Development of a risk based prioritisation protocol for standing waters in Great Britain based on a georeferenced inventory– Phase 2

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Helen Bennion, John Hilton, Mike Hughes, Judy Clark, Duncan Hornby, Martin Kernan and Gavin Simpson

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EXECUTIVE SUMMARY

Introduction

In order to implement a number of EU directives, the Environment Agency, the Scottish Environment Protection Agency and the Nature Conservation bodies all require a procedure to identify lakes at risk of a deterioration in water quality as a result of the presence of a hazard(s) in their catchment. A protocol using a three-tiered hierarchical prioritisation system was developed to assess environmental harm using nutrients and acid deposition as example hazards. In order to carry out these prioritisations, basic information was required on the location, number and size of lakes, in association with ecological and water quality data and target (reference) conditions. Since no single comprehensive inventory of lakes and reservoirs in Great Britain existed, prior to this study, the development of a georeferenced inventory of standing waters in Great Britain and their physical, chemical and ecological properties was an integral part of the project.

Methodology

The project was comprised of two phases, Phase 2 of which is reported here. Phase 1, completed in 2001, was a scoping study to identify the content and structure of the inventory and to design the risk based prioritisation protocol. During Phase 2, the inventory has been populated and the risk based prioritisation protocol further developed, tested and refined. The approach used to develop the risk based prioritisation protocol largely follows the framework for environmental risk assessment and management detailed by the DETR (2000). The scheme is based on the three properties, importance, hazard and sensitivity, and appropriate measures of each were determined. A three-tiered approach was adopted whereby an initial rapid assessment is made at Risk Tier 1 for all standing waters in Great Britain (approximately 14,000 greater than 1ha), based on the minimum of information gained from already available data sources. This assessment is then used to guide the acquisition of further data for more detailed evaluation of a subset of standing waters at Risk Tier 2 (a few hundred to a few thousand) and, in even finer detail at Risk Tier 3 on a very small subset of waters (a few tens) for which remedial action is likely to be taken. Worked examples of the scheme for 30 lakes are presented and the approach to be followed in order to develop a full three-tier, risk-based prioritisation system for lakes with respect to acidification and eutrophication is outlined.

In our protocols, three criteria were used to determine importance to society: large lakes (>50 ha), lakes within Ramsar, SPA or SAC designations and lakes designated as bathing waters. A lake was deemed important if it fell into any one or more of these categories. The list of criteria could be extended relatively easily in the future. Examples of other criteria would be: drinking water abstraction sites; SSSIs; sites with BAP species present; popular tourist sites and or fisheries, etc.

The eutrophication prioritisation scheme

The anthropogenic phosphorus (P) load (human sewage, run-off from land and domestic farm animal waste – the latter data were not available for Scotland) was used as a measure of the eutrophication hazard. The loads were converted into in-lake concentrations using relevant OECD equations, and lakes were given a rank on the basis of the standard Vollenweider classifications of lake trophic status. Lakes in classes 3-5 (high trophic status) were passed through to the first sensitivity analysis. Retention time was used to identify lakes where the algae would remain in the lake long enough to utilise the P in the water. Depth data were unavailable for most lakes so that modelled depths were used in calculations. This has the potential to introduce major errors into the assessment. Lakes in classes 1 and 2 (retention time

>30 days and 3-30 days, respectively) were passed through to the final sensitivity analysis. The Wederburn depth, i.e. an estimate of the average summer thermocline depth, was used to assess the response of a lake to restoration management. This was based on practical experience which shows that deep lakes tend to recover very quickly when P loadings are reduced but shallow lakes often take several decades to recover. Five stratification classes were developed. Lakes in classes 4 and 5 (polymictic but mainly stratified and fully stratified, respectively) were considered sensitive to remediation and were passed for assessment at Risk Tier 2.

The acidification prioritisation scheme

The Risk Tier 1 estimation of hazard and sensitivity to acidification was much simpler since the appropriate data sets had already been compiled for other purposes. Total acid deposition load was used to identify the level of hazard. Five classes were defined and only those in class 1 (<0.5 keq/ha/yr) were not passed through to the sensitivity assessment. Data were already available on the sensitivity of lakes to acidification. The data are available at 1 km square grid scale and relate to the buffering capacity of the dominant soil type and baseline geology within each square. Five sensitivity classes were defined. Only classes 1 and 2 (High and medium-high, respectively) were passed on to the final Risk Tier 1 assessment. The acid deposition class and freshwater sensitivity class for each lake was assessed jointly and lakes with specified combinations of deposition class and sensitivity class were passed through to the Risk Tier 2 assessment.

Risk Tiers 2 and 3

Risk Tier 2 assessments for both acid and eutrophic waters consisted of obtaining data to confirm the Risk Tier 1 model classifications. Assuming these were confirmed, Government policy and other non-quantifiable criteria are likely to be used to select lakes to pass through to Risk Tier 3. Risk Tier 3 assessment is carried out on a very small number of lakes which are likely to receive remedial action. For eutrophic lakes the case for investment is developed, including the quantification of relevant sources and the development and testing of appropriate management strategies using models.

The inventory

The inventory itself contains basic physical characteristics for all standing waters in Great Britain derived from the 1:50 000 Ordnance Survey Panorama digital dataset. For those water bodies >1 hectare (N=14, 353), catchment boundaries were generated and associated attribute data were derived, to allow implementation of the risk based prioritisation protocol. The inventory was linked to external databases using a meta-data system and summary water chemistry data were collated from some of these databases for approximately 400 water bodies. It is hoped that further meta-data and summary data can be added in the future as and when data become available. The database includes a number of queries to allow the risk based prioritisation protocol to be implemented.

All data and documentation are currently available for download from a secure server (http://ecrc.geog.ucl.ac.uk/gblakes).

CONTENTS

1. INTRODUCTION AND OBJECTIVES

The Environment Agency (EA) need to be in a position to establish priorities and work loads that will arise as a result of the requirement to return the quality of standing waters (lakes and reservoirs) to a reference condition. This need arises from a number of drivers, the most urgent of which are the requirements to assess the ecological status of standing waters under the Water Framework Directive (WFD) (European Union, 2000), the coordination of actions which arise from the Eutrophic and Mesotrophic Lake Habitat Action Plans (HAPs) and the implementation of the EA's Eutrophication Strategy. Other agencies in Great Britain have similar requirements and, therefore, this project involves collaboration with English Nature (EN), Countryside Council for Wales (CCW), The Scottish Environment Protection Agency (SEPA) and Scottish Natural Heritage (SNH) represented by SNIFFER. The EA is the lead organisation responsible for coordinating the Eutrophic Lakes HAP and is collaborating with SEPA, the lead agency for the Mesotrophic Lakes HAP. DETR (2000) recommend a risk based approach to investment prioritisation and this approach has been approved by the UK steering group for Mesotrophic and Eutrophic Lakes HAPs.

This project aims to develop a risk based prioritisation system both to identify waters at risk of eutrophication and acidification, and to assess their potential for restoration. In order to prioritise actions and to track progress information is required about the location, size, use, ecological and water quality status, and target (reference) conditions of all standing waters in Great Britain. However, at present no comprehensive inventory of lakes and reservoirs in Great Britain exists and the Agencies have very little information about standing water bodies. Although some information is available from a variety of external sources, none are currently accessible in a co-ordinated format. Hence there is an additional need to develop a geo-referenced inventory of standing waters in Great Britain

A previous Phase (1) of this project, completed in 2001, proposed a tiered approach to prioritising actions based on the risks posed to lakes from activities in their catchments, their sensitivity to these risks and their relative importance to society, and developed the basic characteristics of a standing waters inventory and prioritisation protocol (Bennion *et al*, 2001).

Specific objectives of Phase 2 are:

1) To extend the development of a tiered risk methodology for standing waters.

2) To develop an inventory of standing waters in Great Britain which can hold information relating to the morphometric, use-related and summary data which describe the past, present and target ecological conditions.

3) To populate this inventory with the data required to carry out the tiered risk prioritisation, concentrating on information describing site importance, risks posed by catchment hazards and site sensitivity.

4) To test the prioritisation approach on 30 lakes.

The following chapters describe developments in Phase 2: i) the approach to be followed in order to develop a full three tier, risk-based prioritisation system for lakes with respect to eutrophication and acidification, ii) worked examples of the scheme for a small number of lakes, and iii) the data types in the inventory.

2. RISK BASED PRIORITISATION PROTOCOL

2.1 The three tier approach

It was agreed in Phase 1 of the project that the approach used to develop the risk based prioritisation protocol would largely follow the framework for environmental risk assessment and management detailed in the DETR guidelines (DETR, 2000). The prioritisation of work on standing waters should enable the risk of harm to be placed into an objective framework, ensuring that actions are focussed where they are most beneficial to society (Pollard *et al*, 2000). The approach aims to identify lakes with the highest need for management action, either to prevent harm or to reduce that which has already occurred.

The approach is iterative, with initial simple assessments being used to refine and prioritise subsequent assessments. The scheme, therefore, has been developed in a way that allows relative harm assessments to become progressively more sophisticated via a three tier system (Figure 1). In this way, an initial rapid assessment is made at Risk Tier 1 for all standing waters in Great Britain (approximately 14,000 greater than 1 ha), based on the minimum of information gained from already available data sources. This assessment can then be used to guide the acquisition of further data for more detailed evaluation of a subset of standing waters at Risk Tier 2 (a few hundred to a few thousand) and, in even finer detail at Risk Tier 3 on a very small subset of waters (a few tens) for which remedial action is likely to be taken.

The prioritisation system for lakes is based on three or four, essentially independent, properties:

1) Importance or value to society

2) Hazard posed to a lake from sources of nutrients and acidity

3) Sensitivity of a lake to deterioration in water quality, i.e. following an increase in hazard

4) If deterioration has taken place, for some hazards (e.g. nutrients) it may be possible to assess the likelihood that the damage can be reversed following a managed reduction of the hazard.

There are a number of different ways in which the value of a lake to society could be defined. It was established very early in the development, however, that trying to put a monetary value on lakes was fraught with difficulty, especially when issues of species conservation were the most important feature of the lake. As a result the concept of "Importance" was developed, which is the reason why a lake is of value to society, and is a more easily defined descriptor.

Environmental risk can be defined as the probability of the environment suffering harm from a hazard. In terms of lakes the most important hazards are nutrients and acid deposition. These hazards can cause changes in the ecological condition of the lake, depending on their magnitude. Whilst we are aware that lakes may be exposed to a range of other hazards such as toxic substances, at the current stage of method development, these are not included in the present scheme. However, the scheme could be equally well applied to a range of such hazards, e.g. mine waste, toxic paints, or even hazards such as species introductions.

The degree to which hazards can cause changes in the ecological condition of waters depends on the sensitivity of the system. Sensitivity will depend on physical features (e.g. depth, residence time, exposure etc) and catchment features such as geology and soil type. As for hazard, appropriate measures of sensitivity have been selected according to data availability and the number of lakes being assessed.

Whilst the general approach is the same for all lakes (see Figure 1), the hazard and sensitivity criteria for nutrients (leading to eutrophication) and acidity (leading to acidification) are different and, therefore, the prioritisation protocols for eutrophication and acidification are described separately in chapters 4 and 5, respectively. The importance criteria, however, are the same in both schemes and are described in chapter 3.

As well as identifying a number of lakes to carry through to Risk Tier 2, the Risk Tier 1 analysis suggests a series of different management/monitoring options for many of the other groups of lakes identified (see box numbers in Figures 2 and 4). In addition to the candidate lakes which have potential for restoration, these include:

i) Lakes that are not susceptible to eutrophication or acidification, where only a minimum surveillence would be appropriate.

ii) Lakes likely to be in good condition, but sufficiently sensitive to be at risk of harm; for example a change in trophic or acidity status. These lakes require a precautionary approach to preventative management and/or monitoring to ensure that critical loads of pollutants are not exceeded.

iii) Lakes that are already harmed, for example significantly more eutrophic or acidic than their pristine state, but are unlikely to respond rapidly to remedial management. These lakes would require a policy of no further deterioration or dereliction.

iv) Lakes which have not previously been considered as important but which are likely to be near to their pristine state (i.e. minimally impacted). These lakes require further investigation and could subsequently be designated as conservation sites. Such lakes have particular relevance to the WFD which requires the identification of high status reference lakes.

At Risk Tier 2, where we are dealing with a more manageable number of lakes, data availability constraints are less of a problem than at Risk Tier 1. The main objective of the Risk Tier 2 analysis is to confirm that the assessments made on the basis of models in Risk Tier 1 give a reliable picture of the status of the lake and its likely response to remediation. An important part of Risk Tier 2 assessments is to incorporate local knowledge, by both helping to identify data sets to confirm the physical and ecological properties of the lake and identifying lakes which are particularly sensitive locally for reasons which are not considered in the Risk Tier 1 assessment. It should be an important part of the protocol that issues raised during this process allow previously unprioritised lakes to be included in the prioritised list on the basis of local knowledge (Figure 1). Since the main objective of Risk Tier 2 is to confirm the Risk Tier 1 predictions it may be necessary to commission measurements on lakes where no data exist. In this case, no attempt should be made to obtain all the information identified in the test case tables (Tables 4 and 5). Only the lowest cost measurement(s), giving acceptable confidence in defining the trophic class or acidity status, should be obtained. Data, particularly physical properties such as mean and maximum depth should feed back into the inventory and be used in preference to modelled values in further prioritisation exercises.

Risk Tier 3 assessments are lake specific. They are expected to focus towards collecting new data to identify the main sources of the hazard and to suggest likely remediation strategies, which should be tested, if necessary, by collecting additional new data. The number of lakes which pass through to Risk Tier 3 cannot be determined on purely objective, ecological criteria. The total budget for remedial works available for a particular period, Government policy and objectives and other non-quantifiable factors will be included in the decision making process and may well carry more weight than the quantifiable measures such as hazard loadings. For example, a number of different decision strategies could be used for nutrients. These include:

i) choosing a small number of the most contaminated lakes,

ii) choosing a larger number of lakes which are not too contaminated, giving improvements to a larger number of lakes,

iii) choosing lakes where particular Red List species are at risk due to the pollution, etc.

No further development of the importance assessment is required at Risk Tier 3 beyond that made at Risk Tier 2. Although, in the absence of other criteria, the total number of importance criteria that each site falls into could be summed to identify those with the highest importance. Local information and political decision making, however, will be critical at this stage. The output from the Risk Tier 3 analyses is a clear strategy for investment, specific to each lake, which should bring about an improvement in its status.

2.2 Results of the Risk Tier 1 assessment

The results of the Risk Tier 1 assessment for all 14, 342 lakes >1 ha in Great Britain (excludes 11 lakes in the Isle of Man) are supplied with this report on CD-ROM as a Microsoft Excel97 spreadsheet (tier1_classification.xls). The file contains the list of lake OS names along with their country and water body ID (WBID) and the classes for the criteria used in the eutrophication and acidification prioritisation protocols, as follows:

i) Importance: 0 = low importance; 1 = high importance.

ii) Trophic Status Class: 1 (low trophic status) to 5 (high trophic status).

iii) Retention Class: 1 = high; 2 = intermediate; 3 = low.

iv) Stratification Class: 1 = shallow mixed <3 m; 2 = completely mixed >3 m; 3 = polymictic but mainly mixed; 4 = polymictic but mainly stratified; 5 = stratified.

v) Acid Deposition Class: 1 = <0.5 keq/ha/yr; 2 = 0.5-1.0 keq/ha/yr; 3 = 1.0-1.5 keq/ha/yr; 4 = >1.5 keq/ha/yr.

vi) Freshwater Sensitivity Class (dominant): 1 = high; 2 = medium-high; 3 = medium-low; 4 = low; 5 = none.

