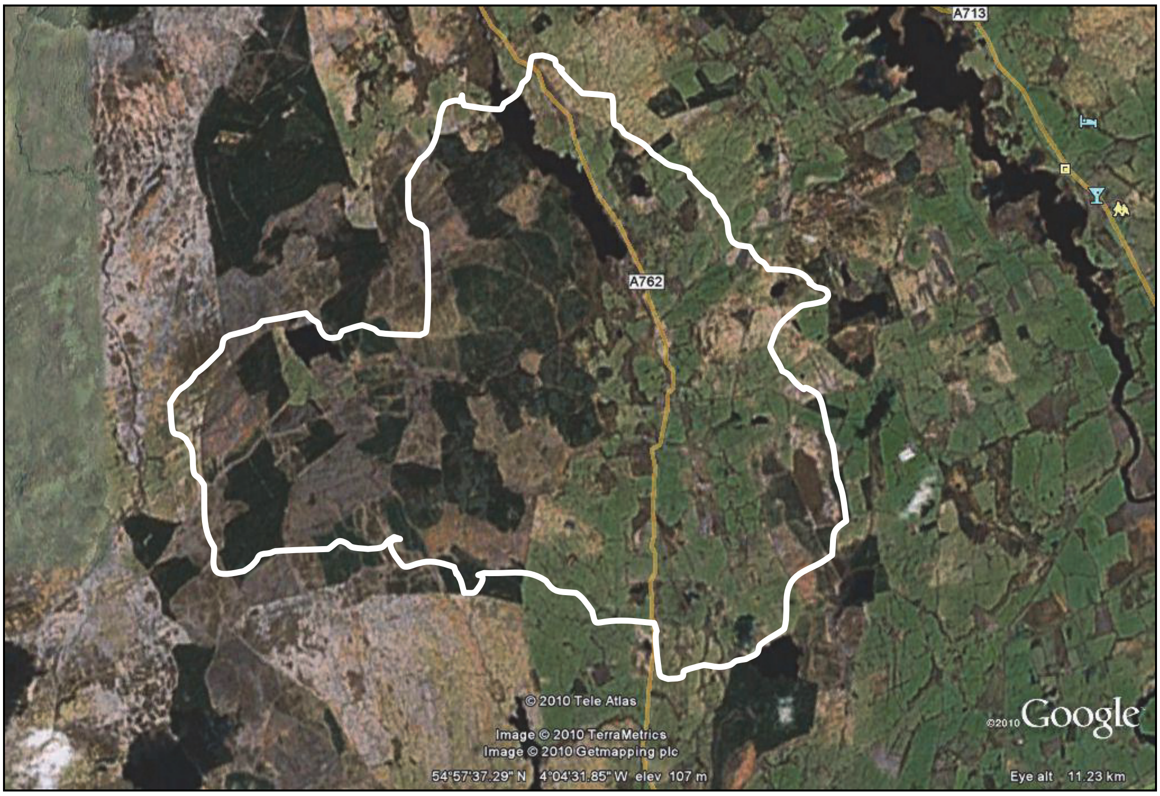
- Chronic increase in nutrient export rates throughout entire catchment due to changes in land use practices
- Clearfelling has taken place in very large areas of the catchment, and there is more mature plantation that may be felled in the near future
- Possible increase in grazing intensity and/or problems with slurry management
- Possible malfunctioning septic tank(s) at Inflow 4

Biomass

- Healthy macrophyte growth – Loch currently in a macrophyte dominated state
- Phytoplankton dominated by green algae in the spring and diatoms in late summer
- Cyanobacteria not thought to be dominant despite occurrence of blooms
- Zooplankton dominated by rotifers in the spring but with both Cladocera and Copepoda present later in the year that could exert top-down control on phytoplankton
- Angling target species not known

Recommendations

- Management needs to focus on addressing the chronic increase in nutrient export throughout the entire catchment, particularly in Laurieston Forest, which occupies the western half of the catchment.
- Land management should be reviewed.
- There should be a moratorium on clearfelling in the catchment, or at the very least, *Forests and Water Guidelines* should be followed.
- Stocking densities and slurry management practices in the eastern part of the catchment should be reviewed and improved as appropriate.
- Septic tank functioning at Inflow 4 needs to be checked, improved and maintained.
- Fisheries policy should ensure that coarse fish are not stocked in the Loch, and that trout and pike are returned.


A713
A762
© 2010 Tele Atlas
Image © 2010 TerraMetrics
Image © 2010 Getmapping plc
54°57'37.29" N 4°04'31.85" W elev 107 m
©2010 Google
Eye alt 11.23 km

Loch Summary Sheet – Milton Loch

Loch and Catchment statistics

- SSSI designation: eutrophic water body
- Considered to be in unfavourable condition due to poor water quality
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 87 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 105 µg P L^{-1}
- 2010 mean chlorophyll *a* 27 µg L^{-1}, growing season chlorophyll 23 µg L^{-1}
- In-loch TP and chlorophyll concentrations are at the high end of eutrophic category according to OECD (1982), sometimes crossing the boundary into hypertrophic status and likely to be much higher than historical levels. TP and chlorophyll levels considerably higher than targets for feature
- NGR NX839715
- Loch area 48 ha
- Catchment area 363 ha
- Maximum depth 1.5 m
- Loch volume 1,274,258 m^3
- Water retention time 0.4 y

Nutrient budget

- Four surface inflows draining 50% of catchment
- Nutrient budget based on measured inflow data very similar to modelled budget indicating that export is as expected for the land use type
- Land use primarily improved grassland for high intensity grazing, with some arable farming
- Angling, shooting and pest control take place on the Loch
- Large but undesignated bird assemblage with estimates of 550 birds occupying the Loch in summer and 2,600 in winter
- Loading from bird population represents around half of the TP budget
- Highest export rate found in Inflow 1, but all subcatchments and surface drained areas require to be managed for nutrients

Issues

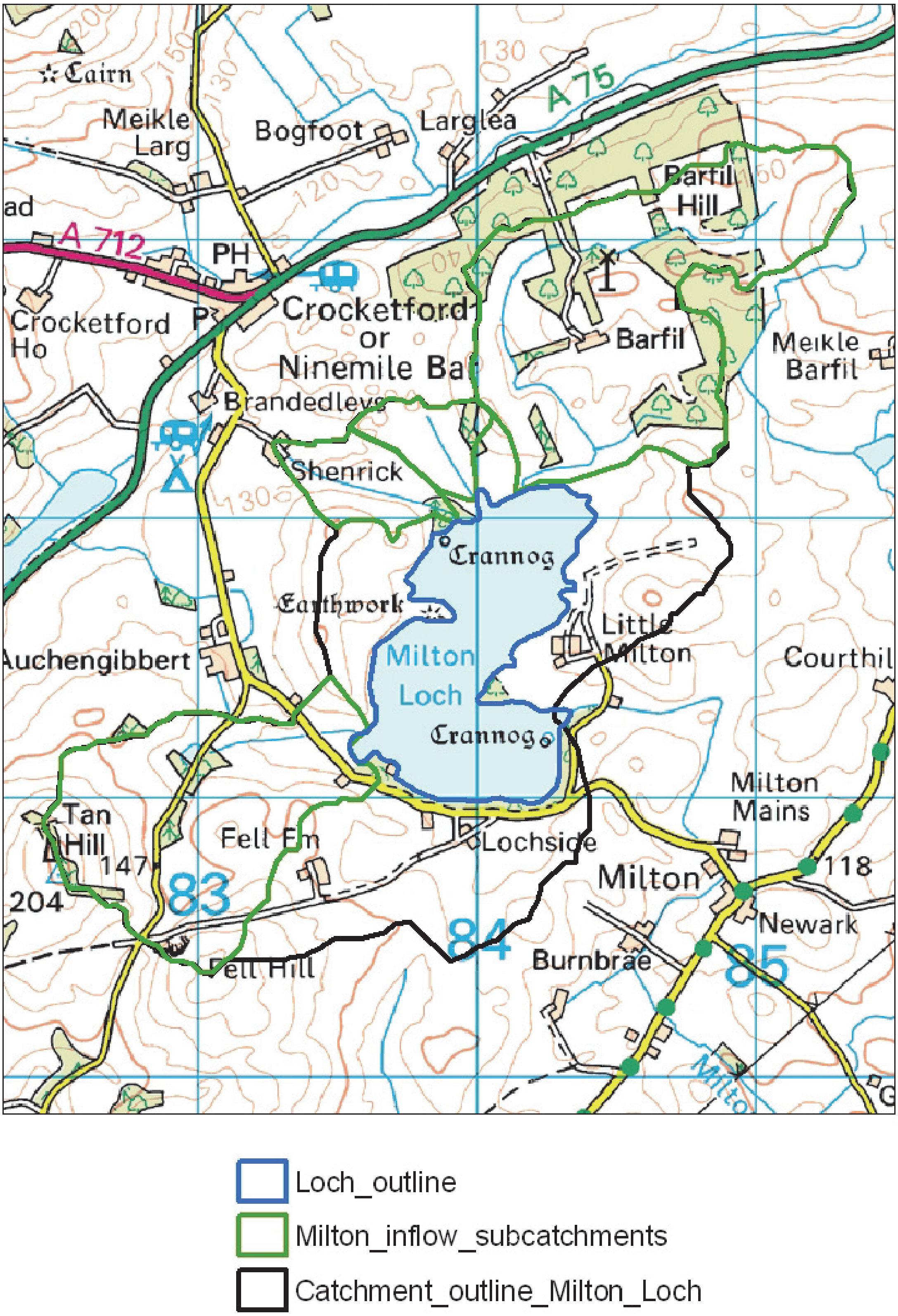
- High export rates from improved grassland used for high intensity cattle grazing throughout entire catchment
- Possible increase in grazing intensity and/or problems with slurry management
- Large bird population contributing nearly half of the P entering the loch

Biomass

- Vigorous and dense macrophyte growth – Loch currently in a macrophyte dominated state, but plant diversity likely to be compromised due to enrichment
- Unusual phytoplankton community, dominated by Cryptophyta in the spring
- Unusual summer bloom of unknown higher plant throughout water column
- Zooplankton dominated by rotifers in the spring and lacking large, grazing *Daphnia* indicating presence of zooplanktivorous fish

Recommendations

- Stocking densities and slurry management practices should be reviewed and improved as appropriate.
- Septic tank functioning at the 5-10 dwellings in the catchment should be checked, improved as required and maintained in the longer term.
- Encouragement of the bird population to use alternative habitats could have a proportionally large beneficial impact.
- Installation of riparian buffer strips along the large areas of open shoreline would help by intercepting nutrients and preventing cattle access to the shore.
- Stocking of pike would encourage large grazing zooplankton, but manipulation of the fish community could be problematic.


Cairn
Meikle Larg
Bogfoot
Larglea
A 75
Barfil Hill
A 712
PH
Crocketford Ho
Crocketford or Ninemile Bar
Barfil
Meikle Barfil
Brandedleys
Shenrick
Crannog
Earthwork
Little Milton
Milton Loch
Auchengibbert
Courthill
Crannog
Milton Mains
Tan Hill
147
204
Fell Fm
Lochside
Milton
118
Newark
83
84
85
Fell Hill
Burnbrae
Loch_outline
Milton_inflow_subcatchments
Catchment_outline_Milton_Loch

Loch Summary Sheet – Kilconquhar Loch

Loch and catchment statistics

- SSSI designation as a eutrophic water body
- considered to be in unfavourable condition due to poor water quality
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 169 µg PL^{-1}
- 2010 growing season (summer and late summer) mean TP 292 µg P L^{-1}
- Predicted Loch TP 143 µg P L^{-1}
- 2010 mean chlorophyll *a* 8 µg L^{-1}, growing season chlorophyll 7 µg L^{-1}
- Predicted chlorophyll 68 µg L^{-1} therefore phytoplankton suppressed by factors other than TP limitation
- In-Loch TP concentrations are within the hypertrophic category of OECD (1982), so are in excess of levels expected in an SSSI feature and are likely to be much higher than historical levels
- NGR NO487017
- Loch area 19.3 ha
- Catchment area 128 ha
- Maximum depth 1.5 m
- Loch volume 453,070 m^3
- Water retention time 1.4 y

Nutrient budget

- No surface inflows to Loch
- Land use primarily arable farming with areas of broadleaved woodland and extensive reedbeds
- No angling, shooting or boating takes place on the Loch
- Large but undesignated bird assemblage with estimates of several thousand birds occupying the Loch
- Loading from bird population represents around 40% of the TP budget

Issues

- High export rates from arable agriculture
- Large bird population contributing nearly half of the P entering the Loch
- Suspected oxic release of P from sediments leading to large rise in TP concentrations in the water column

Biomass

- Vigorous and dense macrophyte growth throughout the Loch
- Diatoms dominant in spring and cyanobacteria prevalent in late summer
- Zooplankton dominated by rotifers throughout the year and lacking large, grazing *Daphnia* indicating possible presence of zooplanktivorous fish

Recommendations

- Reduce the impact on nutrient export from large tracts of arable horticulture in the catchment.
- Encourage bird populations to use alternative habitats, as nearly half of P inputs are thought to arise from this source.


Kilconquhar
Kilconquhar, Leven, KY9 1 UK
Main St
B941
A917
© 2010 Tele Atlas
© 2010 Europa Technologies
©2010 Google
Imagery Date: 1/1/1999
56°12'32.80" N 2°49'33.37" W elev 21 m
Eye alt 2.28 km

Loch Summary Sheet – Dun's Dish

Loch and catchment statistics

- SSSI designation as a eutrophic water body
- Considered to be in unfavourable condition due to poor water quality
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 332 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 532 µg P L^{-1}
- Predicted loch TP 1188 µg P L^{-1}
- 2010 mean chlorophyll 31 µg L^{-1}, growing season chlorophyll 43 µg L^{-1}. Predicted chlorophyll 115 µg L^{-1} so phytoplankton suppressed by factors other than TP limitation
- In-loch TP concentrations within hypertrophic category (OECD, 1982), so in excess of levels expected in an SSSI feature and likely to be much higher than historical levels
- NGR NO647609
- Loch area 10.4 ha
- Catchment area 113.4 ha
- Maximum depth 0.5 m
- Loch volume 26,000 m^3
- Water retention time 0.06 y

Nutrient budget

- One surface water inflow draining 80% of catchment
- Network of field drains and ditches present
- Nutrient budget based on measured inflow data smaller than modelled budget indicating that export is not as high as expected for the land use type
- Nearly half of the catchment given over to arable horticulture
- Shooting takes place on the loch
- Very large breeding bird assemblage is included in the designation
- Loading from bird population represents around three quarters of the TP budget

Issues

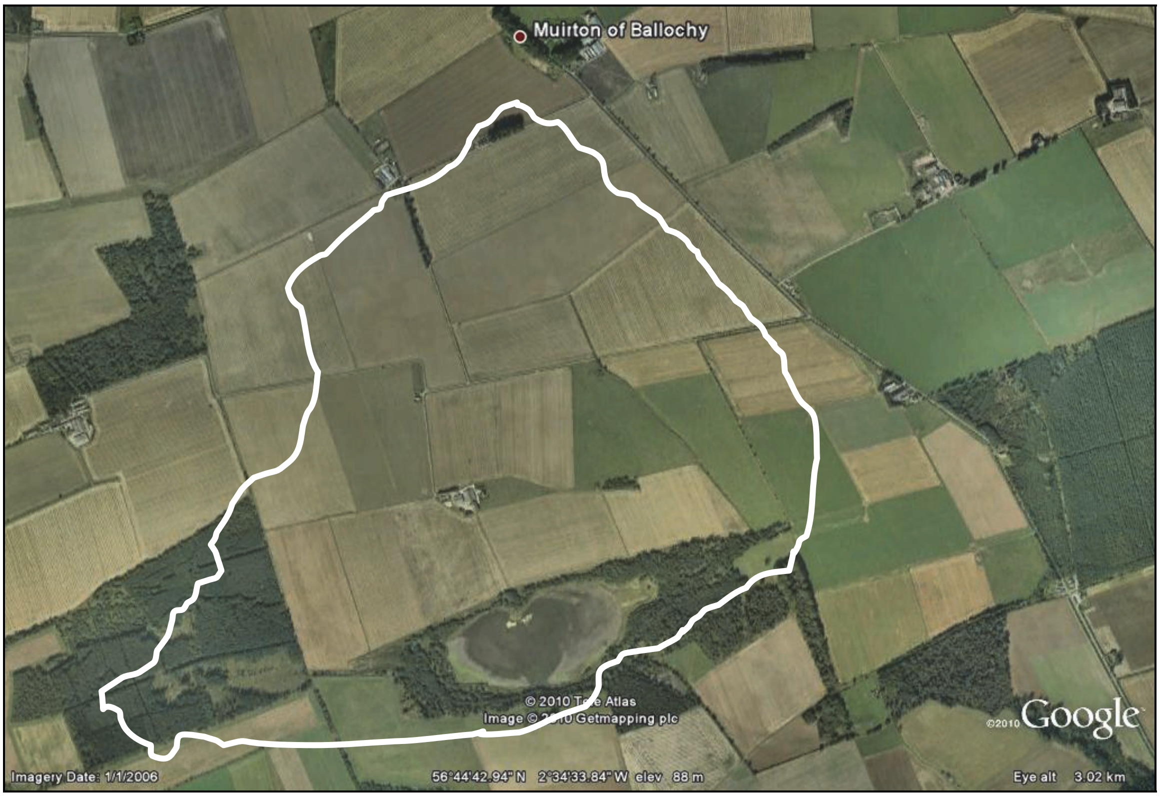
- High export rates from arable horticulture which makes up nearly 50% of catchment land use
- Large designated breeding bird population contributing nearly three quarters of the P entering the loch
- Malfunctioning septic tank to north of loch with effluents entering via Drain 4 which contained large quantities of sewage fungus
- Loch rapidly infilling due to erosion in the catchment