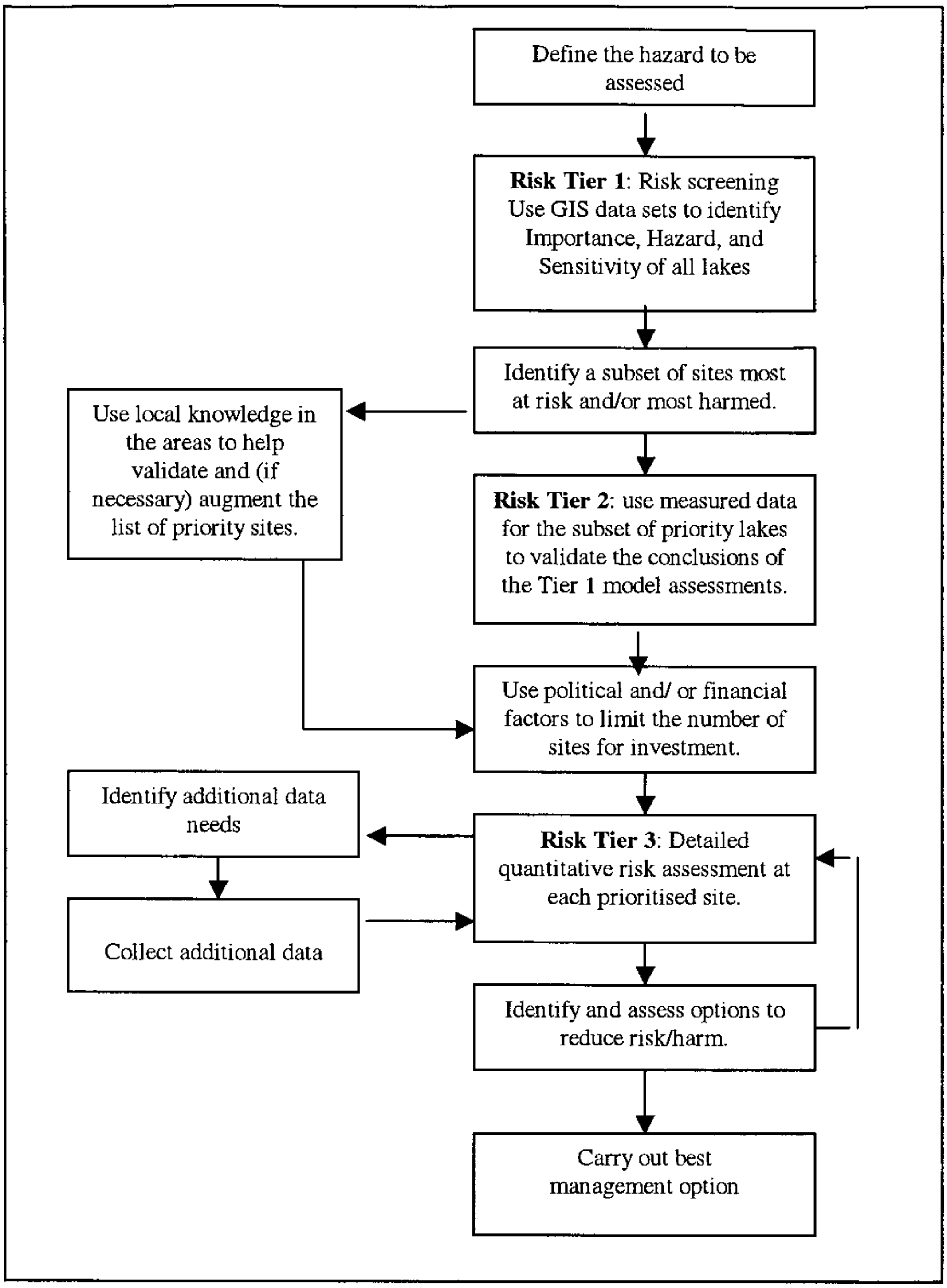

Figure 1 **Outline of the risk based prioritisation protocol approach for lakes (modified from DETR, 2000)**

3. IMPORTANCE

During Phase 1, it was agreed that the concept of a lake's "importance" or "value to society" should be a critical feature of any prioritisation protocol. Therefore, a scoping study was conducted at the start of Phase 2 to agree a set of criteria to be used in assessing the importance of a lake. This study involved wider consultation with the EA, SEPA, the conservation bodies and other relevant parties. It was considered necessary for the indicators of importance to satisfy the key requirements of the WFD, Lake HAPs and the implementation of the Agency's Eutrophication Strategy. Details of the scoping study are reported in the Project Record (Bennion *et al.*, 2003).

Many of the criteria suggested by the consultees were considered either to be too complex or the data were too difficult to obtain for inclusion at Risk Tier 1, where importance has to be assessed for all lakes in Great Britain. It was agreed that data for Risk Tier 1 must be available at the national level, preferably as GIS layers. Therefore, the indicators of importance were finally selected on practical grounds since the data required were relatively easy to obtain, enabling importance to be a key component of site prioritisation in Risk Tier 1 of the protocol. The importance indicators are common to both the eutrophication and acidification schemes and the following were adopted as producing a manageable set of lakes for further analysis at Risk Tier 2:

i) Size (TBL_LD): The WFD requires at least all lakes >50 ha to be classified.

ii) Conservation status: Lakes with high conservation status were identified by the following conservation designations: Ramsar (TBL_RAM), SPA (TBL_SPA) or SAC with aquatic interest (TBL_SAC).

iii) Bathing Waters (TBL_BDIR): There is a legal requirement to control the quality of waters designated under the EU Bathing Waters Directive.

A lake was considered to be important if it had one or more of these attributes. Table 1 illustrates the criteria used for assessment of importance for a subset of lakes.

Table 1 The criteria used for assessing lake importance
(1 indicates that the lake satisfies a criterion; 0 indicates that the lake does not satisfy a criterion)

WBID	OSNAME	Lake Area >50 ha	RAMSAR	SPA	SAC Aquatic	Bathing Water	Importance
35640	Hickling Broad	1	1	1	1	0	1
35655	Barton Broad	1	1	1	1	0	1
20986	Loch Avon	1	1	1	1	0	1
21189	Loch Kinord	1	1	1	1	0	1
21191	Loch Einich	1	1	1	1	0	1
18682	Loch Druidibeag	1	1	1	1	0	1
29844	Malham Tarn	1	1	0	1	0	1
28847	Bassenthwaite Lake	1	0	0	1	0	1
2712	Loch Watten	1	1	1	1	0	1
24843	Loch Leven	1	1	1	0	0	1

An ACCESS query was written (QRY_importance-criteria) to identify important lakes. The query was based on the following tables : TBL_RAM; TBL_BDIR; TBL_SPA; TBL_SAC and KEY_SAC + KEY_SACX; TBL_SSSI and KEY_SSSI; TBL_UK and KEY_UK and XTB_BAP-species-latest-observation. The query includes a number of criteria in addition to those given in Table 1 (e.g. SSSI, BAP species) so that extra criteria can be added by the user as required (see below).

An attempt was made to assess the relative importance of the criteria identified and to develop an appropriate scoring system. Efforts to rank these various indicators, however, were largely unsuccessful and, following extensive discussion, a scoring system was ultimately abandoned. The simple scheme was, therefore, retained, such that a lake is deemed to be important if it meets one or more of the above importance criteria; for example, all lakes shown in Table 1 would be classed as important. When applied to all lakes greater than 1 ha for which catchment based attribute data were generated (N= 14,342), the importance criteria result in a total of 2362 important lakes (England 470, Scotland 1795, Wales 97). Whilst this importance assessment is clearly biased towards certain lake characteristics and omits others, it satisfies the key requirements of the project whilst remaining flexible enough for users to adapt the scheme according to their specific needs. For instance, the conservation bodies may consider the criterion ‘SAC designation’ to be of higher priority than ‘lake size’ for HAP purposes whilst EA and SEPA may wish to place greater emphasis on large lakes for WFD purposes.

Owing to the large numbers of lakes designated as SSSIs (N = 3248) which leads to an additional 886 important lakes, SSSI designation was not included as one of the key criteria for assessing importance. However, this information is available in the inventory for sites in Great Britain (TBL_SSSI) and has been included as an additional importance assessment criterion in the query ‘QRY_importance-criteria’. SSSI status can, therefore, be included in the importance assessment if required. It was recognised that a number of other importance indicators may usefully be introduced to Risk Tier 1 at a later date, once datasets become available, or could be included at Risk Tier 2, as follows:

1) Waters where protected species are present (BAP priority species and Red List species) although many of these lakes are designated as Ramsar, SPA or SACs (or SSSIs). Note that this leads to an additional 525 important lakes. Sites in which protected species are present are given in TBL_BAP. This table includes a field which describes how a record has been associated with a specific water body. The field ‘Matched?’ has the entry ‘direct-hit’ if the grid reference and name gave an exact match with a water body or ‘matched’ to indicate that the site was matched manually using grid reference and/or name on the map. National Biodiversity Network (NBN) species codes are given in the field ‘NBN’. An extra column in the query ‘QRY_importance-criteria’ identifies those lakes which contain a BAP species, in addition to all the previous criteria.

2) Waters used for drinking water abstraction (data not currently available in the inventory).

3) Waters supporting commercial activities such as tourism, hydroelectric power supply and fish farming (data not currently available in the inventory).

Risk Tier 2 analysis for importance will include more thorough checks on the conservation designation to identify those sites where the designation relates specifically to the standing water component and not other factors; for example, a Ramsar site or a Special Protected Area (SPA) may be designated on the basis of its importance to wildfowl but the lake may have little intrinsic conservation value itself. Indeed maintenance of good water quality may not be a key issue for sites where bird populations are the main conservation interest. Conversely, a SSSI may hold a strong population of a threatened or endangered species where good water quality is crucial for its survival. Local knowledge of individual lakes will be important at this stage of the prioritisation. At Risk Tier 2 higher priority may be afforded to some sites because of a local sensitivity or lake specific pollution issue. For instance, damage to salmonid fisheries is a specific issue associated with acidification problems and thus important trout lakes might assume high priority.

In the absence of other factors carrying more weight (chapter 2) one possible method for identifying the highest priority lakes for remediation (i.e. passing from Risk Tier 2 to Risk Tier 3) would be to simply count the number of importance factors which are attributed to each lake. The lakes with the highest counts receive the highest priority.

4. THE EUTROPHICATION PRIORITISATION SCHEME

4.1 Risk Tier 1: Risk screening

A system was developed to screen all lakes in Great Britain with a surface area greater than 1ha with respect to their level of eutrophication. The method systematically reduced the number of lakes passed onto the next stage as shown in Figure 2.

4.1.1 Hazard

Loadings of the nutrient phosphorus (P) were chosen as the relevant parameter to define the level of hazard that each lake is exposed to. However, P loadings have only been measured for a small number of lakes. As a result nutrient loads at Risk Tier 1 were estimated from GIS-derived catchment land use and population data. The total P discharged to each lake from agricultural loss and from humans was estimated using a simplified set of P export coefficients from the literature (KEY_LC from Hilton *et al.*, 1999) for a range of land cover types (QRY_Pload_LC), animals (QRY_Pload_animals) and people (QRY_Pload_human). Total P load (QRY_Pload_catchment), expressed as kg/yr, was then calculated for each lake catchment by summing the total contribution from land use (QRY_Pload_LC_sum), animals (QRY_Pload_animals_sum) and humans (QRY_Pload_human). Animal density data are currently available for England and Wales only and, therefore, were not included in the fully worked P load calculations in order to give Great Britain-wide comparability between the results. The loads including animals were included in the tables for England and Wales and have been compared with loads excluding animals in chapter 6. It is recommended, however, that if animal density data become available for Scotland, that P load from livestock is included in the total P load calculations by summing the contributions.

The discharge of water into each lake was calculated (QRY_water_discharge) from the runoff depth (TBL_ROFF) multiplied by the catchment area (TBL_CT). The total P loads were then converted (QRY_Trophic_status) into in-lake annual mean P concentrations ($\mu g\ l^{-1}$) and then into annual mean chlorophyll a concentrations ($\mu g\ l^{-1}$) using the relevant OECD regression equations which take account of retention time (OECD, 1982; Vollenweider and Kerekes, 1980, respectively). For simplicity, the P concentration values were then classed according to the OECD-Vollenweider trophic classification system (OECD, 1982) as follows:

Trophic Status Class		TP concentration ($\mu g\ l^{-1}$)
Class 1	Low	<4
Class 2	↓	4-10
Class 3		10-35
Class 4		35-100
Class 5	High	>100

Lakes in Trophic Status Classes 3, 4 and 5 were considered to be potentially exposed to high levels of hazard and were passed onto the sensitivity assessment.

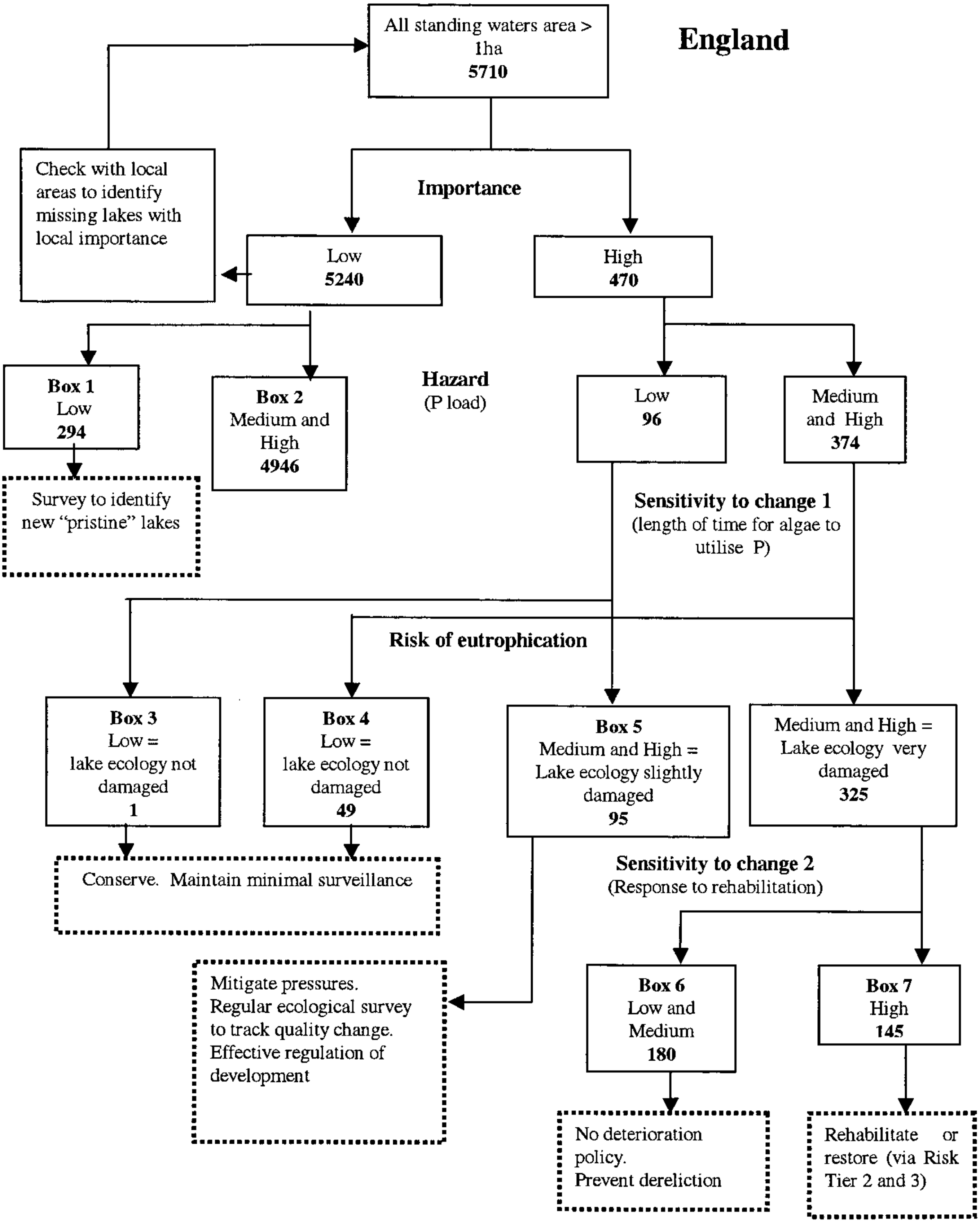

Figure 2a **Outline of the Risk Tier 1 eutrophication prioritisation scheme for England**