Biomass

- Very little submerged macrophyte growth due to extreme shallowness of the loch leading to shifting sediments unsuitable for macrophyte colonisation
- Diatoms dominant in spring and cyanobacteria prevalent in the late summer

Recommendations

- Repair and maintenance of the septic tank arrangements at the farmyard and farmhouse directly up hill to the north of the loch.
- Extension of wetland habitat and riparian buffer vegetation to include inflow and ditch areas and the steep downslope to the north of the loch.
- Changes in land use away from arable horticulture to more environmentally sensitive and less erosive land use practices.
- Water level management to increase depth and restore macrophyte community.
- Create alternative habitat elsewhere.
- If other methods fail, consider dredging of sediments to increase depth and restore macrophyte community, bearing in mind the potential disadvantages of this method.



Muirton of Ballochy
© 2010 Tele Atlas
Image © 2010 Getmapping plc
©2010 Google
Imagery Date: 1/1/2006
56°44'42.94" N 2°34'33.84" W elev 88 m
Eye alt 3.02 km

Loch Summary Sheet – Loch of Aboyne

Loch and catchment statistics

- SSSI designation: mesotrophic water body
- Considered to be in unfavourable condition due to poor water quality
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 44 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 55 µg P L^{-1}
- Predicted loch TP 45 µg P L^{-1} therefore good correspondence with nutrient levels in the inflows and no evidence of sediment release of P
- 2010 mean chlorophyll 15 µg L^{-1}, growing season chlorophyll 20 µg L^{-1}
- Predicted chlorophyll 25 µg L^{-1} therefore phytoplankton responding to TP levels
- In-loch TP concentrations are well into the eutrophic category and are likely to be higher than historical levels
- NGR NO536999
- Loch area 14.4 ha
- Catchment area 124 ha
- Maximum depth 3 m
- Loch volume 283,169 m^3
- Water retention time 0.55 y

Nutrient budget

- Three surface inflows flowing into the Loch each with similar P export rates
- No birds included in designation and no large bird population present
- Nutrient budget based on measured inflow data considerably smaller than modelled budget, indicating export from land use not as high as expected
- No evidence for P release from sediments

Issues

- Loch receiving septic tank effluents from holiday golf lodge
- High level of abstraction reducing flushing rate
- Water-skiing providing a potential switching mechanism to an alternative state i.e. algal dominance
- Highest export rates from the agricultural section of the catchment
- Surrounded on two sides by gold courses

Biomass

- Macrophyte community appears healthy and diverse
- Unusual phytoplankton dynamics with cyanobacteria dominant in spring and Chlorophyta prevalent in the late summer
- Zooplankton dominated by Cladocera indicating top-down control of algae and possible absence of zooplanktivorous fish

Recommendations

- Within-loch measures such as sediment sealing and biomanipulation are unlikely to be effective in Loch of Aboyne, as there was no evidence for major P release from the sediment, and phytoplankton levels were as expected for the amount of P present, i.e. were controlled by bottom-up rather than top-down factors.
- Focus on nutrient management in the agricultural section of the catchment of Inflow 2 could prove worthwhile in reducing the overall nutrient export.
- The coniferous plantation occupying catchment of Inflows 1 and 2 is on very steep ground, so it is important that clearfelling of this plantation does not take place as this is likely to result in a very large release of P directly into the Loch.
- It is considered that water-skiing may be detrimental to the macrophyte community in the Loch and that it represents a danger to the macrophyte dominated state, as nutrient levels are high enough to support an alternative phytoplankton dominated state. Consideration should be given to measures to combat this.

Loch Summary Sheet – Loch Spynie

Loch and catchment statistics

- SSSI designation: eutrophic water body
- Considered to be in unfavourable condition due to poor water quality
- 2010 mean TP based on four samples (winter, spring, summer and late summer) 65 µg P L^{-1}
- 2010 growing season (summer and late summer) mean TP 70 µg P L^{-1}
- Predicted water column TP 118 µg P L^{-1}
- 2010 mean chlorophyll 17 µg L^{-1}, growing season chlorophyll 19 µg L^{-1}
- Predicted chlorophyll 20 µg L^{-1} therefore phytoplankton responding to TP levels
- In-loch TP concentrations are within the expected range for a eutrophic water body according to OECD (1982), but exceed those expected in an SSSI feature (i.e. in naturally eutrophic water bodies)
- NGR NJ236664
- Loch area 17.3 ha
- Catchment area 668.9 ha
- Maximum depth 1 m
- Loch volume 198,218 m^3
- Water retention time 0.13 y

Issues

- Extremely large catchment with varied land use and urban areas. Likely to be high nutrient export rates from many areas
- Pig farm partially within eastern end of the catchment

Nutrient budget

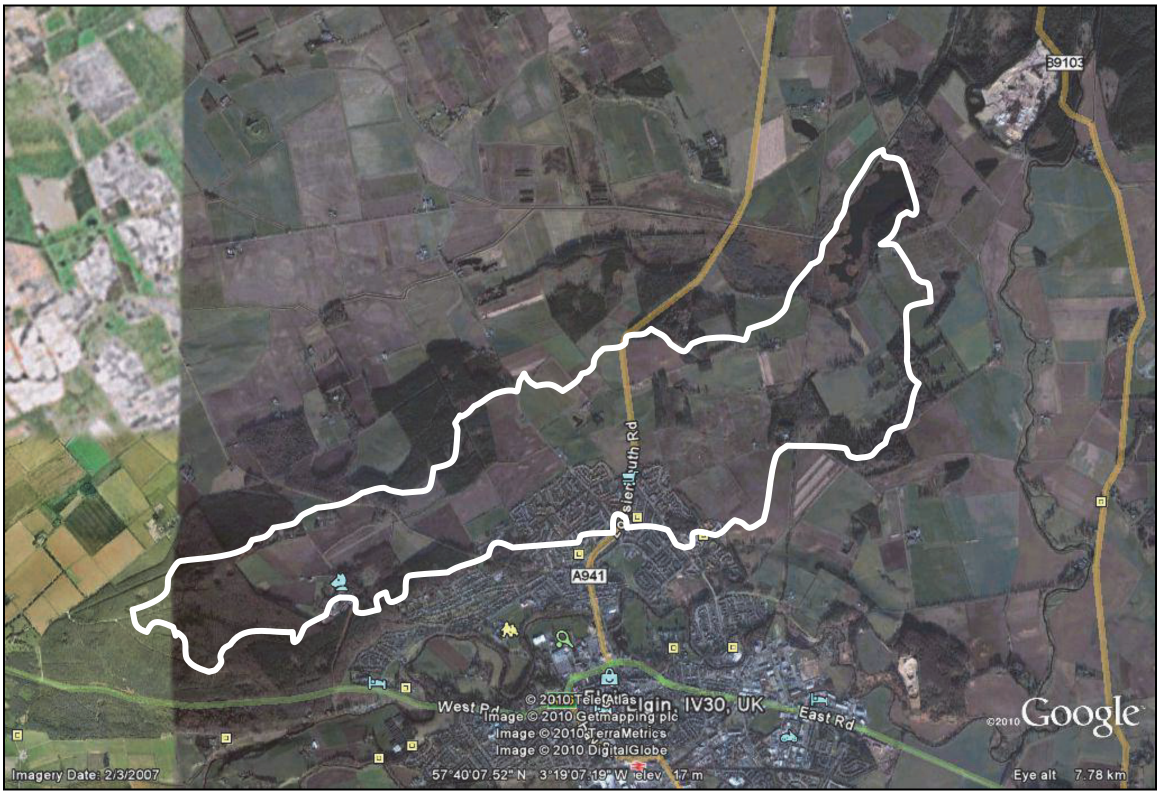
- Only one inflow flowing into the Loch and draining a large and varied subcatchment
- Very large bird population present and included in the designation
- Birds account for over half of the P inputs to the loch
- Nutrient budget based on measured inflow data smaller than modelled budget, indicating export from land use not as high as expected

Biomass

- Macrophyte growth vigorous throughout Loch
- Phytoplankton dynamics show Chlorophyta dominant in spring and diatoms prevalent in late summer
- Cyanobacteria may not be a nuisance in the Loch
- Zooplankton possibly dominated by rotifers and lacking large bodied grazing Cladocera
- Otters present in the Loch, therefore likely to be fish present

Recommendations

- Improve understanding of the catchment area and Loch system.
- Monitor water quality.
- Land use and export rates in the catchment may be addressed in the future.


B9103
A941
West Rd
East Rd
Elgin, IV30, UK
© 2010 Tele Atlas
Image © 2010 Getmapping plc
Image © 2010 TerraMetrics
Image © 2010 DigitalGlobe
©2010 Google
Imagery Date: 2/3/2007
57°40'07.52" N 3°19'07.19" W elev 17 m
Eye alt 7.78 km

APPENDIX 2: PHOTOGRAPHS OF THE LOCHS

White Loch

Photo 1. White Loch from south shore *NX30334 52697 (looking northwest)*	*Photo 2. White Loch from south shore* *NX30334 52697 (looking northwest)*	*Photo 3. White Loch from south shore* *NX30334 52697 (looking north)*	*Photo 4. White Loch from south shore* *NX30334 52697 (looking northeast)*
			
Photo 5. Castle Kennedy estate house from the loch *NX10670 61410 (looking north)*	*Photo 6. Parkland to the west of the house from the loch* *NX10510 61375 (looking northwest)*	*Photo 7. The western shore from the loch* *NX10500 61225 (looking west)*	*Photo 8. The eastern shore from the loch* *NX10815 60610 (looking east)*
			

Mochrum Loch

Photo 9. Mochrum west shore NX30334 52697 (looking south)	*Photo 10. Mochrum west shore NX30043 53685 (looking south)*	*Photo 11. Mochrum west shore NX30043 53685 (looking southwest)*	*Photo 12. Mochrum west shore NX30043 53685 (looking northwest)*
			
Photo 13. Mochrum north shore NX30043 53685 (looking north)	*Photo 14. Mochrum north shore NX30043 53685 (looking northeast)*	*Photo 15. Mochrum west shore NX29879 53223 (looking west)*	*Photo 16. Mochrum west shore NX29879 53223 (looking southwest)*
			

Woodhall Loch

Photo 17. Woodhall west shore NX67736 66559 (looking west)	*Photo 18. Woodhall north shore NX67373 (looking northeast)*	*Photo 19. Woodhall north shore NX66940 67387 (looking northeast)*	*Photo 20. Woodhall west shore NX66585 67891 (looking west)*
			
Photo 21. Woodhall east shore NX67736 66559 (looking east)			
			

Milton Loch

Photo 22. Milton north shore NX83777 71051 (looking north)	*Photo 23. Milton east shore NX83777 71051 (looking northeast)*	*Photo 24. Milton west shore NX84026 72047 (looking west)*	*Photo 25. Milton southwest shore NX83777 71051 (looking west)*
			
Photo 26. Milton north shore NX83777 71051 (looking northwest)			
			

Kilconquhar Loch

Photo 27. Kilconquhar north shore NO48917 01444 (looking north)	*Photo 28. Kilconquhar northeast shore NO48917 01444 (looking north east)*	*Photo 29. Kilconquhar NO48910 01436 (looking southwest)*	*Photo 30. Kilconquhar south shore NO48899 01437 (looking south)*
			
Photo 31. Kilconquhar northeast shore NO48918 01856 (looking north)	*Photo 32. Kilconquhar northwest shore NO48765 01445 (looking north)*	*Photo 33. Kilconquhar north east catchment NO49235 02065 (looking west over the loch)*	*Photo 34. Kilconquhar north shore (from southwest) NO48515 01530 (looking north)*
			

Dun’s Dish

Photo 35. Dun’s Dish looking south over loch *NO64575 61300*	*Photo 36. Dun’s Dish looking north to Damside Farm* *NO64780 61155*	*Photo 37. Dun’s Dish north shore* *NO65035 61000*	*Photo 38. Dun’s Dish Drain 4 with sewage fungus* *NO64610 61055*
			
Photo 39. Dun’s Dish Drain 2 looking west *NO64450 60995*			
			

Loch of Aboyne

Photo 40. Loch of Aboyne undisturbed eastern arm *NJ53950 99835*	*Photo 41. Loch of Aboyne west shore from east shore* *NJ53790 00035*	*Photo 42. Loch of Aboyne north shore from loch* *NJ53615 00015*	*Photo 43. Loch of Aboyne north shore from east* *NJ53740 00065*
			
Photo 44. Loch of Aboyne north east shore from loch *NJ53620 99915*	*Photo 45. Loch of Aboyne north shore from loch* *NJ53570 99775*	*Photo 46. Loch of Aboyne east shore with* Equisetum *and* Potamogeton *NJ53525 99770*	*Photo 47. Loch of Aboyne south shore containing caravan park* *NJ53765 99925*
			

Loch Spynie

Photo 48. Loch Spynie bird hide on southeast shore *NJ23769 66582*	*Photo 49. Loch Spynie west shore* *NJ23887 66489*	*Photo 50. Loch Spynie wet woodland at northeast end* *NJ24015 66835*	*Photo 51. Loch Spynie reedswamp at southwest end* *NJ23255 65975*
			
Photo 52. Loch Spynie pig farm partially within catchment *NJ23995 66310*	*Photo 53. Loch Spynie arable land* *NJ23335 65745*	*Photo 54. Loch Spynie Canal looking north east* *NJ23310 66295*	*Photo 55. Loch Spynie at bird hide* *NJ23735 66410*
			