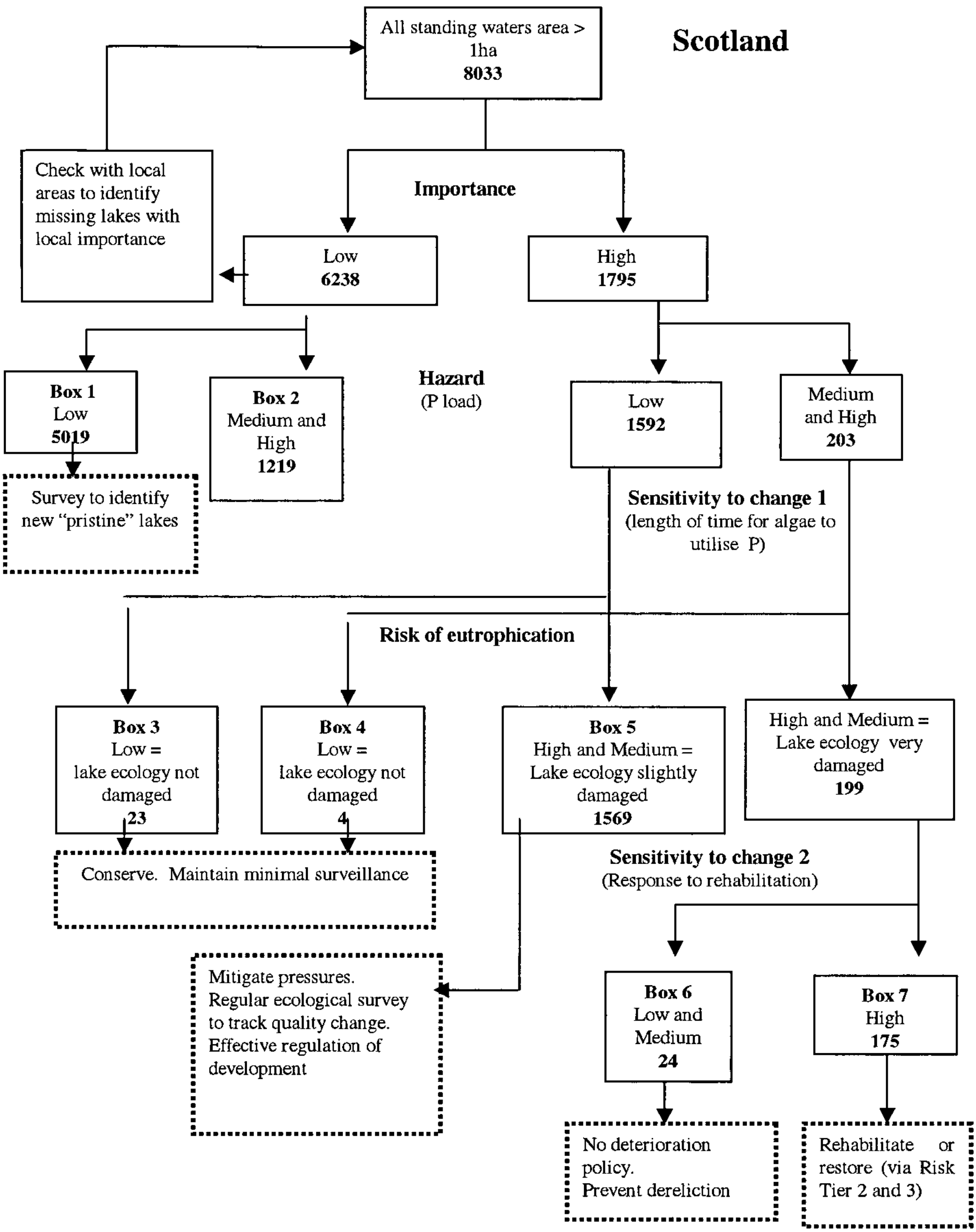

Figure 2b **Outline of the Risk Tier 1 eutrophication prioritisation scheme for Scotland**

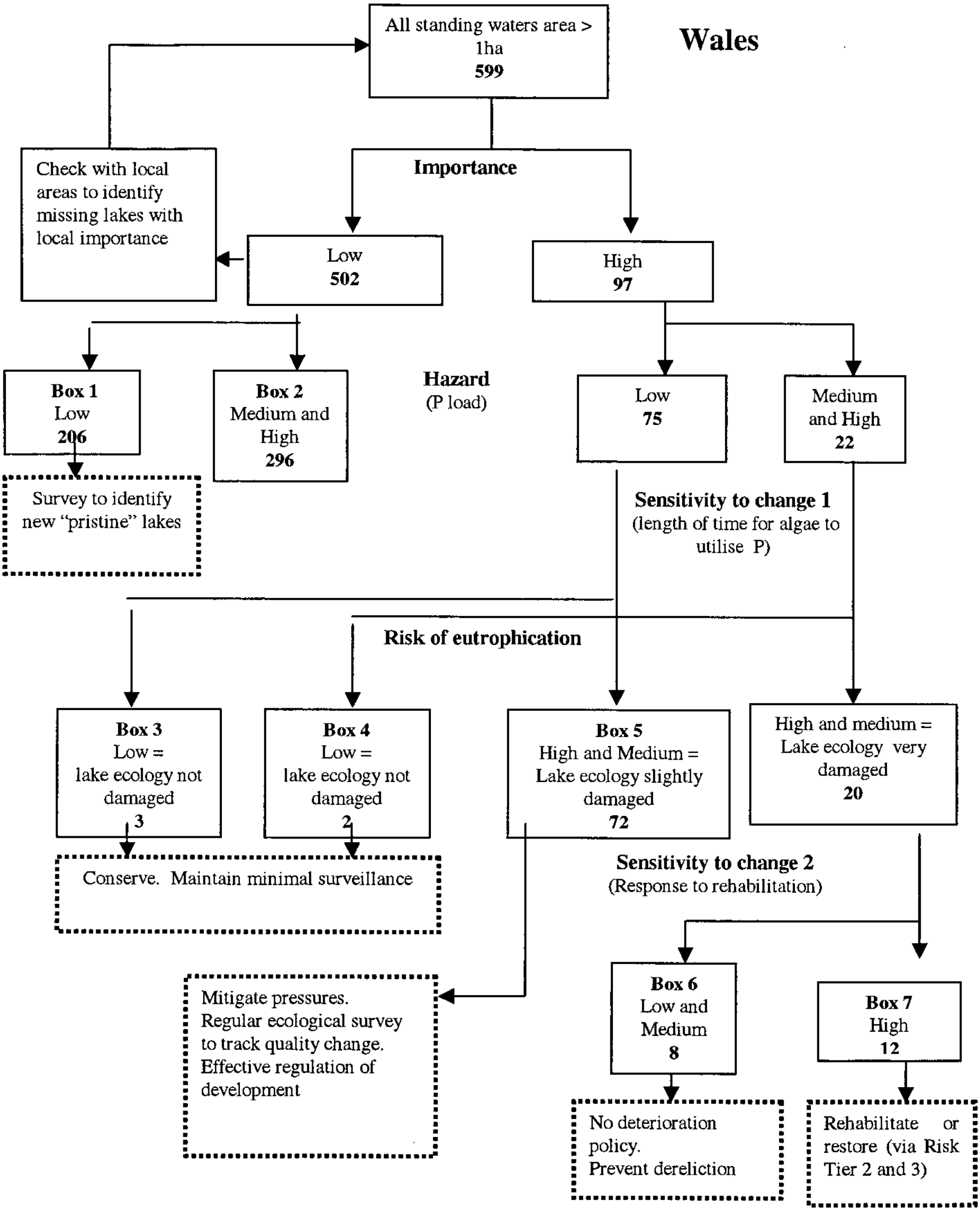

Figure 2c **Outline of the Risk Tier 1 eutrophication prioritisation scheme for Wales**

4.1.2 Sensitivity

At Risk Tier 1 for eutrophication, two sensitivity measures have been applied sequentially. Firstly, the lake retention time was used to provide an indication of the ability of algae to utilise the nutrients. The higher the retention time, the greater the opportunity for the algae to use the P and thus the more sensitive the lake to eutrophication. Retention time was one of the criteria proposed by Reynolds in Phase 1 for assessing sensitivity of lakes to eutrophication (Bennion *et al*, 2001).

Where possible, measured mean lake depth data were used in the calculation of retention time (QRY_water_discharge) but, owing to the lack of bathymetric surveys for the majority of lakes, mean depth was based on modelled data in most cases (see section 7.3 for details). The use of modelled depth data introduces possible errors into the calculations. The retention times are classed into three groups, according to the Reynolds scheme, as follows:

Retention Class	Sensitivity to change	Retention time	
Class 1	Very sensitive	High retention	(>30 days)
Class 2	Slightly sensitive	Intermediate retention	(3-30 days)
Class 3	Insensitive	Low retention	(<3 days)

Lakes falling into Retention Class 3 were not passed onto the next assessment. Reynolds (in Bennion *et al*, 2001) also suggested incorporating alkalinity (as a surrogate for major cation concentrations) into the sensitivity estimation in order to take account of the reduced sorption of P onto suspended and bed sediments at high ionic strengths, but a national coverage of alkalinity data was not available in time to be included in the model. He also proposed the inclusion of an assessment of the area of sediment surface less than 3 m deep as an indicator of the rate of sediment P recycling. However, these data were unavailable for most lakes. There was an option to use the stratification class as a surrogate but, in the end, it was decided not to incorporate this factor since, a) the Vollenweider equations take some account of sediment recycling and b) the stratification class was found to be more useful in the next stage of the assessment and its use at two stages had potential to heavily bias the analyses.

Current experience of lake restoration schemes for eutrophic lakes suggests, that deep lakes, where there is little interaction between the sedimentary P store and the water column, recover rapidly following reductions in nutrients. Conversely, shallow lakes, where the sediments are continuously resuspended and are in intimate contact with the water column often take many decades to recover their earlier trophic staus. In this context, the terms "shallow" and "deep" are relative terms, being more related to the mixing status of a lake than to the actual depth. Reynolds (1992) showed that the stability of the water column can be predicted with reasonable reliability using the ratio between the Wederburn depth at an 8 m/s wind speed and the maximum depth. The Wederburn depth is calculated from the following equation:

$$H_s = \frac{[\rho_w (u^*)^2 L]^{1/2}}{[g \, \Delta \rho_w \;]}$$

where:

H_s = depth of the seasonal thermocline where density gradient >0.02 kg m^{-3} m^{-1}
ρ_w = density of water = 1000 kg m^{-3}
$(u^*)^2 = (\rho_a\, c\, (u_{10})^2/\rho_w)$
where ρ_a is the density of air = 1.2 kg m^{-3}
c = coefficient of frictional drag of the water on the wind = 1.3 10^{-3}
u_{10} = wind speed at 10 m above water surface (m/s)
L = lake width/maximum fetch. ($\approx$ (Surface area $/\pi)^{0.5}$
g = gravitational constant = 9.81 m s^{-2}
$\Delta\ \rho_w$ = 0.9 kg m^{-3} (minimum difference for sustained thermocline)

If the ratio derived from the Wederburn depth (QRY_Wederburn-depth) divided by the maximum depth is less than or equal to 1 then the lake is unlikely to stratify for significant periods of the summer. Lakes with values of the ratio significantly greater than 1 are likely to stratify all of the summer. However, lakes do not immediately change from being fully stratified to being fully mixed but go through a state known as polymictic, where the lake stratifies more or less of the time, depending on how far the ratio departs from the value of 1. The thermocline depth at wind speeds of 4 m/s and 16 m/s (0.5x and 2x the reference wind speed) were chosen to indicate boundaries where lakes were likely to move from polymictic conditions to be either more completely stratified or more completely fully mixed. This resulted in five classes (QRY_tier1-class), as follows:

Stratification Class	Response to restoration	Degree of stratification
Class 1	Low	Shallow mixed (<3 m max depth)
Class 2	↓	Completely mixed (>3 m max depth)
Class 3		Polymictic but mainly mixed
Class 4		Polymictic but mainly stratified
Class 5	High	Stratified

Stratification Classes 4 and 5 were assumed to be more likely to recover quickly following a reduction in nutrient loading and were passed through to the Risk Tier 2 assessment.

4.1.3 Risk assessment

In the Risk Tier 1 analysis, the different criteria (importance, hazard, sensitivity 1, sensitivity 2) were applied sequentially, the number of lakes passing to the next filter reducing at each step (QRY_tier1-class) (Figure 2). All 'important' lakes were passed forward. The lakes were then separated into low hazard (Trophic Status Classes 1 and 2) and medium and high hazard (Trophic Status Classes 3, 4 and 5). Trophic Status Classes 3, 4 and 5 were passed onto the first sensitivity assessment (i.e. the likelihood that the algae can utilise the P during its stay in the lake). In our analysis we have assumed that all lakes in Retention Class 3 (short retention time/rapidly flushed) are unlikely to be damaged and that medium/ high trophic status lakes with Retention Class 3 are damaged but not sufficiently seriously that remedial work is required. Conversely all lakes in the high trophic status/medium to long retention time classes are assumed to be seriously degraded ecologically and passed onto the second sensitivity assessment. It is possible to be more subtle at this stage, particularly with respect to the low trophic status, high retention time lakes. In these cases, even though the load is relatively low, at long retention times it may be possible for algae to utilise all the P and attain significant algal concentrations. Hence, there is a case for re-combining low trophic status/high retention time lakes back into the damaged group requiring rehabilitation. We have not included this step in our assessment. Further work, using data from low and medium loaded lakes with high retention times is required to clarify the criteria for passing lakes through this last Risk Tier 1 assessment. High trophic status lakes with long retention times were classified according to their stratification potential. Lakes in Stratification Classes 4 and 5, which stratify, were passed onto the Risk Tier 2 assessment. This does not mean that remedial measures should not be attempted on lakes in Stratification Classes 1, 2 and 3 but it should be recognised that the returns will be achieved very slowly. Figure 2 gives the number of lakes passed through at each stage of the assessment for the three countries in Great Britain. Box numbers have been allocated to identify the key groups of lakes arising from the scheme, as follows (produced using QRY_NutrientBox_England, QRY_NutrientBox_Scotland and QRY_NutrientBox_Wales):

Box 1: Low Importance, Low Hazard. Some of these lakes may be useful as reference lakes and therefore a survey is recommended to identify new "pristine" lakes.

Box 2: Low Importance, Medium-High Hazard. These lakes are therefore low priority.

Box 3: High Importance, Low Hazard, Low Sensitivity to enrichment. It is assumed that owing to their low sensitivity the ecology of these lakes is not likely to be damaged

Box 4: High Importance, Medium-High Hazard, Low Sensitivity to enrichment. It is assumed that owing to their low sensitivity the ecology of these lakes is not likely to be damaged.

Box 5: High Importance, Low Hazard, Medium-High Sensitivity to enrichment. In spite of low P loads, it is assumed that owing to their high sensitivity the ecology of these lakes may be slightly damaged.

Box 6: High Importance, Medium-High Hazard, Medium-High Sensitivity to enrichment, Low-Medium Sensitivity to rehabilitation. Owing to high P load and their high sensitivity the ecology of these lakes is likely to be damaged. Given their low likelihood of response to rehabilitation, these lakes should be monitored and managed to prevent further deterioration.

Box 7: High Importance, Medium-High Hazard, Medium-High Sensitivity to enrichment, High Sensitivity to rehabilitation. Owing to high P load and their high sensitivity the ecology of these lakes is likely to be damaged. Given their high likelihood of response to rehabilitation, these lakes should be high priority for restoration.

Table 2 provides an illustration of the criteria used for the risk asssessment at Risk Tier 1 of the eutrophication scheme for a subset of 15 lakes. Lakes in Box 7 such as Tatton Mere, Grafham Water, Llangorse Lake, Loch Ussie, Windermere and Hanmer Mere are at high risk of enrichment but are likely to respond well to restoration whereas Upton Broad, Loch Gelly, Loch of Skene, and Kenfig Pool are at high risk of enrichment but are not likely to respond well to remediation (Box 6). Bassenthwaite Lake, Loch of Swannay, Lake Bala, Loch Lomond and Llyn Cwellyn are at lower risk of enrichment than the former lochs but in spite of low P loads, the ecology of these lakes may be slightly damaged owing to their high sensitivity (Box 5).

Table 2 The criteria used for the risk asssessment at Risk Tier 1 of the eutrophication scheme for a subset of 15 lakes

WBID	OSNAME	Trophic Status Class	Retention Class	Stratification Class	Eutrophication scheme box number
32804	Tatton Mere	5	1	5	7
38310	Grafham Water	4	1	5	7
36202	Upton Broad	4	1	1	6
29233	Windermere	3	1	5	7
28847	Bassenthwaite Lake	2	2	5	5
25077	Loch Gelly	5	1	1	6
20757	Loch of Skene	4	2	1	6
16456	Loch Ussie	3	1	5	7
1678	Loch of Swannay	2	1	3	5
24447	Loch Lomond	1	1	5	5
34780	Hanmer Mere	5	1	4	7
42170	Kenfig Pool	4	1	1	6
40067	Llangorse Lake	3	1	4	7
34987	Llyn Tegid or Bala Lake	2	1	5	5
34002	Llyn Cwellyn	1	1	5	5

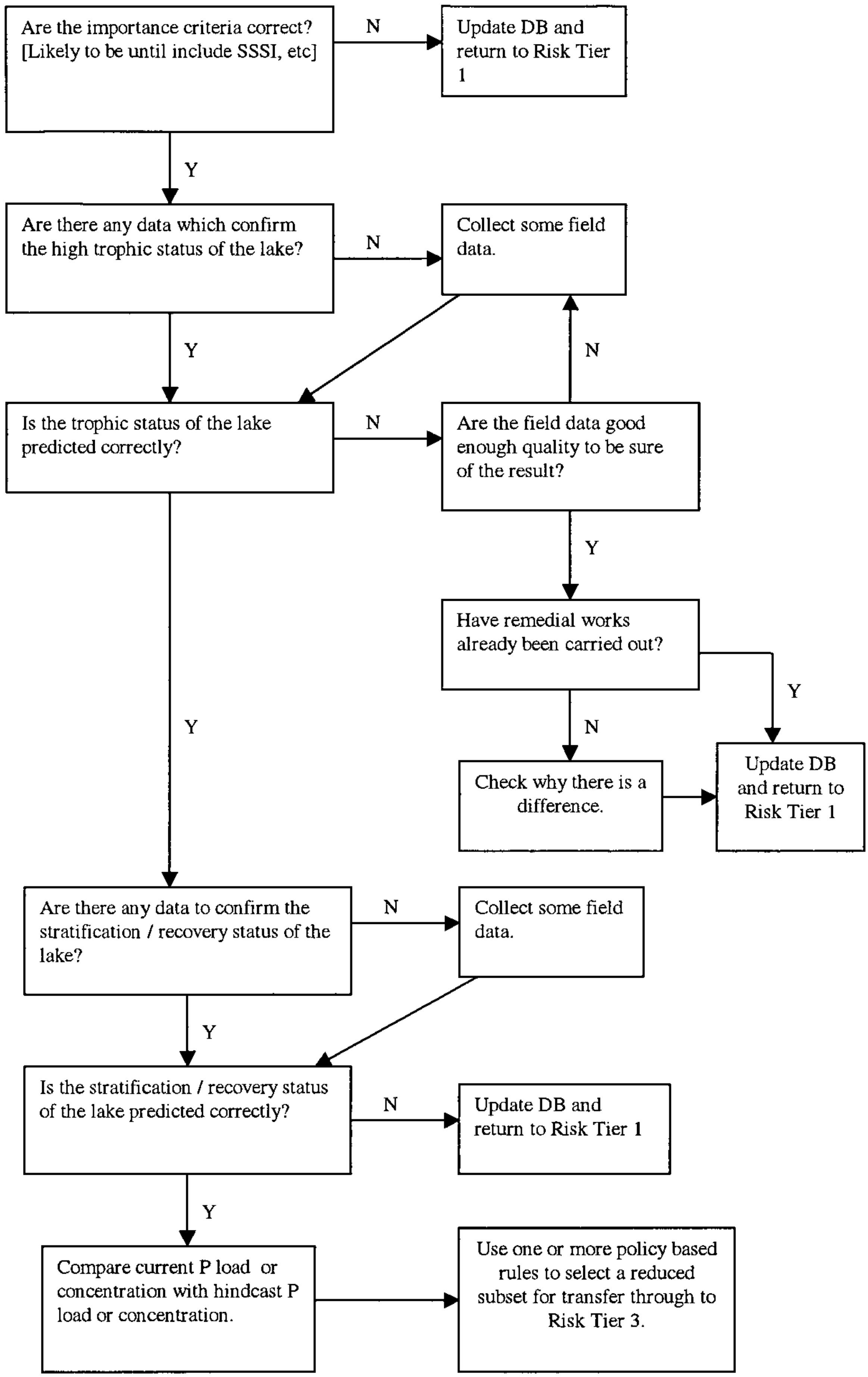

Figure 3 **Outline of protocol for checking that a lake has correctly passed from Risk Tier 1 to Risk Tier 2 and for moving lakes from Risk Tier 2 to Risk Tier 3 in the eutrophication scheme**

4.2 Risk Tier 2: Generic quantitative risk assessment on sub-set of lakes

As stated earlier, the main objective of Risk Tier 2 screening is to confirm the assessment developed in Risk Tier 1 of the most vulnerable lakes. This more detailed assessment of lake status uses measured data to demonstrate whether a site has been affected by eutrophication. Figure 3 outlines the protocol for checking that a lake has correctly passed from Risk Tier 1 to Risk Tier 2 and for moving lakes through from Risk Tier 2 to Risk Tier 3. Firstly the importance assessment is checked against more detailed data on conservation and ecological value to confirm that the lake itself is important. Next, the modelled current trophic status class (hazard) is compared with measured data that describe trophic status to confirm whether the trophic status has been correctly predicted. It is possible that the model may have significantly over- or underestimated measured lake TP and the reason for this should be established. A check should be made on whether any remedial work has already been undertaken to reduce nutrient loads. Next, data to confirm the stratification status, and thereby the recovery potential of the lake, should be collated and compared with the modelled data to assess the accuracy of the predictions. If at any stage there are discrepancies between modelled and measured data, the database should be amended and the protocol re-run. Finally a state-changed assessment should be made by comparing current P loads or concentrations with hindcast values, or better, palaeolimnological data.

4.2.1 Current status

At Risk Tier 2 measured chemical variables of in-lake nutrient concentrations and loadings can be included to assess the current trophic status of the lake more accurately than that modelled at Risk Tier 1. Available data on simple measures of trophic status such as annual mean TP, SRP, nitrate, chlorophyll a, Secchi depth and oxygen should be collated, and where possible measured P load data. Additionally, available biological data can be collated, for example, on macrophytes (including the Palmer TRS and lake type), contemporary diatom assemblages and occurrence of algal blooms, to further confirm current trophic status. Again, it is important to stress that the objective is to confirm the Risk Tier 1 trophic state classification. It is useful to collect all available data but new data should be limited to the most cost-effective means of making the confirmation. The meta-database contained within the georeferenced inventory provides a useful starting point for sourcing data for specific lakes. However, these measures only show the current trophic status. They cannot, in isolation, indicate whether a water body is naturally nutrient rich, or has been enriched from its pristine state.

4.2.2 Damage or temporal change

At Risk Tier 2, the smaller number of lakes being assessed allows the sensitivity to enrichment measures to be further refined. Lake retention times can be more accurately established by including measured depth data rather than modelled depth data. Where lake depth measurements are unavailable, it is recommended that a bathymetric survey be undertaken to collect such data. Furthermore, measured profile data, where available, could be incorporated to confirm the stratification status of the lakes, which was simply modelled at Risk Tier 1.

A temporal or state-changed perspective can be introduced at Risk Tier 2 to assess degree of enrichment. Export-coefficient models to hindcast nutrient load and lake nutrient concentrations are available for England and Wales (Johnes *et al.*, 1996; Moss *et al*, 1996) and for Scotland (Ferrier *et al*, 1997). The Johnes *et al* (1996) model can be applied to any lake in England and Wales and to date the model for Scotland has been applied to around 200 lochs

(Fozzard *et al*, 1999). A comparison of the hindcast P load or concentration with the current P load or concentration allows an assessment of the extent of eutrophication at a given site to be made. However, it should be noted that the Johnes *et al.* (1996) hindcast model only models nutrient enrichment from a limited number of anthropogenic sources. The discharge from, for example, a sewage treatment works into the lake from a population located outside the catchment would not be identified. The same would be true for a naturally eutrophic catchment or if remedial action had already been implemented. In these cases input of local knowledge is vital.

Palaeolimnology can also be employed to assess whether a lake has become enriched and has the benefit that it does include sources of P other than agriculture and sewage treatment works. Diatoms (*Bacillariophyceae:* unicellular, siliceous algae) are sensitive to water quality changes and are good indicators of lake nutrient levels. Consequently, diatoms have been successfully employed to develop models (transfer functions) for quantitatively inferring past lake TP (e.g. Bennion, 1994; Bennion *et al*, 1996a). The approach is able to provide estimates of baseline (reference) TP concentrations in lakes, and when coupled with dating of sediment cores, can determine the timing, rates and possible causes of eutrophication at a particular site (e.g. Bennion *et al*, 1996b; Bennion *et al*, 2000). At Risk Tier 2, a low resolution analysis of diatoms preserved in a lake sediment core could be undertaken to assess degree of eutrophication.

4.3 Risk Tier 3: Detailed quantitative risk assessment at site specific level

Lakes that passed the Risk Tier 2 filter into Risk Tier 3 would then need to be subjected to a very detailed local assessment to develop the case for investment and to fully assess the management options (methods) and targets for recovery or remediation. For eutrophication, this step would be the development of a Eutrophication Control Action Plan (ECAP) (Environment Agency, 2000).

4.3.1 Current status

Firstly, a site specific assessment of local importance and uses should be carried out and any local or regional political issues identified. A comprehensive chemical and biological survey is then required. For the measurement of mean phosphorus and/or chlorophyll a concentrations, periodic analysis over at least one year should be undertaken, with a minimum resolution of quarterly (seasonal) sampling, and ideally at least a fortnightly sampling regime. This would enable the seasonal characterisation of the site, which is important because of the high seasonal variation in nutrient concentration, with possibly serious biological implications that might not be detected through less frequent sampling. A full biological survey should also be carried out to identify the presence (or absence) of nutrient sensitive taxa, e.g. for diatoms, macrophytes and invertebrates.

GIS export coefficient modelling, validated by in river concentration monitoring, could be employed to quantify the main sources of nutrients in the catchment. The collection of nutrient budget data is advised to assess the relative contribution from diffuse and point sources. These mass balance data could then be used, along with in-lake chlorophyll-a concentrations, to populate and validate a Phytoplankton Responses to Environmental Change model (PROTECH) of the lake (Reynolds and Irish, 1997). PROTECH simulates the dynamics of phytoplankton and can subsequently be used to test different management scenarios.

4.3.2 Extent of damage and targets for recovery

A detailed palaeoecological assessment, building on that carried out at Risk Tier 2, would provide information on the baseline biology of the site and an independent measure of the baseline nutrient status via multi-proxy methods and transfer functions (e.g. Sayer *et al*, 1999; Bennion *et al*, 2000). Modern analogue techniques could be used to identify targets for recovery or remediation (Flower *et al*, 1997).

Where these data were not available, further monitoring and data analysis would need to be undertaken to produce sufficient data to enable management decisions to be made.

5. THE ACIDIFICATION PRIORITISATION SCHEME

5.1 Risk Tier 1: Risk screening

For risk screening at the national scale the acidification scheme has been developed as detailed below, which as for the eutrophication scheme, systematically reduces the number of lakes passed onto the next stage as shown in Figure 4.

5.1.1 Hazard

For acid deposition, the estimate of hazard at Risk Tier 1 is more straightforward than for nutrients because national maps of loads of sulphur and nitrogen deposition have already been developed.

The total acid deposition load best represents the pollution hazard for acidification. Acid deposition data (non-marine sulphate, nitrate, ammonium and chloride minus non-marine calcium and magnesium), expressed in keq/ha/yr, were provided by CEH Edinburgh, the most recent available data being for the period 1995-97 (TBL_DEP). The data are modelled on a 5km grid and provide the best available picture of the acidification hazard for the whole country. The scheme does not include the hazard associated with acid mine drainage but could be adapted if suitable data become available.

The acid deposition values were classified into four classes:

Acid Deposition Class		Total acid deposition load (keq/ha/yr)
Class 1	Low	<0.5
Class 2	↓	0.5-1.0
Class 3		1.0-1.5
Class 4	High	>1.5

Lakes in Acid Deposition Class 1 are considered not to be at risk because of the low load and thus do not pass on to Risk Tier 2.

5.1.2 Sensitivity

As for the hazard assessment, the sensitivity assessment for the acid deposition scheme is somewhat simpler than for the nutrients scheme. A large amount of research was conducted in the 1980s on the susceptibility of surface waters to acidification.

A published national map of the sensitivity of surface waters to acidification is already available (Hornung *et al*, 1995). The map was developed specifically to identify areas where lakes and streams were likely to be sensitive to acidification by acid deposition, using national geology, soils and land-use datasets. The data are available nationally on a 1 km grid. A sensitivity classification related to buffering capacity was allocated based on the dominant soil type within each square. The geology data are based on the sensitivity map produced by Edmunds and Kinniburgh (1986) whereby each of the geological map units from the 1:650,000 Geology Map of Britain was allocated to one of four buffering capacity classes. The sensitivity map used in this project is not modified for land use. Twelve possible combinations of geological and soil sensitivities were generated which were subsequently aggregated to five classes of sensitivity to acidification:

Freshwater Sensitivity Class (FWS)	
Class 1	High sensitivity
Class 2	Medium-high sensitivity
Class 3	Medium-low sensitivity
Class 4	Low sensitivity
Class 5	Non-sensitive

For the purposes of this project, the dominant freshwater sensitivity class (FWS) for each lake catchment was calculated (i.e. the freshwater sensitivity class of the largest area in the catchment) (TBL_FWCX). There are no freshwater sensitivity data for Orkney and the Shetlands. In order to include all waterbodies in the scheme at Risk Tier 1, sensitivity classes were ascribed for lochs on Shetland and Orkney using solid and drift geology data.

All lakes in Freshwater Sensitivity Classes 3, 4 or 5 are considered not to be at risk because of their insensitivity to acidification and therefore do not pass on to Risk Tier 2.

5.1.3 Risk assessment

By combining classes of acid deposition load and freshwater sensitivity, lakes where the likelihood of acidification is greatest and those areas where there is no risk of acidification can be identified. The following deposition-sensitivity combinations are used in the scheme to identify lakes at risk of acidification. This accounts for the fact that relatively low deposition in highly sensitive areas may cause acidification.

Acid Deposition Class	**Freshwater Sensitivity Class**
2	1
3	1
3	2
4	1
4	2

In the Risk Tier 1 analysis, the different criteria (importance, hazard, sensitivity) were applied sequentially, the number of lakes passing to the next filter reducing at each step (Figure 4). All important lakes were passed forward. The lakes were then separated into low hazard (Acid Deposition Class 1) and medium and high hazard (Acid Deposition Classes 2, 3 and 4) and the latter were passed onto the sensitivity assessment. All Acid Deposition Class 1 sites are considered not to be at risk of acidification as the loads are very low. All Freshwater Sensitivity Class 3 to 5 sites are considered not to be at risk of acidification because of their low sensitivity. Furthermore, any lake with >5% tilled or agriculturally improved land in the catchment is considered not to be at risk because it is assumed that the land will be subject to liming. Lakes in the combined Acid Deposition-Freshwater Sensitivity classes given above as at risk were passed onto the Risk Tier 2 assessment. Figure 4 gives the number of lakes passed through at each stage of the assessment for the three countries in Great Britain. Box numbers have been allocated to identify the key groups of lakes arising from the scheme, as follows (produced using the set of queries 'QRY_AcidBox' listed on page A1-25):

Box 1: Low Importance, Low Hazard. Some of these lakes may be useful as reference lakes and therefore a survey is recommended to identify new "pristine" lakes.

Box 2: Low Importance, Medium-High Hazard. These lakes are therefore low priority.

Box 3: Low risk of acidification. It is assumed that owing to either their low hazard and/or their low sensitivity the ecology of these lakes is not likely to be damaged by acidification.

Box 4: High risk of acidification. Owing to high acid deposition load and their high sensitivity the ecology of these lakes is likely to be damaged by acidification. These lakes should be monitored and given high priority for restoration.

Table 3 provides an illustration of the criteria used for the risk assessment at Risk Tier 1 of the acidification scheme for a subset of 13 lakes. All of the lakes classified in acidification scheme Box 2 have low importance but have relatively high acid deposition loads. Those classified into Box 4 are important waters with high acid deposition loads and high sensitivity to acidification. Those lakes with Acid Deposition Class 4 and Freshwater Sensitivity Class 1 are at the highest risk, i.e. Loch Middle and Widdop Reservoir.

Table 3 The criteria used for the risk asssessment at Risk Tier 1 of the acidification scheme for a subset of 13 lakes

WBID	OSNAME	Acid Deposition Class	Freshwater Sensitivity Class	Acidification scheme box number
2200	Loch na h-Uamhachd	2	1	4
11600	Loch na Bà Ruaidhe	2	1	2
22920	Loch Anlaimh	2	1	2
23086	Lochan Gaineamhach	3	1	4
22932	Loch Finnart	3	1	4
22700	Dubh Lochan	3	1	2
24091	Dubh Loch	3	2	2
28060	Loch Middle	4	1	2
30604	Widdop Reservoir	4	1	4
28854	Bowscale Tarn	4	2	4
24606	Lochan Dubh Mhuilinn	4	2	2
27540	Moodlaw Loch	4	2	2
29081	Bleaberry Tarn	4	3	2

5.2 Risk Tier 2: Generic quantitative risk assessment on sub-set of lakes

After the identification of the most vulnerable areas through the screening process in Risk Tier 1, the next stage allows a more detailed assessment of lake status by incorporating measured data to demonstrate whether a site has been affected by acidification. Figure 5 outlines the protocol for checking that a lake has correctly passed from Risk Tier 1 to Risk Tier 2 and for moving lakes through from Risk Tier 2 to Risk Tier 3. Firstly the importance assessment is checked against more detailed data on conservation and ecological value to confirm that the lake itself is important. Next, the current acidity status is assessed with measured chemical and biological data to confirm whether the lake is acid and thus likely to be sensitive to acidification. A check should be made on whether any remedial work has already been undertaken to reduce acidity, e.g. liming. Next, critical loads and exceedances are calculated for each lake to assess the accuracy of the Risk Tier 1 risk assessments based on acid deposition load and dominant freshwater sensitivity classes. If at any stage there are discrepancies between modelled and measured data, the database should be ammended and the protocol re-run. Finally a state-changed assessment should be made by comparing current pH or Acid Neutralising Capacity (ANC) with hindcast values.