APPENDIX 3: WATER QUALITY DATA FOR THE EIGHT STUDY LOCHS

Sample	Received	pH	Conductivity	Alkalinity	SRP	TSP	TP	TON	TAN	NO_2	Mean Cha	Mean ratio	Silica	Dry SS	Ash SS	Org SS	BOD_5	Soluble Fe	Mn
			µS cm^{-1}	meq L^{-1}	µg P L^{-1}	µg P L^{-1}	µg P L^{-1}	mg N L^{-1}	µg N L^{-1}	µg N L^{-1}	µg L^{-1}		mg SiO_2 L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	µg L^{-1}	µg L^{-1}
SNH WO Composite	**16-Feb-10**	7.13	89	0.31	10	16	36	0.57	333	10	2.39	1.04	4.28	2.90	0.72	2.18	....	157	....
SNH WO Surf	**16-Feb-10**	7.51	86	0.33	10	18	24	0.57	331	10	....	....	4.24	1.24	0.16	1.08	....	182	....
SNH WO Forest inflow 1	**16-Feb-10**	7.57	69	0.22	8	13	8	0.20	293	6	....	....	3.98	1.12	0.26	0.86	1.7	117	....
SNH WO Forest inflow 2	**16-Feb-10**	7.41	66	0.13	10	16	15	0.26	372	8	....	....	4.00	0.60	0.54	0.06	1.7	184	....
SNH WO Road inflow	**16-Feb-10**	7.28	98	0.58	8	13	16	0.51	322	12	....	....	2.88	1.44	0.64	0.80	1.8	171	....
SNH WH Surf	**18-Feb-10**	7.30	253	0.80	5	14	40	0.51	393	10	....	....	6.90	3.14	0.80	2.34	....	94	....
SNH WH Comp	**18-Feb-10**	7.84	182	0.80	3	14	25	0.50	349	9	11.45	1.04	6.92	3.62	1.16	2.46	....	109	....
SNH WH 5m	**18-Feb-10**	7.74	184	0.82	4	13	26	0.51	367	9	....	....	6.87	2.76	0.54	2.22	....	47	....
SNH WH 8.5m	**18-Feb-10**	7.61	185	0.78	3	10	26	0.48	298	8	....	....	6.74	3.06	0.54	2.52	....	31	....
SNH MO Surf	**18-Feb-10**	7.35	84	0.13	20	33	45	0.28	286	8	4.27	1.06	2.76	0.86	0.08	0.78	....	149	....
SNH MO 3.75m	**18-Feb-10**	7.14	82	0.11	21	31	42	0.28	294	8	....	....	2.78	1.16	0.00	1.16	....	166	....
SNH MO NW inflow	**18-Feb-10**	7.02	80	0.10	11	18	31	0.27	283	8	....	....	3.02	1.80	0.32	1.48	1.6	202	....
SNH MO SW inflow	**18-Feb-10**	6.33	91	0.21	6	8	16	0.19	295	10	....	....	3.45	1.06	0.10	0.96	0.1	521	....
SNH MO SE inflow	**18-Feb-10**	5.62	141	0.02	7	10	11	0.01	282	7	....	....	4.81	0.74	0.10	0.64	0.2	505	....
SNH MO car park inflow	**18-Feb-10**	6.08	59	0.13	8	13	14	0.01	284	8	....	....	2.22	6.70	1.14	5.56	0.2	225	....
SNH SP inflow 1	**22-Feb-10**	7.40	544	2.06	25	31	67	6.50	319	21	....	....	11.11	2.56	1.52	1.04	1.6	362	....
SNH SP outflow	**23-Feb-10**	7.80	502	2.14	12	27	61	4.37	284	26	13.16	1.12	9.51	4.54	1.10	3.44	....	125	....
SNH DD inflow 1	**23-Feb-10**	8.18	472	2.81	12	19	20	6.33	305	7	....	....	9.48	1.10	0.28	0.82	1.5	19	....
SNH DD outflow	**23-Feb-10**	8.18	390	2.42	8	19	69	0.68	302	10	8.21	1.01	5.08	8.20	3.46	4.74	....	67	....
SNH DD drain 1 upstream	**23-Feb-10**	7.93	409	2.36	16	21	28	3.03	291	8	....	....	11.43	1.38	0.30	1.08	1.5	37	....
SNH DD drain 1 downstream	**23-Feb-10**	7.70	394	2.39	15	22	32	4.13	286	7	....	....	11.24	1.44	0.34	1.10	1.5	38	....
SNH DD drain 2	**23-Feb-10**	7.57	432	2.73	17	20	25	5.62	277	8	....	....	11.10	3.10	1.44	1.66	1.6	98	....
SNH DD drain 3	**23-Feb-10**	7.11	374	2.07	58	72	77	6.41	299	16	....	....	9.64	3.92	1.80	2.12	1.6	114	....
SNH DD drain	**23-Feb-10**	6.81	413	2.27	622	722	734	8.06	7567	82	....	....	10.52	31.04	10.14	20.90	11.9	225	....
SNH KL Out	**24-Feb-10**	8.02	625	3.33	5	10	48	0.03	296	4	....	....	10.54	4.52	0.96	3.56	2.5	177	....
SNH MIL Surf	**23-Mar-10**	9.03	208	1.77	9	19	53	0.51	76	15	33.34	1.30	0.00	9.04	1.84	7.20	....	97	....
SNH MIL inflow 2	**23-Mar-10**	7.84	162	1.22	10	20	32	0.36	76	9	....	....	3.27	12.04	5.84	6.20	5.3	220	....
SNH MIL inflow 1	**23-Mar-10**	6.78	117	0.75	71	92	100	0.61	146	15	....	....	3.68	2.64	1.24	1.40	2.0	833	....
SNH MIL inflow 3	**23-Mar-10**	7.63	300	2.01	16	30	54	4.67	138	14	....	....	4.46	11.64	8.24	3.40	<1	177	....
SNH WO 8m	**23-Mar-10**	7.80	88	0.37	6	9	27	0.57	61	11	....	....	3.87	3.64	1.24	2.40	....	190	....
SNH WO Surf	**23-Mar-10**	7.77	88	0.34	5	7	27	0.45	67	12	....	....	3.85	4.04	1.24	2.80	....	193	....
SNH WO Comp	**23-Mar-10**	7.49	88	0.32	4	5	27	0.44	61	11	11.63	1.51	3.83	5.44	1.64	3.80	....	204	....
SNH WO 5m	**23-Mar-10**	7.65	88	0.33	5	8	26	0.44	63	11	....	....	3.84	2.64	0.64	2.00	....	209	....
SNH WO inflow 4	**23-Mar-10**	6.93	61	0.14	5	11	21	0.43	63	8	....	....	3.94	6.04	2.64	3.40	1.0	228	....
SNH WO inflow 3	**23-Mar-10**	6.24	50	0.07	6	14	23	0.25	52	7	....	....	4.68	1.64	0.44	1.20	1.0	282	....
SNH WO inflow 5	**23-Mar-10**	6.50	50	0.35	9	15	32	0.39	73	9	....	....	3.87	8.04	4.04	4.00	1.4	254	....
SNH WO inflow 1	**23-Mar-10**	7.16	59	0.17	5	14	26	0.23	50	6	....	....	3.33	7.84	4.04	3.80	<1	257	....
SNH WO inflow 2	**23-Mar-10**	7.04	62	0.11	8	20	26	0.21	56	6	....	....	3.43	6.04	2.44	3.60	<1	287	....
SNH WO inflow 6	**23-Mar-10**	7.19	91	0.49	4	10	25	0.21	67	7	....	....	1.52	6.24	3.04	3.20	2.5	164	....
SNH WH Comp	**24-Mar-10**	7.67	186	0.81	5	6	25	0.30	62	7	20.52	1.29	3.36	6.84	6.04	0.80	....	118	....
SNH WH 8.5m	**24-Mar-10**	7.80	186	0.82	5	5	22	0.30	52	7	....	....	3.43	7.64	3.44	4.20	....	135	....
SNH WH 5m	**24-Mar-10**	7.90	187	0.77	5	5	44	0.29	58	6	....	....	3.31	7.24	1.64	5.60	....	29	....
SNH WH Surf	**24-Mar-10**	8.11	188	0.84	6	7	24	0.32	54	8	....	....	3.51	7.84	0.24	7.60	....	43	....
SNH MO 3.75m	**24-Mar-10**	7.14	81	0.16	6	17	32	0.03	55	4	....	....	1.53	2.64	0.24	2.40	....	114	....
SNH MO Surf	**24-Mar-10**	7.21	80	0.15	6	16	32	0.02	66	5	8.72	1.39	1.47	3.24	0.44	2.80	....	141	....