5.2.1 Current status

For any water body the current acidity status is provided by simple measures of pH and alkalinity (or ANC). For example, a pH based classification scheme (the "spatial state" for acidification) was proposed under the EA Lake Classification project (Johnes *et al*, 2000). Additionally, available biological data can be collated, for example, on macrophytes (including the Palmer TRS and lake type), contemporary diatom assemblages and fish populations, to further confirm current acidity status. If the lake is currently alkaline, then it is unlikely to be sensitive to acidification. The meta-database contained within the georeferenced inventory provides a useful starting point for sourcing data for specific lakes. Such measures, however, cannot indicate whether a water body is naturally acid, or has been acidified from its pristine, pre-industrial state by acid deposition.

5.2.2 Damage or temporal change

At Risk Tier 2, critical loads can be used in place of the Risk Tier 1 Freshwater Sensitivity classes to improve the sensitivity assessment. Critical load models determine the maximum loading that can be placed on a lake system without the likely occurrence of long term damage to ecosystem structure and function. They provide a direct measure of both current damage and potential damage from acid deposition when used in conjunction with acid deposition data (i.e. hazard). For linking damage to the deposition load, critical load exceedance is used. The difference between using Freshwater Sensitivity classes and critical loads is that the latter are lake specific and require actual data to be collected for each site. In order to calculate critical loads for sulphur deposition, full analysis of major ion water chemistry is required (Ca, K, Mg, Na, NH_4, Cl, SO_4, NO_3). For the inclusion of nitrogen in the models (as recommended internationally) further catchment data are required to quantify the retention of N which reduces the net acidification effect of N deposition; they are lake area, catchment area, landcover data (available nationally at 30 m resolution), proportions of each soil type within the catchment and total N deposition (NO_x + NH_x). These models are well developed under a DETR funded programme for UK freshwaters and are used to feed into policy formulation for emissions reductions (Curtis *et al.*, 2000). The models can be used to quantify the change in ANC from a pre-industrial state (cf. EA Lake Classification state-changed scheme – Johnes *et al.*, 2000, and the Scottish standing waters classification scheme – Fozzard *et al.*, 1999).

Palaeolimnology can be employed to assess whether a lake has been acidified. Diatoms are sensitive to water quality changes and are particularly good indicators of lake pH. Consequently, diatoms have been successfully employed to develop models (transfer functions) for quantitatively inferring past lake pH (e.g. Stevenson *et al*, 1991). The approach is able to provide estimates of baseline (reference) pH concentrations in lakes, and when coupled with dating of sediment cores, can determine the timing, rates and possible causes of acidification at a particular site (e.g. Flower and Battarbee, 1983). At Risk Tier 2, a low resolution analysis of diatoms preserved in a lake sediment core could be undertaken to assess degree of acidification.

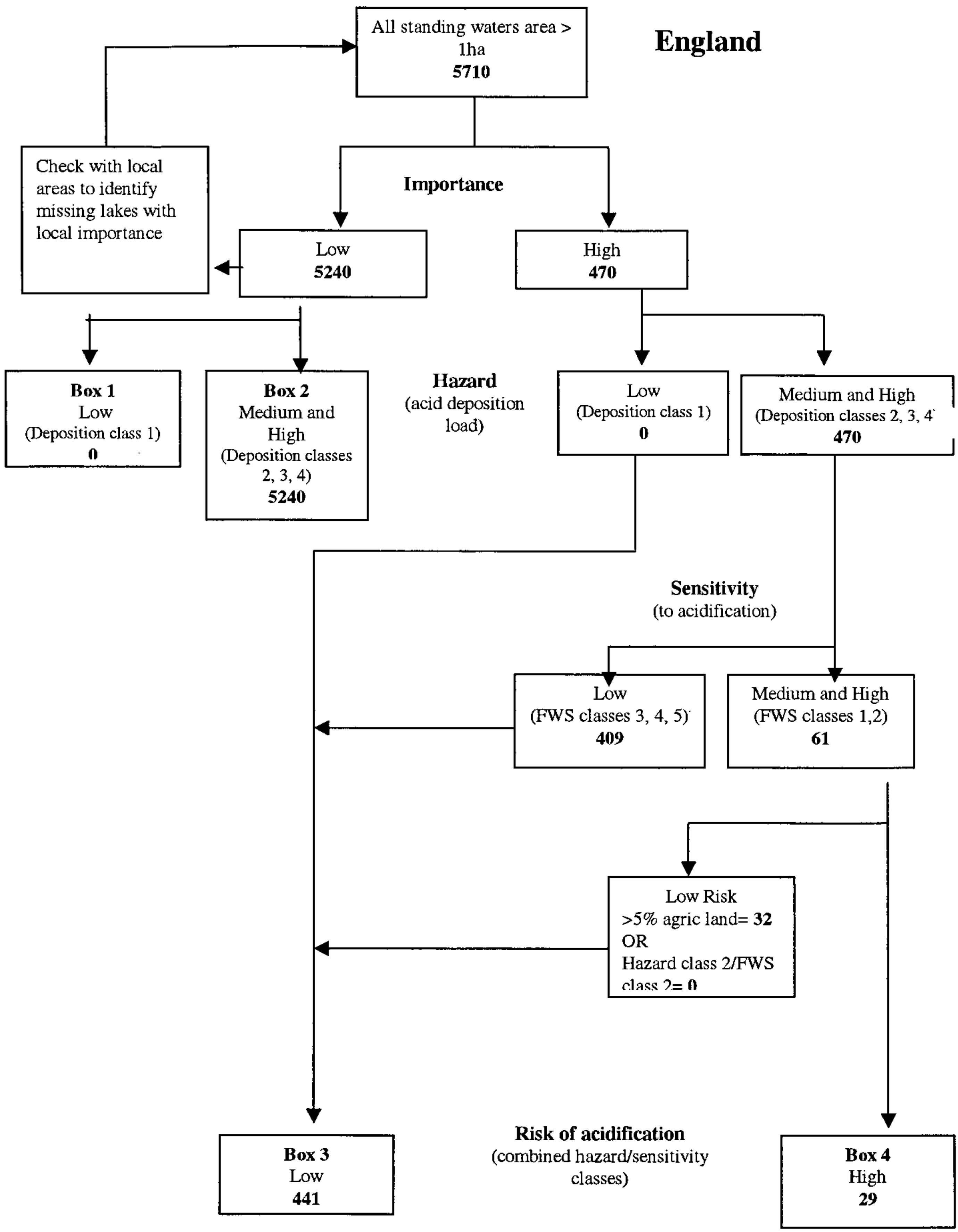

Figure 4a Outline of the Risk Tier 1 acidification prioritisation scheme for England

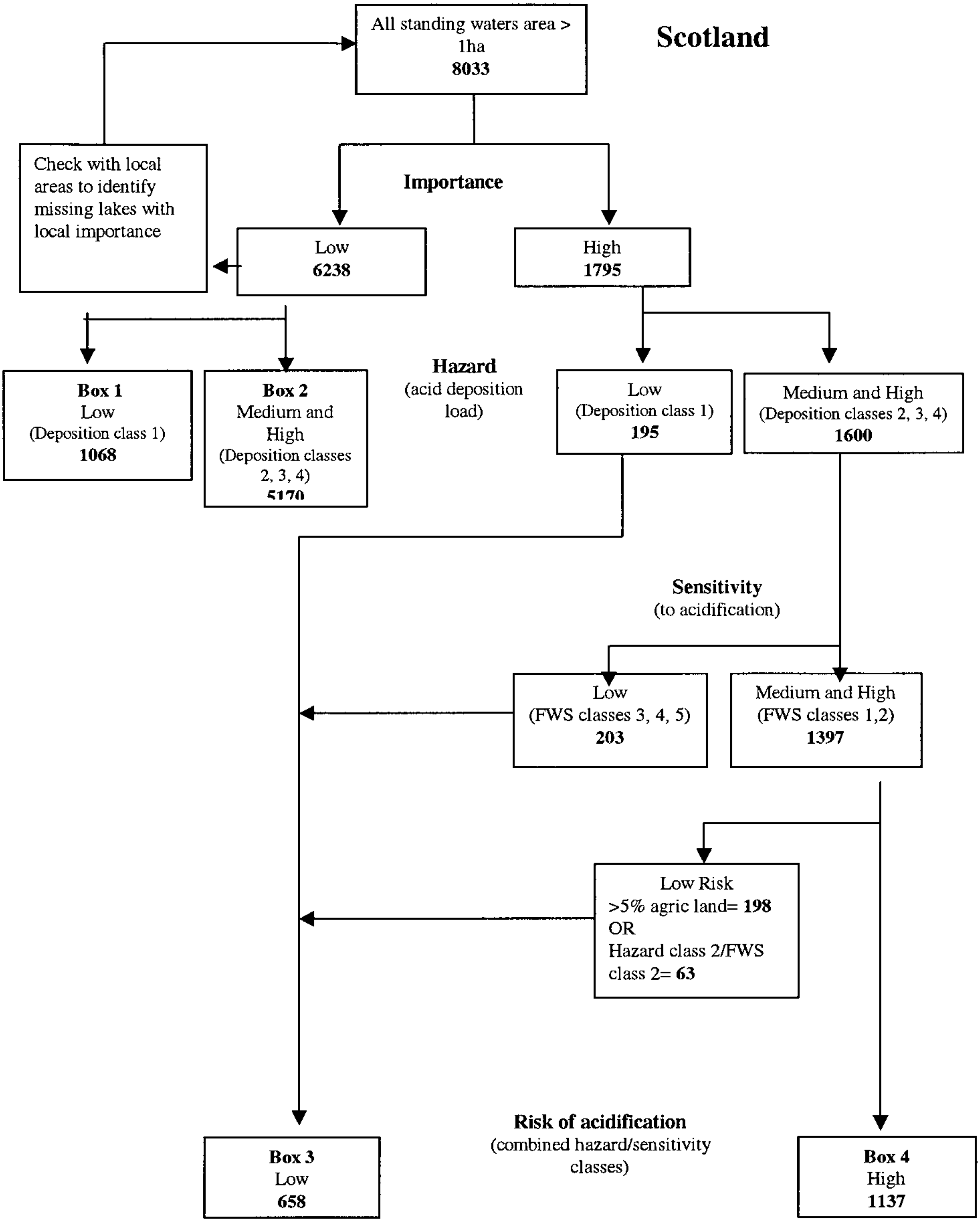

Figure 4b Outline of the Risk Tier 1 acidification prioritisation scheme for Scotland

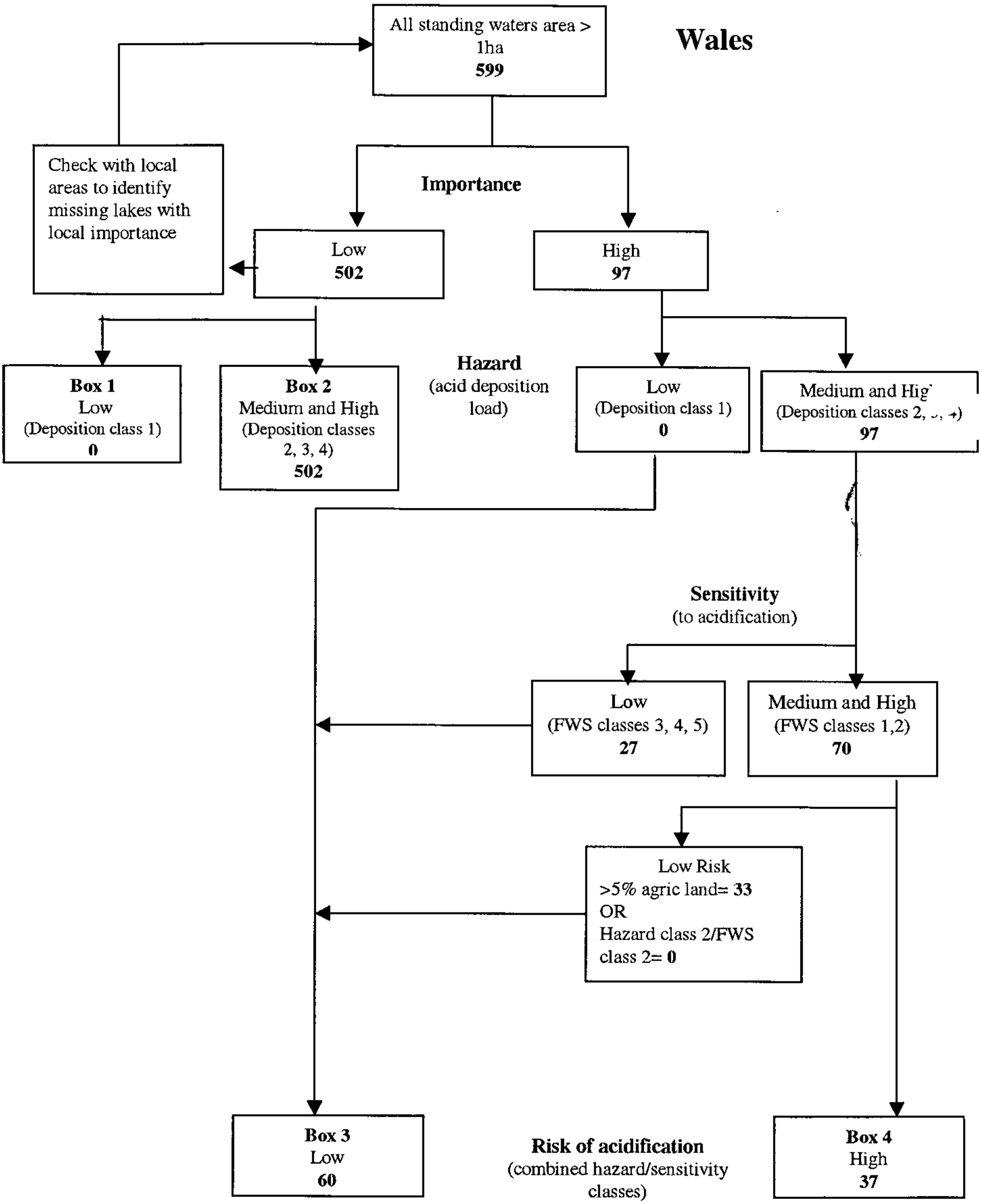

Figure 4c **Outline of the Risk Tier 1 acidification prioritisation scheme for Wales**