Sample	Received	pH	Conductivity	Alkalinity	SRP	TSP	TP	TON	TAN	NO_2	Mean Cha	Mean ratio	Silica	Dry SS	Ash SS	Org SS	BOD_5	Soluble Fe	Mn
SNH MO NW inflow	**24-Mar-10**	6.91	80	0.11	10	18	22	0.08	62	5	....	....	1.20	1.84	0.64	1.20	<1	194	....
SNH MO SW inflow	**24-Mar-10**	6.54	103	0.23	7	10	15	0.19	65	7	....	....	2.67	2.24	0.04	2.20	<1	433	....
SNH MO SE inflow	**24-Mar-10**	5.72	139	0.03	11	14	24	0.03	60	6	....	....	3.66	1.44	0.04	1.40	<1	670	....
SNH MO car park inflow	**24-Mar-10**	6.20	65	0.15	9	11	17	0.02	63	7	....	....	1.37	2.64	0.04	2.60	<1	319	....
SNH Kil Surf 1	**31-Mar-10**	8.33	692	3.04	7	15	45	0.05	12	3	11.11	1.52	7.83	7.24	2.64	4.60	....	30	....
SNH KIL Surf 2	**31-Mar-10**	8.35	618	3.11	5	13	50	0.02	14	3	....	....	7.74	6.44	1.84	4.60	....	16	....
SNH KIL 1m1	**31-Mar-10**	8.38	620	3.13	5	15	44	0.02	15	2	....	....	7.85	7.44	2.64	4.80	....	26	....
SNH KIL 1m2	**31-Mar-10**	8.35	619	3.08	5	15	45	0.02	15	1	....	....	7.73	7.24	2.24	5.00	....	46	....
SNH KIL Outflow	**31-Mar-10**	8.29	618	3.08	5	17	53	0.02	16	1	....	....	7.69	7.04	1.84	5.20	....	61	....
SNH AB Surf	**31-Mar-10**	7.97	212	0.77	6	14	23	0.34	275	14	4.10	1.15	6.37	3.64	1.24	2.40	....	243	....
SNH AB 1 m	**31-Mar-10**	7.86	211	0.67	6	18	20	0.35	282	15	....	....	6.21	5.04	1.64	3.40	....	294	....
SNH AB 2 m	**31-Mar-10**	7.75	212	0.68	6	20	31	0.35	284	15	....	....	6.25	3.44	0.04	3.40	....	59	....
SNH AB 2.75m	**31-Mar-10**	7.67	212	0.66	4	11	21	0.35	297	15	....	....	6.25	3.84	0.64	3.20	....	109	....
SNH AB Inflow 3	**31-Mar-10**	7.55	138	0.60	3	6	6	0.27	27	3	....	....	14.17	1.64	0.64	1.00	7.0	29	....
SNH AB Outflow	**31-Mar-10**	7.53	211	0.63	3	12	15	0.34	281	14	....	....	6.61	3.24	0.24	3.00	....	263	....
SNH AB Inflow 2	**31-Mar-10**	7.41	109	0.57	7	17	25	0.44	57	7	....	....	3.27	13.44	5.64	7.80	4.4	203	....
SNH AB Inflow 3	**31-Mar-10**	7.09	334	0.61	15	17	25	1.72	22	3	....	....	11.90	1.04	0.04	1.00	2.5	140	....
SNH SP Shore	**01-Apr-10**	7.84	518	2.39	6	14	60	1.99	32	12	15.90	1.23	5.04	9.64	1.64	8.00	....	55	....
SNH SP Inflow	**01-Apr-10**	7.41	413	1.54	19	24	57	4.35	105	20	....	....	8.30	13.04	2.64	10.40	2.8	240	....
SNH SP Outflow	**01-Apr-10**	7.93	512	2.38	5	19	64	1.64	44	11	....	....	4.55	8.84	1.84	7.00	....	102	....
SNH DD Draw 4	**01-Apr-10**	7.08	333	1.61	118	131	187	7.15	292	53	....	....	8.88	12.04	2.64	9.40	4.8	183	....
SNH DD Drain 3	**01-Apr-10**	7.04	414	2.07	197	247	408	8.60	201	63	....	....	9.43	52.30	39.30	13.00	3.5	367	....
SNH DD Surf	**01-Apr-10**	7.62	320	1.98	55	76	193	0.38	17	6	29.63	1.26	1.84	98.95	65.62	33.34	....	188	....
SNH DD Inflow	**01-Apr-10**	7.93	465	2.33	27	40	88	6.80	40	9	....	....	8.29	19.24	12.44	6.80	2.7	448	....
SNH DD Outflow	**01-Apr-10**	8.03	346	2.04	18	32	150	1.71	38	8	....	....	4.32	61.64	39.84	21.80	....	235	....
SNH DD Ditch 1	**01-Apr-10**	7.60	317	1.31	20	36	79	4.65	146	12	....	....	7.76	23.44	17.64	5.80	2.8	277	....
SNH DD Ditch 2	**01-Apr-10**	7.59	377	2.05	16	23	51	7.50	32	7	....	....	9.41	4.64	2.84	1.80	3.2	86	....
SNH KIL Surf 1	**16-Jun-10**	9.72	513	1.52	11	29	48	0.03	38	1	2.74	1.55	7.04	4.44	2.24	2.20	2.7	13	....
SNH KIL Surf 2	**16-Jun-10**	9.67	513	1.65	10	13	65	0.05	18	1	....	....	5.03	8.24	7.44	0.80	....	13	0.02
SNH KIL 1m 1	**16-Jun-10**	9.84	505	1.51	6	39	50	0.03	17	0	....	....	6.86	7.04	6.64	0.40	....	16	0.01
SNH KIL 1m 2	**16-Jun-10**	9.72	512	1.62	6	27	58	0.07	35	1	....	....	4.41	9.04	5.84	3.20	2.7	22	0.02
SNH KIL Outflow	**16-Jun-10**	9.59	511	1.52	4	24	56	0.03	40	0	....	....	7.46	8.44	5.44	3.00	....	21	....
SNH WH Comp	**17-Jun-10**	8.48	193	1.00	30	51	56	0.03	56	0	4.79	1.45	4.12	4.04	0.24	3.80	4.8	21	0.02
SNH WH Surf	**17-Jun-10**	8.16	196	1.04	23	39	99	0.03	20	0	....	....	3.41	3.24	0.44	2.80	....	38	....
SNH WH 5m	**17-Jun-10**	8.03	194	0.98	22	38	68	0.03	18	0	....	....	3.52	4.64	0.84	3.80	....	41	0.02
SNH WH 8.5 m	**17-Jun-10**	7.78	194	0.99	30	44	78	0.03	33	0	....	....	3.98	5.24	0.64	4.60	....	35	0.02
SNH MO Surf	**17-Jun-10**	7.83	87	0.20	6	26	39	0.03	16	1	2.22	1.18	0.42	2.64	1.44	1.20	2.2	61	....
SNH MO 3.75 m	**17-Jun-10**	7.89	80	0.17	7	24	39	0.03	58	1	....	....	0.34	1.44	0.84	0.60	....	48	0*
SNH MO NW Inflow	**17-Jun-10**	7.34	82	0.17	6	23	49	0.14	35	2	....	....	0.77	3.24	0.44	2.80	....	141	....
SNH MO SW Inflow	**17-Jun-10**	6.65	141	0.61	6	21	31	0.13	40	4	....	....	4.13	2.44	0.24	2.20	....	442	....
SNH MO SE Inflow	**17-Jun-10**	5.72	124	0.20	71	123	176	0.05	42	4	....	....	4.51	19.64	5.04	14.60	....	2714	....
SNH MO Car Park Inflow	**17-Jun-10**	6.00	58	0.31	21	49	81	0.04	63	11	....	....	2.77	22.24	4.04	18.20	....	1321	....
SNH MO W Inflow	**17-Jun-10**	5.77	59	0.23	22	57	60	0.05	73	13	....	....	1.16	17.04	1.84	15.20	....	2627	....
SNH WO Comp	**23-Jun-10**	7.58	88	0.40	8	24	35	0.25	87	9	2.56	1.20	1.86	3.04	0.04	3.00	2.6	128	....
SNH WO Surf	**23-Jun-10**	7.44	88	0.40	5	22	28	0.22	23	7	....	....	1.50	2.84	0.44	2.40	....	117	....
SNH WO 5m	**23-Jun-10**	7.37	87	0.40	6	20	28	0.26	50	7	....	....	2.09	2.44	0.44	2.00	....	154	....
SNH WO 8m	**23-Jun-10**	6.64	89	0.42	8	25	25	0.27	189	13	....	....	3.40	2.44	0.64	1.80	....	257	....
SNH WO inflow 2	**23-Jun-10**	7.02	64	0.19	14	35	44	0.41	21	7	....	....	3.69	3.64	0.24	3.40	....	519	....