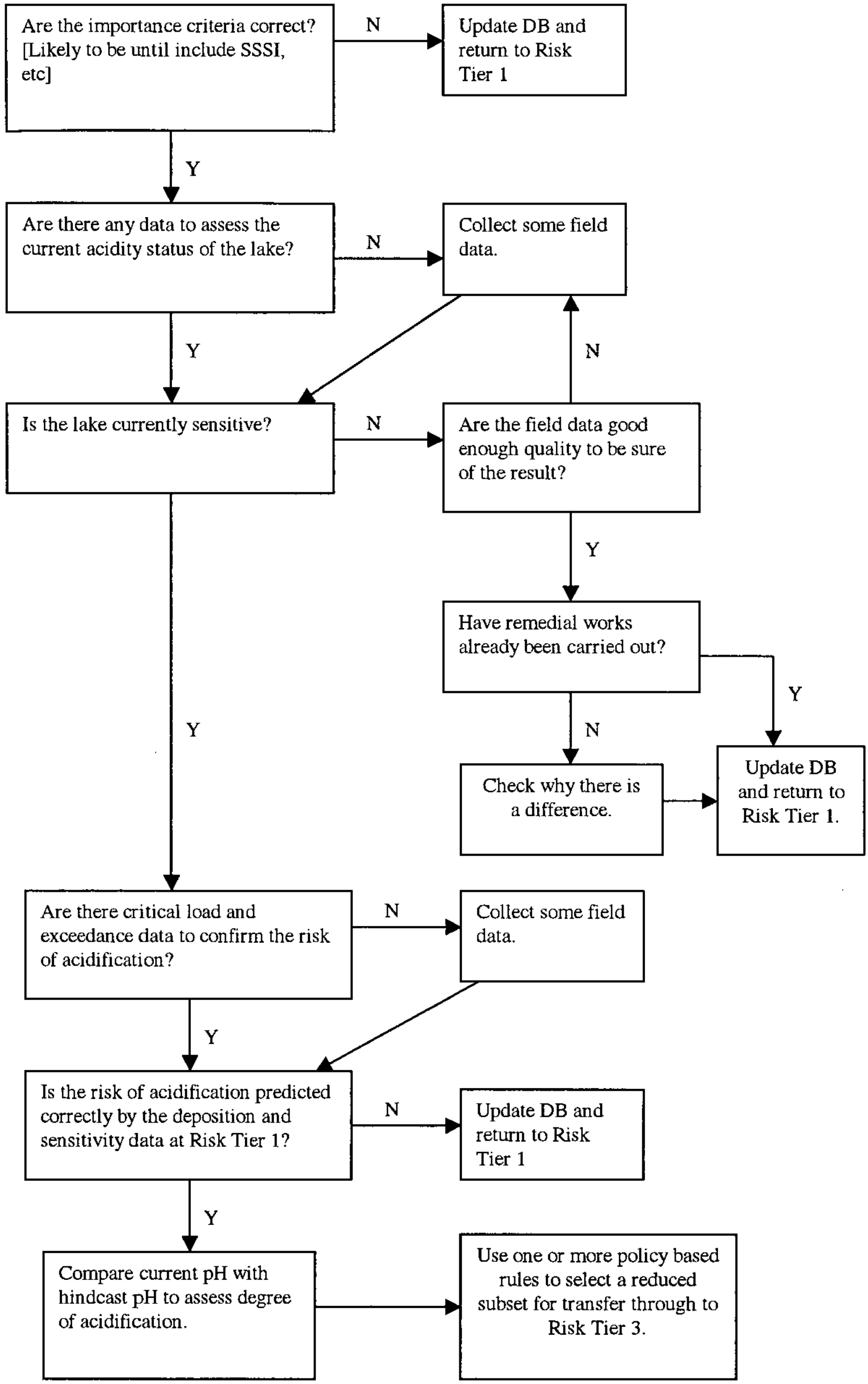

Figure 5 Outline of protocol for checking that a lake has correctly passed from Risk Tier 1 to Risk Tier 2 and for moving lakes from Risk Tier 2 to Risk Tier 3 in the acidification scheme

5.3 Risk Tier 3: Detailed quantitative risk assessment at site specific level

Lakes that passed the Risk Tier 2 filter into Risk Tier 3 would then need to be subjected to a very detailed local assessment to develop the case for investment and to fully assess the management options (methods) and targets for recovery or remediation.

5.3.1 Current status

Firstly, a site specific assessment of local importance and uses should be carried out and any local or regional political issues identified. Where current data are absent, a comprehensive chemical and biological survey is required. For chemistry, periodic analysis over at least one year should be carried out, with a minimum resolution of quarterly (seasonal) sampling, and ideally at least a monthly sampling regime. This would enable the seasonal characterisation of the site, which is important because of the potential seasonal variation in acid anion leaching and in acidity status, with possibly serious biological implications that might not be detected through less frequent sampling. A full biological survey should also be carried out to identify the presence (or absence) of acid sensitive taxa, e.g. for diatoms, macrophytes, invertebrates, fish.

5.3.2 Extent of damage and targets for recovery

A detailed palaeoecological assessment, building on that carried out at Risk Tier 2, would provide information on the baseline biology of the site and an independent measure of the baseline acidity status (see critical loads models in Risk Tier 2) via multi-proxy methods and transfer functions (e.g. Jones *et al*, 1993). Modern analogue techniques could be used to identify targets for recovery or remediation (Flower *et al*, 1997). The Model of Acidification of Groundwater in Catchments (MAGIC) is a dynamic, process-oriented mathematical model and can be used to hindcast and forecast pH under a range of future scenarios (Jenkins *et al*, 1990, 1997). MAGIC uses data on soil chemistry, deposition history, land use history and knowledge of physical and chemical processes such as weathering rates in order to predict chemical status of a water body at any given time. The model requires many data and is unsuitable for application at the national scale but nevertheless could be applied at Risk Tier 3. The MAGIC model hindcast pH values and trends can be compared with those produced by the diatom pH transfer function (e.g. Jenkins *et al*, 1990). Alternatively, the more sophisticated but less data hungry models, WHAM and SCAMP (Tipping, 1998), can be used.

Where these data were not available, further monitoring and data analysis would need to be undertaken to produce sufficient data to enable management decisions to be made.

6. APPLICATION OF THE PRIORITISATION PROTOCOL TO 30 TEST LAKES

6.1 The testing procedure

A total of 30 lakes were selected to test the performance of the prioritisation protocol. The objective was to test how well importance, hazard and sensitivity (and thereby risk) estimates at Risk Tier 1 were supported by measured data or more sophisticated modelled data, and thereby how the risk assessments can be improved at Risk Tier 2. If at any stage there are discrepancies between modelled and measured data, the database should be amended and the protocol re-run.

Thus on a lake-by-lake basis, following the procedures outlined in Figures 3 and 5, the aim was to:

i) Confirm that the importance criteria for each priority lake, as identified in Risk Tier 1, are correct by checking against more detailed data on conservation and ecological value.

ii) Confirm that the current trophic status of the lake has been correctly predicted at Risk Tier 1 in the eutrophication scheme, and assess the current acidity status of the lake in the acidification scheme by collating chemical and biological data.

iii) Confirm that no previous remediation schemes have been carried out, e.g. P removal at point sources in the catchment of the lake or liming of acid lakes.

iv) Confirm whether the depth, stratification and recovery status of the lake has been correctly estimated at Risk Tier 1 in the eutrophication scheme.

v) Calculate critical loads and exceedances to assess accuracy of risk assessments made at Risk Tier 1 in the acidification scheme.

vi) Assess degree of enrichment by comparing current P loads or concentrations (preferably measured but otherwise modelled at Risk Tier 1) with those hindcast by export-coefficient models and/or diatom transfer functions in the eutrophication scheme. Likewise, assess degree of acidification by comparing current pH or ANC with values hindcast by diatom transfer functions in the acidification scheme.

The test exercise, therefore, involved the collation of existing data, where available, for the selected lakes, as follows:

i) Data related to conservation interest such as reason for SAC or SSSI designation, and presence of rare plant/animal species or important communities, to confirm aquatic importance.

ii) For the eutrophication scheme, current mean TP concentration, mean chlorophyll a and OECD trophic status class to confirm trophic status of the lake, plus additional data to confirm trophic status such as occurrence of hypolimnetic deoxygenation, frequency of algal blooms, changes in diatom assemblages and the Trophic Ranking

Score and Lake Type based on macrophyte community data (Palmer *et al*, 1992). For the acidification scheme, current measured mean pH and mean alkalinity to assess status of the lake, plus additional data to confirm status such as changes in diatom assemblages, the Trophic Ranking Score and Lake Type based on macrophyte community data (Palmer *et al*, 1992) and fish data.

iii) Data on management actions and remediation schemes to confirm whether any restoration has been carried out to date.

iv) Measured mean and maximum lake depth, retention time and stratification data, to confirm stratification and recovery status for the eutrophication scheme.

v) Critical load and exceedance data to improve upon risk assessments made using acid deposition loads and dominant freshwater sensitivity classes at Risk Tier 1 in the acidification scheme. Two sets of critical loads and exceedance data were collated: the Henriksen critical load and exceedance values (Henriksen *et al*, 1992) which are based on the critical loads for brown trout, and the diatom model critical load and exceedance values (Battarbee *et al*, 1996). Since the diatom community is regarded as the most sensitive aspect of the biota, it can be argued that the diatom model critical load can be used to identify the point of first change within the lake ecosystem. Negative critical load exceedance values indicate that the load is not exceeded whilst positive values indicate that the load is exceeded.

vi) For the eutrophication scheme, hindcast P concentration from the Reading model for England and Wales (Johnes *et al*, 1996) and the PLUS model for Scotland (Ferrier *et al*, 1997) and/or P concentration from diatom P transfer functions (e.g. Bennion *et al*, 1996a). The hindcast TP concentrations produced by the export-coefficient models were compared with those derived from the diatom models. For the acidification scheme, hindcast ANC and/or hindcast pH from diatom transfer functions (e.g. Stevenson *et al*, 1991).

6.2 Application of the protocol to 30 test lakes

The results for each of the test lakes are given in Tables 4 and 5 and are summarised below. In each case the box number into which the lake falls in either the eutrophication (Figure 2) or acidification (Figure 4) prioritisation scheme, as appropriate, is given.

1. Llyn Tegid (Bala) / 34987

Aquatic importance is confirmed (Ramsar, SSSI, BAP species). The lake contains nationally scarce plant species and the internationally rare *Luronium natans*, as well as a unique fish community. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 2 slightly underestimates the measured class of 3, although if animals are included then trophic status is correctly predicted. The high retention time suggests that the lake is sensitive to enrichment and available data suggest that the lake has become enriched and is currently productive; e.g. there is a shift to more nutrient-rich diatom taxa from 1980, summer hypolimnetic deoxygenation occurs, blue-green algal blooms have been observed since 1995 and the macrophyte classification puts the lake in the eutrophic category. Stratification class 5 indicates that the lake would respond to restoration. The lake is classified into Box 5 in the eutrophication scheme.

2. Llangorse Lake / 40067

Aquatic importance is confirmed (cSAC, SSSI, BAP species). The lake is a cSAC for its Magnopotamion-Hydrocharition plant communities. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 3 (or 4 with animals included) underestimates the measured class of 5. The high retention time suggests that the lake is sensitive to enrichment and available palaeolimnological and monitoring data indicate enrichment from c.1950; e.g. a shift to planktonic, nutrient-rich diatom taxa in 1950s, summer hypolimnetic deoxygenation, an increase in frequency of algal blooms in 1960s and 1970s, and a eutrophic macrophyte classification. However, sewage diversions were introduced in 1981 and 1992 and a subsequent return to more mesotrophic diatom taxa has been observed since 1985. The stratification class of 4 indicates that the lake would respond to restoration and, therefore, the data support the risk assessment results. The lake is classified into Box 7 in the eutrophication scheme.

3. Butterstone Loch / 23531

Aquatic importance is confirmed (cSAC, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae* / Isoeto-Nanojuncetea) and also contains *Najas flexilis*. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 3 agrees with the current measured trophic status. The high retention time suggests that the lake is sensitive and both the palaeolimnological data and PLUS model indicate enrichment, e.g. an increase in nutrient-rich planktonic diatom taxa since 1960. Fish cages were installed on the loch in 1980. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 7 in the eutrophication scheme.

4. Loch Davan / 21123

Aquatic importance is confirmed (Ramsar, cSAC, SPA, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae*/Isoeto-Nanojuncetea) and contains *Elatine hexandra* and *Nuphar pumila.* Both retention class and stratification class are correctly modelled. The modelled trophic status class of 3 agrees with the current measured trophic status. The intermediate retention time suggests that the lake is only slightly sensitive to enrichment and whilst there has been an increase in nutrient-rich diatom taxa since c.1960, the lake is still in relatively good condition with relatively few plankton and a mesotrophic macrophyte flora. The stratification class of 1 indicates that the lake would have limited response to restoration. The loch is classified into Box 6 in the eutrophication scheme.

5. Loch Eck / 24996

This loch was classed as important at Risk Tier 1 based on size only but a more thorough assessment of conservation status at Risk Tier 2 highlights its aquatic importance (SSSI, BAP species) as the lake contains *Coregonus lavaretus*. Stratification class is correctly modelled. The modelled trophic status class of 1 slightly underestimates current measured TP values but nevertheless the loch is correctly modelled as being nutrient poor. Whilst the lake is sensitive to enrichment (retention time class 1), the nutrient hazard is low and therefore the lake is at low risk of enrichment. This is confirmed by palaeolimnological and PLUS data which both indicate stable nutrient concentrations and the loch currently has an oligotrophic macrophyte community. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 5 in the eutrophication scheme.

6. Loch of Harray / 1753

This loch was classed as important at Risk Tier 1 based on size only but a more thorough assessment of conservation status at Risk Tier 2 highlights its aquatic importance (SSSI, BAP species). The lake contains a number of protected species including *Potamogeton friesii, Potamogeton filiformis, Ruppia cirrhosa, Chara baltica, Chara curta, Chara aspera* v. *curta, Chara aspera*, and *Tolypella nidifica* v. *glomerata*. Measured retention time and stratification data are not available to compare with the modelled values. The modelled trophic status class of 3 agrees with the current measured trophic status. The high retention time suggests that the lake is sensitive to enrichment and indeed palaeolimnological data, the PLUS model and monitoring data indicate enrichment, e.g. an increase in nutrient-rich diatom taxa and algal blooms observed since the mid 1990s. The stratification class of 2 indicates that the lake would have limited response to restoration. The loch is classified into Box 6 in the eutrophication scheme.

7. Kilbirnie Loch / 26566

The lake has no aquatic importance other than its large size. Stratification class is correctly modelled. The modelled trophic status class of 4 agrees with the current measured trophic status. The high retention time (class 1) suggests that the lake is sensitive to enrichment and this is supported by palaeolimnological data and PLUS model data which both indicate eutrophication, e.g. an increase in nutrient-rich, planktonic diatom taxa from c.1915 and large ratio between hindcast and current TP concentrations. Furthermore, algal blooms have been frequently observed. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 7 in the eutrophication scheme.

8. Loch Leven / 24843

Aquatic importance is confirmed (Ramsar, NNR, SPA, SSSI, BAP species). The lake contains a number of protected species including *Potamogeton filiformis, Ranunculus reptans, Ranunculus hederaceus, Limosella aquatica, Chara aspera* v. *aspera*, and *Tolypella nidifica* v. *glomerata*. The modelled trophic status class of 4 agrees with the current measured trophic status. The retention class is correctly modelled. The high retention time (class 1) suggests that the lake is sensitive to enrichment and the available data provide clear evidence of eutrophication, e.g. regular cyanobacteria blooms since 1960s, and an increase in nutrient-rich, planktonic diatom taxa from c.1850 and particularly from 1940. The modelled stratification class of 5 is based on the measured maximum depth of the loch which is c. 25 m and indicates that the lake would respond to restoration. There is indeed evidence of recovery since c.1985 following the cessation of P effluent entry to the loch from a woollen mill in 1988 and the introduction of STW tertiary treatment and sewage diversion in the mid-1990s, e.g. decline in phytoplankton abundance from mid-1970s and decrease in nutrient-rich diatom taxa. However the recovery has been relatively slow because most of the loch is shallow and well-mixed with a mean water depth of 4.5m and thus the measured stratification class is closer to 3. The loch is classified into Box 7 in the eutrophication scheme.

9. Loch Lomond / 24447

Aquatic importance is confirmed (National Park, Bathing Water, BAP species). The lake contains a number of protected species such as *Pilularia globulifera, Elatine hydropiper, Rumex aquaticus*, and *Coregonus lavaretus*. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 1 slightly underestimates current measured TP values but nevertheless the loch is correctly modelled as being nutrient poor. The high retention time suggests that the lake is sensitive to enrichment. Whilst the PLUS model and monitoring data indicate stable conditions, the palaeolimnological data provide an indication of slight enrichment, e.g. the North basin core is dominated by nutrient-poor diatom taxa throughout but there are slight changes since 1950 with the appearance of more nutrient-rich planktonic taxa. The loch currently has an oligotrophic macrophyte community. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 5 in the eutrophication scheme.

10. Loch of the Lowes / 23559

Aquatic importance is confirmed (cSAC, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae* / Isoeto-Nanojuncetea) and also contains a number of protected plant species including *Potamogeton filiformis, Najas flexilis*, and *Elatine hexandra*. Both retention class and stratification class are correctly modelled. However, the modelled trophic status class of 2 underestimates the current trophic status class of 3. The loch has a mesotrophic macrophyte community. The high retention time (class 1) suggests that the lake is sensitive to enrichment and indeed both the palaeolimnological and PLUS model data indicate enrichment, e.g. an increase in nutrient-rich diatom taxa especially since c.1940. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 5 in the eutrophication scheme.