Sample	Received	pH	Conductivity	Alkalinity	SRP	TSP	TP	TON	TAN	NO_2	Mean Cha	Mean ratio	Silica	Dry SS	Ash SS	Org SS	BOD_5	Soluble Fe	Mn
SNH WO inflow 3	**23-Jun-10**	7.11	84	0.38	12	26	44	0.17	5	5	….	….	5.24	33.64	12.04	21.60	….	181	….
SNH WO inflow 4	**23-Jun-10**	7.60	491	3.89	62	71	86	5.34	26	14	….	….	6.49	24.64	16.64	8.00	….	61	….
SNH WO inflow 5	**23-Jun-10**	7.57	130	0.76	15	31	44	0.89	61	16	….	….	4.63	3.04	0.84	2.20	….	196	….
SNH WO inflow 6	**23-Jun-10**	7.37	140	1.01	102	126	150	0.85	407	35	….	….	2.92	6.04	1.24	4.80	….	160	….
SNH MIL Surf	**23-Jun-10**	10.12	156	1.22	12	36	91	0.06	35	8	19.32	1.09	0.65	8.24	0.24	8.00	19.3	200	….
SNH MIL inflow 2	**23-Jun-10**	7.70	447	3.98	7	26	61	1.77	613	113	….	….	6.28	7.64	2.44	5.20	….	192	….
SNH SP Surf	**07-Jul-10**	9.04	365	1.02	6	22	41	0.03	38	2	3.76	1.36	2.07	4.24	0.84	3.40	….	7	….
SNH SP Outflow	**07-Jul-10**	7.94	540	2.03	11	21	30	7.20	35	25	….	….	12.40	3.44	0.64	2.80	4	95	….
SNH SP Inflow	**07-Jul-10**	7.17	382	1.20	25	54	79	0.23	164	14	….	….	2.78	4.24	0.24	4.00	….	21	….
SNH DD Surf	**08-Jul-10**	9.76	335	2.23	486	590	625	0.22	28	8	5.81	1.41	13.18	16.64	9.04	7.60	….	247	0*
SNH DD Inflow	**08-Jul-10**	8.12	502	3.47	69	92	96	0.94	59	38	….	….	12.26	7.44	2.84	4.60	7	41	….
SNH DD Outflow	**08-Jul-10**	7.56	412	2.86	167	221	470	0.19	922	65	….	….	2.77	110.64	62.04	48.60	….	468	….
SNH AB Surf	**08-Jul-10**	7.83	184	0.64	29	43	52	0.02	43	5	17.78	1.85	2.66	10.84	1.24	9.60	….	140	0*
SNH AB 1m	**08-Jul-10**	7.83	183	0.59	6	10	51	0.02	4	3	….	….	2.67	14.44	3.44	11.00	….	77	0*
SNH AB 2m	**08-Jul-10**	7.79	182	0.58	4	8	60	0.02	2	3	….	….	2.67	10.44	2.64	7.80	….	82	0*
SNH AB 2.75m	**08-Jul-10**	7.74	183	0.59	6	10	35	0.02	4	3	….	….	2.68	12.64	2.64	10.00	….	97	0*
SNH AB Inflow 1	**08-Jul-10**	6.96	344	0.97	4	7	25	1.09	19	4	….	….	12.80	4.24	0.84	3.40	7	126	….
SNH AB Inflow 2	**08-Jul-10**	6.81	314	1.81	7	11	55	0.94	448	35	….	….	11.01	4.84	3.44	1.40	7	152	….
SNH AB Inflow 3	**08-Jul-10**	7.58	163	1.18	5	11	24	0.11	26	5	….	….	10.81	17.84	6.84	11.00	6	130	….
SNH WH 5m	**25-Aug-10**	8.82	202	1.07	11	16	104	0.01	0	2	….	….	2.82	13.24	3.64	9.60	….	120	0*
SNH MO SW Inflow	**25-Aug-10**	6.76	108	1.08	9	13	28	0.08	0	6	5.47	1.00	3.39	4.24	0.44	3.80	9	490	….
SNH WH 8m	**25-Aug-10**	8.74	200	0.28	11	20	106	0.01	0	2	39.15	0.93	2.81	14.64	4.44	10.20	….	90	0*
SNH WH Comp	**25-Aug-10**	8.99	200	1.10	10	20	87	0.01	3	2	….	….	2.71	14.44	4.24	10.20	….	49	….
SNH MO Surf	**25-Aug-10**	8.15	81	0.20	14	27	30	0.02	0	3	….	….	0.70	3.64	0.44	3.20	….	82	….
SNH MO Carpark Inflow	**25-Aug-10**	6.04	69	0.13	13	21	69	0.03	18	8	….	….	4.62	18.64	3.04	15.60	7	1077	….
SNH White Surf	**25-Aug-10**	8.64	198	1.09	7	13	85	0.02	21	2	….	….	2.81	13.84	4.04	9.80	….	70	….
SNH WO Inflow 2	**26-Aug-10**	7.81	57	0.18	21	39	42	0.23	58	10	….	….	4.30	3.04	1.24	1.80	6	540	….
SNH MO 3.75m	**25-Aug-10**	7.19	82	0.16	14	14	53	0.02	8	3	….	….	0.66	2.44	0.04	2.40	….	127	0*
SNH MO NW Inflow	**25-Aug-10**	6.58	76	0.14	14	31	27	0.08	24	9	….	….	2.65	2.04	0.44	1.60	7	378	….
SNH WO Surf	**26-Aug-10**	7.03	80	0.39	7	10	22	0.08	9	9	….	….	1.98	2.64	0.44	2.20	….	306	….
SNH MO SE Inflow	**25-Aug-10**	5.76	137	0.15	20	36	159	0.03	41	5	….	….	7.72	80.84	28.84	52.00	10	1265	….
SNH Black Loch outflow	**25-Aug-10**	6.85	134	0.56	11	23	48	0.06	10	4	7.18	1.17	3.18	5.24	0.24	5.00	….	159	….
SNH WO 5m	**26-Aug-10**	7.37	83	0.41	9	10	28	0.10	58	11	4.79	1.00	2.21	3.44	1.24	2.20	….	346	0.22
SNH WO Comp	**26-Aug-10**	7.13	84	0.38	7	7	26	0.10	32	10	….	….	2.10	3.24	1.24	2.00	….	325	….
SNH WO Inflow 5	**26-Aug-10**	7.22	93	0.47	19	32	41	0.42	13	10	….	….	5.17	3.24	0.44	2.80	6	620	….
SNH WO Inflow 1	**26-Aug-10**	7.45	63	0.25	7	13	20	0.08	27	6	….	….	4.43	1.64	0.64	1.00	5	374	….
SNH WO Inflow 6	**26-Aug-10**	7.56	99	0.72	11	21	34	0.09	66	6	….	….	2.95	10.04	4.84	5.20	6	383	….
SNH MIL Inflow 1	**26-Aug-10**	6.73	268	2.15	73	101	121	0.68	212	15	….	….	6.52	3.64	0.44	3.20	10	1502	….
SNH WO 8m	**26-Aug-10**	7.04	87	0.46	10	25	38	0.16	177	20	….	….	2.73	7.24	2.84	4.40	….	387	0.58
SNH MIL Surf	**26-Aug-10**	7.69	204	1.68	14	50	118	0.19	2050	51	27.01	0.69	3.12	7.44	1.04	6.40	….	146	….
SNH MIL Inflow 3	**26-Aug-10**	7.89	412	3.13	17	18	45	4.90	55	17	….	….	6.61	13.64	9.64	4.00	7	154	….
SNH MIL Inflow 2	**26-Aug-10**	7.06	378	3.02	42	63	99	1.11	20	41	….	….	8.55	4.64	1.24	3.40	8	1032	….
SNH MIL Inflow 4	**26-Aug-10**	7.44	219	1.92	21	23	23	1.62	333	41	….	….	5.35	2.24	0.44	1.80	7	261	….
SNH DD Outflow	**08-Sep-10**	8.02	269	1.41	117	166	316	0.06	5	23	….	….	2.38	53.07	20.07	33.00	….	161	….
SNH DD Surf	**08-Sep-10**	8.34	341	2.08	170	226	439	0.03	6	5	79.50	1.34	4.63	99.40	38.07	61.34	….	250	0*
SNH DD Drain	**08-Sep-10**	7.05	178	0.57	482	542	634	2.40	342	50	….	….	5.86	59.74	57.74	2.00	….	147	….
SNH SP Inflow	**08-Sep-10**	7.56	543	2.07	39	53	57	6.48	6	27	….	….	13.27	7.07	4.40	2.67	5	181	….
SNH SP Outflow	**08-Sep-10**	7.67	401	1.69	14	33	88	0.14	7	6	….	….	0.71	9.07	0.73	8.33	….	87	….