11. Loch Lubnaig / 24459

Aquatic importance is confirmed (cSAC, BAP species). The lake contains *Pilularia globulifera, Ranunculus hederaceus*, and *Nuphar pumila*. The stratification class is correctly modelled. The modelled trophic status class of 1 slightly underestimates current measured TP values but nevertheless the loch is correctly modelled as being nutrient poor. The lake has moderate sensitivity to enrichment (retention time class 2) and the nutrient hazard is low and, therefore, the lake is at low risk of enrichment. This is confirmed by palaeolimnological and PLUS data which both indicate stable nutrient concentrations, and the loch currently has an oligotrophic macrophyte community. The stratification class of 5 indicates that the lake would respond to restoration. The loch is classified into Box 5 in the eutrophication scheme.

12. Lake of Menteith / 24919

This lake was classed as important at Risk Tier 1 based on size only but a more thorough assessment of conservation status at Risk Tier 2 highlights its aquatic importance (SSSI, BAP species). The lake contains a number of protected species such as *Najas flexilis, Nuphar pumila, Elatine hexandra*, and *Elatine hydropiper*. The modelled trophic status class of 2 slightly underestimates the current trophic status class of 3. The loch has a mesotrophic macrophyte community. The retention class is correctly modelled. A high retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, e.g. an increase in nutrient-rich planktonic diatom taxa since 1920, and still further since 1980, the first reports of algal blooms in the 1980s, and a relatively high ratio between hindcast and current TP concentrations. There has been a fishery on the loch since the 1980s. The modelled stratification class of 5 indicates that the lake would respond to restoration. However, this is based on the maximum water depth of 23.5m and in fact most of the lake is shallow and well-mixed (mean water depth 6m) and thus the measured stratification class is likely to be closer to 3. The lake is classified into Box 5 in the eutrophication scheme.

13. Grasmere / 29184

The lake has no aquatic importance other than its large size, although there is a 1977 record of *Elatine hexandra.* Both retention class and stratification class are correctly modelled. However, the modelled trophic status class of 2 underestimates the current trophic status class of 3. The export model takes no account of the large numbers of tourists which increase the load to the sewage treatment works which discharges to the lake. Currently treated sewage is discharged into the hypoliminion in an attempt to reduce the P available for algal uptake in the hypoliminion in the summer, thus making the data difficult to interpret. The lake has an oligotrophic macrophyte community. The lake has moderate sensitivity to enrichment (retention time class 2) and the export coefficient model suggests that there has been an increase in TP concentrations. The stratification class of 5 indicates that the lake would respond to restoration. The lake is classified into Box 5 in the eutrophication scheme.

14. Windermere / 29233

Aquatic importance is confirmed (Bathing Waters, BAP species). The lake contains the protected species *Austropotamobius pallipes* and there are a number of old records of rare plant species. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 3 agrees with the current measured trophic status. The high retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, most notably in the more productive south basin, e.g. an increase in nutrient-rich planktonic diatom taxa from c. 1930, most markedly since 1970, an increase in *Oscillatoria* blooms in the late 1960s and an increase in blue-green algal blooms since the late 1980s. A major STW was installed in 1964. The stratification class of 5 indicates that the lake would respond to restoration. The recent introduction of P stripping to the STW at Windermere has induced a significant improvement in trophic status, confirming the model predictions. The lake is classified into Box 7 in the eutrophication scheme.

15. Esthwaite Water / 29328

Aquatic importance is confirmed (Ramsar, SSSI, BAP species) and the lake contained the rare plant species *Najas flexilis* prior to 1982. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 3 agrees with the current measured trophic status although the model underestimates actual concentrations. The lake has a mesotrophic macrophyte community. The high retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, e.g. an increase in nutrient-rich planktonic diatom taxa from c.1950, algal blooms recorded since 1970s, a relatively high ratio between hindcast and current TP concentrations, and an increase in measured SRP concentrations. The enrichment appears to be attributed largely to the start of STW discharge in 1973. The stratification class of 5 indicates that the lake would respond to restoration. In spite of external P load reduction since 1986 from the STW, the lake has been slow to recover. Data suggest that this is because P inputs from fish farm cages on the lake, which were introduced after the P removal was introduced at the sewage treatment works, almost exactly match the amount of P removed from the STW. The lake is classified into Box 7 in the eutrophication scheme.

16. Bassenthwaite Lake / 28847

Aquatic importance is confirmed (cSAC, NNR, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae*/Isoeto-Nanojuncetea). The lake also contains a number of protected species including *Luronium natans* and *Coregonus albula.* The retention class of 2 is correctly modelled but the stratification status is modelled as 5 when in fact measured data places the lake in stratification class 3. The modelled trophic status class of 2 underestimates the current trophic status class of 3 and according to the Palmer classification the lake has a predominantly eutrophic macrophyte community. The lake has moderate sensitivity to enrichment (retention time class 2) and available data provide evidence of enrichment, e.g. the export coefficient model suggests that there has been an increase in TP concentrations, and an increase in nutrient-rich planktonic diatom taxa was observed, most markedly from c. 1960. The measured stratification class of 3 indicates that the lake would have a moderate response to restoration. P stripping was introduced at the STW in 1995 and further P reduction at Keswick STW is in progress. The lake is classified into Box 5 in the eutrophication scheme.

17. Chew Valley Lake / 43096

Aquatic importance is confirmed (SPA, SSSI, BAP species), The lake contains a number of protected species including *Limosella aquatica*, and there is an old record of *Austropotamobius pallipes.* The lake is also a drinking water supply. Retention class is correctly modelled but the stratification status is modelled as 5 whereas measured data places the lake in stratification class 3. This is because the depth model has considerably overestimated maximum lake depth. The modelled trophic status class of 5 agrees with the current measured trophic status which is hypertrophic. The macrophyte community is classified as eutrophic. The high retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, e.g. a high ratio between hindcast and current TP concentrations using the export-coefficient model. Deoxygenation is common in the hypolimnion, during periods of stratification, and a bubbler destratifyer has been installed which although inefficient moves the stratification class towards the boundary of classes 2 and 3. The lake, therefore, would have only a moderate response to restoration. The lake is classified into Box 7 in the eutrophication scheme.

18. Rutland Water / 36479

Aquatic importance is confirmed (Ramsar, SPA, SSSI, BAP species). The lake contains the protected species *Limosella aquatica* and is also a drinking water supply. The stratification status is modelled as 5 whereas measured data places the lake in stratification class 4. This is because the depth model has considerably overestimated maximum lake depth. The modelled trophic status class of 4 overestimates the measured trophic status class of 2. This probably resulted from the introduction of iron salts into river water pumped into the reservoir (a practice subsequently stopped) which precipitated large amounts of P. The high modelled retention time (class 1) suggests that the lake is sensitive to enrichment although there are insufficient data to confirm that eutrophication has occurred. However, deoxygenation is common in the hypolimnion and algal blooms are frequently observed. The measured stratification class of 4 indicates that the lake would have a relatively good response to restoration although underpowered destratification equipment has been installed in the lake. The lake is classified into Box 7 in the eutrophication scheme.

19. Darwell Reservoir / 44955

The lake has no conservation importance but it is a large water body and is used for drinking water supply. Retention class is correctly modelled but the stratification status is modelled as 1 whereas measured data places the lake in stratification class 5. This is because the depth model has considerably underestimated maximum lake depth. The lake has been artificially deepened using a dam. The modelled trophic status class of 3 underestimates the current trophic status class of 5, largely because the lake receives pumped water from a local river, a nutrient source that is not accounted for by the model. The high retention time (class 1) suggests that the lake is sensitive to enrichment although there are insufficient data to confirm that eutrophication has occurred. However, deoxygenation is common in the hypolimnion soon after stratification. The measured stratification class of 5 indicates that the lake would respond to restoration. The lake is classified into Box 6 in the eutrophication scheme.

20. Slapton Ley / 46472

This lake was classed as important at Risk Tier 1 based on size only but a more thorough assessment of conservation status at Risk Tier 2 highlights its aquatic importance (NNR, SSSI, BAP species). The lake contains the protected species *Chara connivens*, and there are old records of other rare plant species. Retention class has been modelled as 1 whereas the measured class is 2 and likewise stratification class has been modelled as 4 whereas the measured data places the lake in class 1. These errors arise because both mean and maximum lake depth have been overestimated by the depth model. The modelled trophic status class of 4 slightly underestimates the current trophic status class of 5. The macrophyte community is classified as eutrophic. The lake has moderate sensitivity to enrichment (measured retention class 2) and available data provide evidence of enrichment, e.g. the export coefficient model suggests that there has been an increase in TP concentrations, an increase in nutrient-rich planktonic diatom taxa was observed, most markedly from c. 1960, hypolimnetic deoxygenation has been observed most notably since 1970 and frequency of blooms has increased since the 1970s. The measured stratification class of 1 indicates that the lake would have limited response to restoration. The lake is classified into Box 7 in the eutrophication scheme.

21. Crose Mere / 35211

Aquatic importance is confirmed (Ramsar, SSSI). Both retention class and stratification class are correctly modelled. The modelled trophic status class of 4 slightly underestimates the current trophic status class of 5 and this may be due to the naturally high P concentrations in the Shropshire meres region owing to geological sources of P. The macrophyte community is classified as eutrophic. The high retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, e.g. an increase in nutrient-rich planktonic diatom taxa from c. 1900 and frequent algal blooms have been observed for many decades. The measured stratification class of 5 indicates that the lake would respond to restoration. The lake is classified into Box 7 in the eutrophication scheme.

22. Barton Broad / 35655

Aquatic importance is confirmed (Ramsar, NNR, SPA, cSAC, SSSI, BAP species). The lake is a cSAC for natural eutrophic lakes with Magnopotamion or Hydrocharition-type vegetation. The retention class is correctly modelled but stratification class is modelled as 4 whereas measured data gives a class of 1. This is because maximum lake depth is overestimated by the depth model. The modelled trophic status class of 5 slightly overestimates the current trophic status class of 4. This is most likely because the lake has recently undergone a P removal programme. A lake restoration programme has been in place since the late 1970s which has involved reduction in P load from STWs and sediment removal in the 1990s. The lake has moderate sensitivity to enrichment (retention class 2) and available data provide evidence of enrichment, e.g. export coefficient modelled increase in TP concentrations, an increase in nutrient-rich planktonic diatom taxa from c. 1970, loss of submerged macrophyte community, hypolimnetic deoxygenation and algal blooms. The measured stratification class of 1 indicates that the lake would have limited response to restoration. The lake is classified into Box 7 in the eutrophication scheme.

23. Rollesby Broad / 35981

Aquatic importance is confirmed (cSAC, SSSI, BAP species). The lake is a cSAC for natural eutrophic lakes with Magnopotamion or Hydrocharition-type vegetation, and is also used as a drinking water supply. The stratification class is modelled as 5 whereas measured data gives a class of 1. This is because maximum lake depth is considerably overestimated by the depth model. The modelled trophic status class of 5 agrees with the current measured trophic status although the model overestimates actual concentrations. The high modelled retention time (class 1) suggests that the lake is sensitive to enrichment and available data provide evidence of eutrophication, e.g. an increase in nutrient-rich planktonic diatom taxa from c. 1940, a high ratio between export-coefficient hindcast and current TP concentrations, loss of submerged macrophyte community, and hypolimnetic deoxygenation. The measured stratification class of 1 indicates that the lake would have limited response to restoration. The lake is classified into Box 7 in the eutrophication scheme.

24. Malham Tarn / 29844

Aquatic importance is confirmed (Ramsar, cSAC, NNR, SSSI, BAP species). The lake is a cSAC for hard oligo-mesotrophic waters with benthic vegetation of *Chara* sp. Retention class is correctly modelled and although profile data were not available the modelled stratification class of 4 seems intuitively to be correct. The modelled trophic status class of 3 agrees with the current measured trophic status. The macrophyte community is classified as eutrophic (*Chara* sub-group). The high retention time (class 1) suggests that the lake is sensitive to enrichment but owing to the relatively low hazard, the lake is at reasonably low risk of enrichment. Indeed palaeolimnological data indicate little change in nutrient conditions with a relatively stable diatom assemblage dominated by non-planktonic species. The modelled stratification class of 4 indicates that the lake would have a relatively good response to restoration. The lake is classified into Box 7 in the eutrophication scheme.

25. Coniston Water / 29321

The lake has no conservation importance but it is a large water body. Both retention class and stratification class are correctly modelled. The modelled trophic status class of 2 agrees with the current measured trophic status and the macrophyte community is also classified as oligotrophic. The high retention time (class 1) suggests that the lake is sensitive to enrichment but owing to the relatively low hazard, the lake is at reasonably low risk of enrichment. Palaeolimnological diatom data provide evidence of slight nutrient enrichment but there is still minimal oxygen reduction in the hypolimnion. The stratification class of 5 indicates that the lake would respond well to restoration. The lake is classified into Box 5 in the eutrophication scheme.

26. Priest Pot / 29323

This lake was classed as important at Risk Tier 1 based on size only but a more thorough assessment of conservation status at Risk Tier 2 highlights its aquatic importance (Ramsar, SSSI). The stratification class is correctly model even though maximum depth is considerably overestimated by the depth model. The modelled trophic status class of 3 slightly underestimates the current trophic status class of 4. The lake has moderate sensitivity to enrichment (retention class 2) and whilst there are insufficient data to provide evidence of enrichment, the lake is currently productive with complete anoxia for four months each year and regular dense algal blooms. The stratification class of 5 indicates that the lake would respond well to restoration. The lake is classified into Box 7 in the eutrophication scheme.

27. Llyn Idwal / 33836

Aquatic importance is confirmed (Ramsar, cSAC, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae* / Isoeto-Nanojuncetea). The lake contains a number of protected species including *Isoetes echinospora, Pilularia globulifera* and *Elatine hexandra*. This lake has high acid deposition (class 4) and high sensitivity (class 1) but it is not identified as at high risk of acidification in the scheme because, according to the land cover data, there is >5% agriculturally improved land in the catchment and thus it is assumed that the land will be subject to liming. However, catchment studies indicate that that there is no improved grassland in the catchment of Llyn Idwal and liming does not take place and therefore the land cover data appear to be incorrect for this site. Palaeolimnological studies indicate that the lake has not acidified as the diatom record is dominated by taxa indicative of circumneutral, nutrient-poor conditions. The lack of sensitivity to acidification can be attributed to a high buffering capacity (Ca = 89 μeq/l). The macrophyte community is classified as oligotrophic. The lake is classified into Box 3 in the acidification scheme.

28. Llyn Cwellyn / 34002

Aquatic importance is confirmed (cSAC, SSSI, BAP species). The lake is a cSAC for its oligotrophic to mesotrophic character (*Littorelletae uniflorae*/Isoeto-Nanojuncetea). The lake contains a number of protected species including Arctic charr and *Luronium natans*. This lake has high acid deposition (class 4) and high sensitivity (class 1) but it is not identified as at high risk of acidification because there is >5% agriculturally improved land in the catchment and thus it is assumed that the land will be subject to liming. Palaeolimnological studies demonstrate that the lake has acidified with a marked decline in planktonic diatom taxa and an increase in acid tolerant taxa since the 1860s. However, there are signs of recovery since the mid 1980s with a decline in acid taxa. This appears to be a response to a combination of a decline in S deposition and agricultural liming. The diatom critical load is only slightly exceeded. The macrophyte community is classified as oligotrophic. The lake is classified into Box 3 in the acidification scheme.

29. Loch Chon / 24754

The lake has no conservation importance but it is a large water body. This lake has high acid deposition (class 4) and high sensitivity (class 1) and is thus at high risk of acidification. Palaeolimnological studies confirm that the lake has acidified with an increase in acid tolerant diatom taxa since 1850. The diatom critical load suggest reasonable high exceedance. Chemical and biological monitoring data indicate that lake pH has increased since the late 1980s but the exact causes of recovery are yet to be fully established. The macrophyte community is classified as oligotrophic. The loch is classified into Box 4 in the acidification scheme.

30. Loch Dee / 27948

The lake has no conservation importance but it is a large water body. This lake has high acid deposition (class 4) and high sensitivity (class 1) and is thus at high risk of acidification. Palaeolimnological studies confirm that the lake has strongly acidified with an increase in acid tolerant diatom taxa since 1850. The loch is classified into Box 4 in the acidification scheme.