Sample	Received	pH	Conductivity	Alkalinity	SRP	TSP	TP	TON	TAN	NO_2	Mean Cha	Mean ratio	Silica	Dry SS	Ash SS	Org SS	BOD_5	Soluble Fe	Mn
SNH SP Surf	**08-Sep-10**	8.20	400	1.69	7	42	98	0.02	4	3	34.88	1.20	0.13	12.40	1.73	10.67	....	122	0*
SNH AB Inflow 1	**07-Sep-10**	7.51	262	1.22	9	16	21	0.98	6	6	....	....	13.90	3.07	0.07	3.00	5	67	....
SNH DD Inflow 1	**08-Sep-10**	7.86	573	3.93	51	82	94	2.31	39	4	....	....	13.32	9.40	3.07	6.33	9	146	....
SNH AB Outflow	**07-Sep-10**	8.12	182	0.59	7	18	61	0.02	0	3	....	....	2.93	14.07	1.07	13.00	....	70	....
SNH AB Surf	**07-Sep-10**	7.94	181	0.58	6	22	57	0.01	23	2	21.88	1.11	2.94	10.73	0.73	10.00	....	170	....
SNH KIL Surf 1	**07-Sep-10**	7.93	498	2.16	431	466	536	0.01	2	3	....	....	4.63	4.40	0.07	4.33	....	16	....
SNH AB 2m	**07-Sep-10**	8.05	183	0.60	20	35	55	0.01	16	2	....	....	3.03	12.07	0.73	11.33	....	72	0*
SNH KIL Surf 2	**07-Sep-10**	7.97	498	2.15	392	413	518	0.01	0	3	10.43	1.21	5.09	5.40	0.40	5.00	....	38	....
SNH AB 3m	**07-Sep-10**	8.06	182	0.58	9	25	49	0.01	60	3	....	....	3.00	11.73	0.40	11.33	....	74	0*
SNH AB 1m	**07-Sep-10**	7.92	181	0.62	19	26	44	0.01	12	2	....	....	3.00	9.73	0.07	9.67	....	90	0*
SNH KIL 1m 1	**07-Sep-10**	7.88	498	2.18	382	459	554	0.01	4	2	....	....	4.67	5.40	0.73	4.67	....	51	0.09
SNH KIL Outflow	**07-Sep-10**	7.81	500	2.17	307	410	430	0.01	4	3	....	....	5.21	3.73	0.40	3.33	....	43	....
SNH KIL 1m 2	**07-Sep-10**	8.04	500	2.22	351	444	585	0.01	8	2	....	....	5.18	6.40	1.07	5.33	....	32	0.14

Note Mn result 0* ~ too low to detect.

APPENDIX 4: NUTRIENT BUDGET DATA

Table 1. Phosphorus loss coefficients for land uses recorded

Land use category	Phosphorus export coefficient* kg ha^{-1} yr^{-1}
Improved grassland	0.47
Water	0.135
Broadleaved woodland	0.215
Coniferous woodland	0.145
Dwarf shrub heath	0.09
Open dwarf shrub heath	0.09
Neutral grassland	0.09
Calcareous grassland	0.09
Acid grassland	0.09
Non-rotational horticulture	1.565
Arable horticulture	1.565
Arable cereals	1.565
Suburban/rural development	2.105
Continuous urban development	2.105
Bog	0.03
Inland bare ground	0.045

*Coefficients from Marsden et al. (1995) - median values for medium land slope category

Table 2. TP export estimated from loss coefficients and from concentrations measured in inflows

Loch		Modelled TP loading (tonnes)	TP loading based on measured inflow concentrations (tonnes)
White Loch	Surface run-off (100%) (no surface inflows)	0.0678	n/a
	Inputs from birds	0.2922	n/a
	Septic tank	0.0032	n/a
	Total budget	0.3632	n/a
Mochrum Loch	Inflow 1	0.0929	0.5023
	Inflow 2	0.0228	0.1046
	Inflow 3	0.005	0.036
	Inflow 4	0.0007	0.0057
	Surface run-off (29%)	0.0483	0.265
	Inputs from birds	0.0714	0.0715
	Total budget	0.2411	0.9851
Woodhall Loch	Inflow 1	0.0175	0.0213
	Inflow 2	0.0077	0.0196
	Inflow 3	0.0013	0.0042
	Inflow 4	0.0185	0.0401

	Inflow 5	0.5493	0.8901
	Inflow 6	0.0307	0.0909
	Surface run-off (12%)	0.1454	0.1454
	Inputs from birds	0.0296	0.0296
	Total budget	0.8	1.2412
Milton Loch	Inflow 1	0.0099	0.013
	Inflow 2	0.0481	0.0534
	Inflow 3	0.0407	0.0295
	Inflow 4	0.0039	0.002
	Surface run-off (48%)	0.0887	0.0904
	Inputs from birds	0.1552	0.1552
	Total budget	0.3465	0.3435
Kilconquhar Loch	Surface run-off (100%) (no surface inflows)	0.1081	n/a
	Inputs from birds	0.0715	n/a
	Total budget	0.1796	n/a
Dun's Dish	Inflow 1	0.1281	0.0377
	Surface run-off (21%)	0.0341	0.01
	Inputs from birds	0.1552	0.1552
	Septic tank	0.0032	0.0032
	Total budget	0.3206	0.2061
Loch of Aboyne	Inflow 1	0.0691	0.0122
	Inflow 2	0.025	0.0133
	Inflow 3	0.0017	0.0018
	Surface run-off (28%)	0.0347	0.0106
	Inputs from birds	0.0296	0.0296
	Total budget	0.1601	0.0675
Loch Spynie	Inflow 1	0.5403	0.131
	Surface run-off (8%)	0.0406	0.0114
	Inputs from birds	0.2922	0.2922
	Total budget	0.8731	0.4346

Table 3. TP export rates estimated from loss coefficients and from concentrations measured in inflows

Loch	Inflow	Modelled TP export rate (kg ha^{-1} yr^{-1})	TP export rates based on measured inflow concentrations (kg ha^{-1} yr^{-1})
Mochrum Loch	Inflow 1	0.1495	0.8378
	Inflow 2	0.1843	0.8455
	Inflow 3	0.3296	2.3768
	Inflow 4	0.1074	0.8903
Woodhall Loch	Inflow 1	0.1756	0.2137
	Inflow 2	0.1491	0.3772
	Inflow 3	0.124	0.3978
	Inflow 4	0.1919	0.6354
	Inflow 5	0.2724	0.4629
	Inflow 6	0.2257	0.6676
Milton Loch	Inflow 1	0.7187	0.9461
	Inflow 2	0.4615	0.5486
	Inflow 3	0.5387	0.4245
	Inflow 4	0.3786	0.1974
Dun's Dish	Inflow 1	1.4319	0.4216
Loch of Aboyne	Inflow 1	0.5081	0.0985
	Inflow 2	0.4249	0.2274
	Inflow 3	0.1318	0.1393

Table 4. Surrogate flow data

Catchment or sub-catchment	Ten year mean annual discharge (m^3) (1999-2008)*
White Loch	2669766
Mochrum Loch	27067356
Mochrum Inflow 1	15456749
Mochrum Inflow 2	3188792
Mochrum Inflow 3	389254
Mochrum Inflow 4	164982
Woodhall Loch	30675215
Woodhall Inflow 1	1184564
Woodhall Inflow 2	617208
Woodhall Inflow 3	125815
Woodhall Inflow 4	748958
Woodhall Inflow 5	22822436
Woodhall Inflow 6	1615422
Milton Loch	4343005
Milton Inflow 1	117419
Milton Inflow 2	833931
Milton Inflow 3	596522
Milton Inflow 4	88278
Kilconquhar Loch	237761
Dun's Dish	641531
Dun's Dish Inflow 1	506546
Loch of Aboyne	1527412
Loch of Aboyne Inflow 1	701052
Loch of Aboyne Inflow 2	331651
Loch of Aboyne Inflow 3	72663
Loch Spynie	2195772
Loch Spynie Inflow 1	2015102

*Most recent available flows, corrected for catchment size and rainfall differences between target and gauged catchments

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Policy and Advice Directorate, Great Glen House,
Leachkin Road, Inverness IV3 8NW
T: 01463 725000

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