In addition to the individual site results, a comparison was made between the measured current TP concentrations of all of the test lakes and those modelled by the eutrophication prioritisation protocol. Figure 6a shows the scatterplot of measured current mean TP concentrations against those modelled for lakes in England, Wales and Scotland using nutrient inputs from people and land cover only (i.e. without animals). The most striking observation is that, with a small number of exceptions, the modelled values generally underestimate the measured concentrations. It appears that the model performs reasonably well at concentrations less than 50 $\mu g\ l^{-1}$ but that larger errors occur at concentrations above these and thus the R^2 value is low. To examine the effect of including the animal component in the modelled TP concentrations, a comparison was made between the measured current TP concentrations and the modelled data both without (Figure 6b) and with (Figure 6c) animals for those lakes in England and Wales where animal density data were available. Whilst notable outliers remain, especially in the most productive waters, the overall relationship between measured and modelled data is improved with the inclusion of the animal component. There are site-specific reasons for the strongest outliers, for example at Crose Mere the TP is underestimated by the model owing to geological inputs of P and at Barton Broad, P has been removed from Stalham and North Walsham STWs and therefore the model overestimates measured values. Anomalies such as these would be identified at Risk Tier 2 when local information is collated for each site.

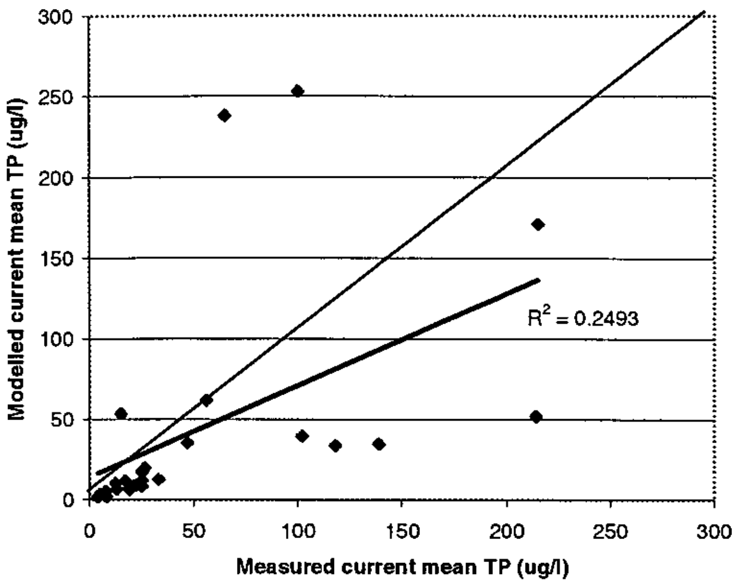

Figure 6a Scatterplot of measured current mean TP concentrations versus those modelled by the eutrophication protocol using people and land cover only for selected test lakes in England, Wales and Scotland.
The linear regression line, the R^2 value and the 1:1 line are shown.

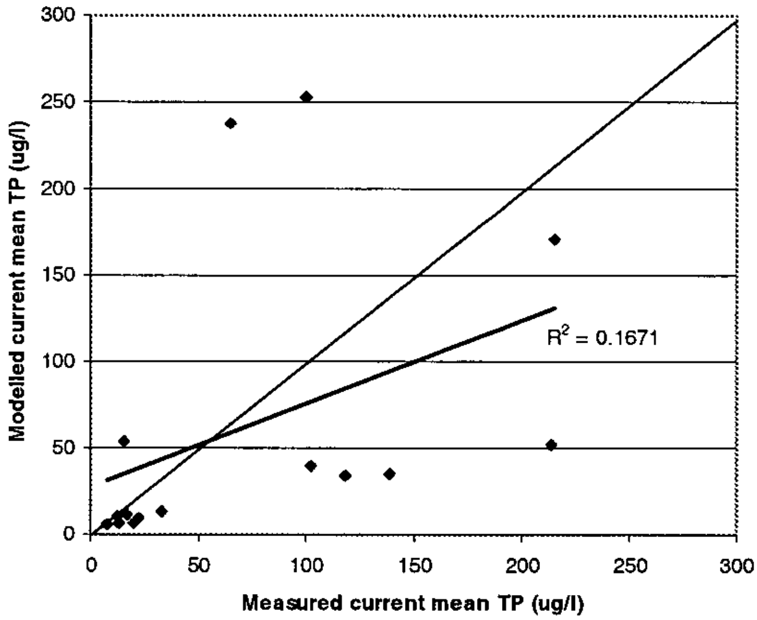

Figure 6b Scatterplot of measured current mean TP concentrations versus those modelled by the eutrophication protocol using people and land cover only for selected test lakes in England and Wales.
The linear regression line, the R^2 value and the 1:1 line are shown.

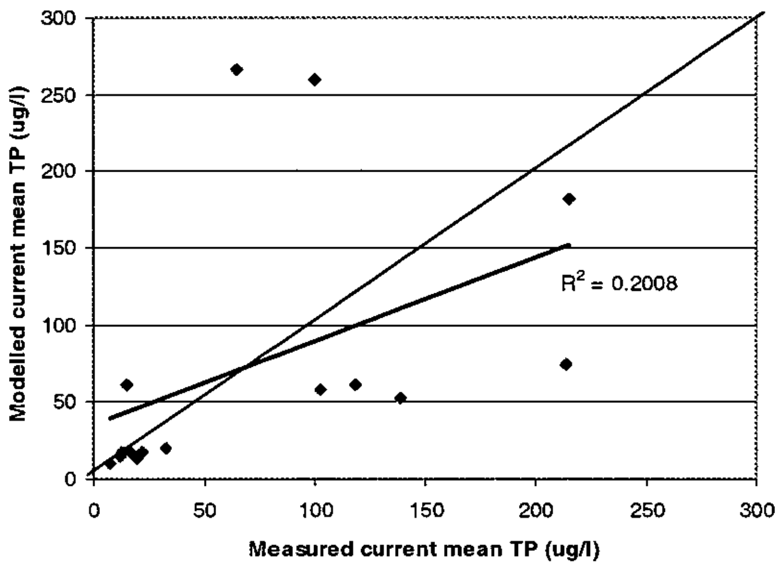

Figure 6c Scatterplot of measured current mean TP concentrations versus those modelled by the eutrophication protocol using people, land cover and animals for selected test lakes in England and Wales.
The linear regression line, the R^2 value and the 1:1 line are shown.

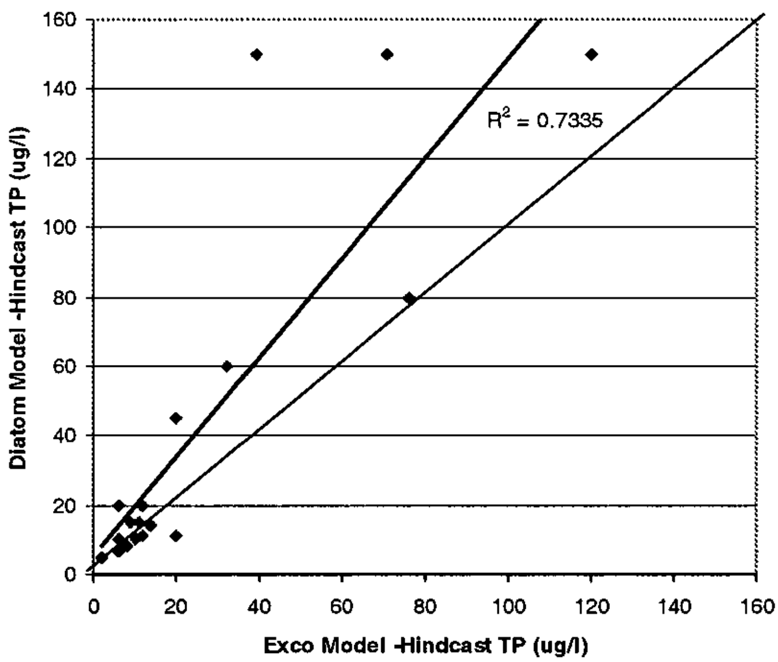

Figure 7 Scatterplot of Hindcast TP concentrations produced by the export coefficient models versus the diatom models for selected test lakes in England, Wales and Scotland.
The linear regression line, the R^2 value and the 1:1 line are shown.

A comparison was also made between the hindcast TP concentrations produced by the export-coefficient approach and those derived from the diatom models to evaluate the reliability of using these techniques for assessing changes in nutrient levels (Figure 7). In the absence of historical measured values to provide a three-way validation, it is not possible to state whether the values produced by the methods are correct or which of the models gives the closest estimate of actual past concentrations in situations when discrepancies between the two sets of data occur. However, Figure 7 illustrates that there is good agreement between the export-coefficient and diatom hindcast concentrations with a R^2 value of 0.73.

6.3 Conclusions based on the test exercise

A number of general conclusions can be drawn from the test exercise:

i) The eutrophication protocol reliably models high risk of enrichment in most cases. For example palaeolimnological and export coefficient data provide evidence of enrichment at a number of lakes predicted to be at high risk including Llyn Tegid, Llangorse Lake, Butterstone Loch, Loch of Harray, Kilbirnie Loch, Loch Leven, Loch of the Lowes, Lake of Menteith, Windermere, Esthwaite Water, Bassenthwaite Lake, Slapton Ley, Crose Mere, Barton Broad and Rollesby Broad.

ii) The eutrophication protocol reliably models low risk of enrichment in most cases. For example palaeolimnological and export coefficient data provide little evidence of enrichment at a number of lakes predicted to be at relatively low risk including Loch Eck, Loch Lomond, Loch Lubnaig, Malham Tarn and Coniston Water.

iii) The eutrophication protocol appears to reliably model likelihood of response to restoration based on the limited number of examples available. For example there is evidence of recovery following nutrient reduction at Windermere and Llangorse Lake, which have stratification classes of 5 and 4, respectively. In contrast, Barton Broad with a stratification class of 1 has been slow to respond to remediation. In a few cases, however, the stratification class is over-estimated by the model because the model is based on maximum rather than mean water depth. The greatest errors occur in largely shallow, well-mixed waters where the deep water zones represent a relatively small area of the water body as a whole (e.g. kettle holes in Loch Leven and Lake of Menteith).

iv) The modelled current P concentration in the eutrophication protocol frequently underestimates measured current P concentration. Data in Table 5 and illustrated in Figure 6 suggest that the main reason for this is that the modelled values are based on nutrient inputs from people and land cover only and do not include the animal component. For England and Wales, where data are available for P load estimates with and without animals, six give the same predicted trophic status class for both load estimates, both of which agreed with the measured class. In four other cases the inclusion of animals increased the predicted trophic status class by one to give the same class as field observations. In the other cases there were special, site-specific situations which explained the differences. If a catchment has been poorly defined this will introduce additional error into the modelled current P loads and thus concentrations.

v) There is a poor match between modelled and measured current P concentrations for a small number of the test lakes which cannot be explained simply by the absence of animal data. In these cases there is a site-specific reason for the discrepancy. For example, at Rutland Water trophic status is overestimated because large amounts of P are precipitated by Fe; at Barton Broad trophic status is overestimated most likely because the lake has recently undergone a P removal programme; at Darwell Reservoir trophic status is underestimated because the lake receives pumped water from a local river, a nutrient source that is not accounted for by the model; and at Crose Mere trophic status is underestimated probably because of the naturally high P concentrations in the region arising from the P-rich geology. Clearly any source of P other than people and land cover or any major sink/removal of P will result in a poor match between modelled and measured P concentrations.

vi) In the eutrophication scheme, retention times and stratification classes are modelled incorrectly for a small number of lakes owing to errors in the lake depth model used to estimate lake mean and maximum depth. In most of these cases, the model overestimates the depths, resulting in a higher stratification class than that produced from measured profile data, thereby suggesting that the lake will respond better to restoration than it is likely to in reality. This problem arises especially for lowland lakes with large surface areas because the depth model utilises the positive relationship between lake area and depth. Of the test lakes, this problem was apparent at Chew Valley Lake, Rutland Water, Slapton Ley, Barton Broad and Rollesby Broad. As a result, lakes fall through to Risk Tier 2 when they should not. This is, in effect, a fail safe situation and the measurement of actual depths as part of Risk Tier 2 should allow the real situation to be reassessed. There was only one case, Darwell Reservoir, where the model underestimates actual depth data and this is because the lake has been artificially deepened. Stratification class is also incorrectly modelled in lakes such as Loch Leven and Lake of Menteith which are mostly shallow and well mixed but which have a deep basin (see point iii above).

vii) There was good agreement between the modelled hindcast TP concentrations produced by the export-coefficient approach and the diatom transfer function approach. Given that the former is based on nutrient export from catchment sources and the latter is based on the relationship between algal taxa and TP concentrations in the actual water column, the concordance between the two data sets was encouraging. The results for the test lakes suggest that for most sites, these techniques can be used with reasonable confidence to assess degree of enrichment.

viii) The acidification protocol appears to work well for assessing the risk of acidification, although only a small number of test cases were used here. At Lochs Chon and Dee, palaeolimnological evidence of acidification confirms that the lochs are correctly predicted as being at high risk. At Llyn Idwal and Llyn Cwellyn the scheme predicted lower risk of acidification owing to the presence of agriculturally improved land in the catchments. In the case of Llyn Idwal, however, the land cover data are incorrect as there is no improved grassland in the catchment. This is a data resolution issue. The test results also highlight the issue of data resolution with the dominant freshwater sensitivity classes. These are based on a 1 km grid and therefore cannot be expected to capture all local influences on lake water chemistry, e.g. Llyn Idwal has a high modelled sensitivity class of 1 but in fact has a high buffering capacity with Ca concentrations of 89 μeq/l and, therefore, has not experienced acidification. In contrast, Llyn Cwellyn did experience acidification from the mid 1800s but there appears to be evidence of recovery in recent decades which can be attributed partly to agricultural liming, as correctly modelled by the risk protocol.

ix) Overall, the text exercise illustrates that the risk protocol performs well. Inevitably, however, the need for nationally available datasets at Risk Tier 1 means that there will always be issues of data resolution and errors may occur. The test results highlight the importance of data validation and more thorough checks using lake specific information at Risk Tier 2.

Table 4 **Summary of data collated for a subset of lakes used to test the acidification protocol**

	Measured		Modelled		Modelled	Modelled Critical loads				Measured			
Site name/ WBID	Mean depth (m)	Max depth (m)	Acid deposition load (keq/ha/yr)	Acid deposition class	Domfws class	Henriksen critical load - total acidity (keq/ha/yr)	Henriksen critical load exceedance (keq/ha/yr)	Diatom critical load - total acidity (keq/ha/yr)	Diatom critical load exceedance (keq/ha/yr)	Current mean pH	Current mean alkalinity (ueq/l)	Hindcast Diatom pH	Palmer TRS/ Lake type
Llyn Idwal 33836	3.4	13	2.58	4	1	4.19	-2.21	1.07	0.9	6.72	70	6.48	5.48 / 3
Llyn Cwellyn 34002	22.6	36	1.97	4	1	2.8	-1.54	0.97	0.146	6.35	37	6.73	5.68 / 3
Loch Chon 24754	7.6	25	1.99	4	1	1.39	-0.08	0.63	0.69	5.68	12	6.3	/ 2
Loch Dee 27948	4.3	14	2.23	4	1	na	na	na	na	5.27	na	6.9	na

Table 5 Summary of data collated for a subset of lakes used to test the eutrophication protocol

	Modelled		Measured		Modelled			Measured			Current Modelled (note 1)			Current Measured			Hindcast data (note 2)		
Site name / WBID	Mean depth (m)	Max depth (m)	Mean depth (m)	Max depth (m)	Strat. class	Ret. time (yrs)	Ret. class	Strat. class	Ret. time (yrs)	Ret. class	Mean TP conc (ug/l)	Mean annual chl a (ug/l)	Trophic status class	Mean TP conc (ug/l)	Mean annual chl a (ug/l)	Trophic status class	TP conc - export coefficient models (ug/l)	TP conc - Diatom model (ug/l)	Palmer TRS/ Lake type
Llyn Tegid (Bala) 34987	na	na	24	43	5	0.45	1	5	0.24	1	6.8 (17.7)	3.1 (10.2)	2	13	7.2	3	6	10	6.87 / 8
Llangorse Lake 40067	na	na	2	7.5	4	0.24	1	4	0.19	1	33.8 (61.3)	17.3 (35.9)	3	118	14.5	5	39	150	8.43 / 10a
Butterstone Loch 23531	na	na	3.4	7.6	5	0.12	1	5	0.11	1	12.2 (-)	5.2 (-)	3	25	na	3	6	20	/ 5a
Loch Davan 21123	na	na	1.2	2.7	1	0.03	2	1	0.024	2	19.8 (-)	8.4 (-)	3	26.5	na	3	20	11	6.97 / 5a
Loch Eck 24996	na	na	15.3	42.4	5	0.29	1	5	na	na	1.9 (-)	0.6 (-)	1	4	na	2	2	5	5.87 / 3
Loch of Harray 1753	na	na	2.7	4.3	2	0.38	1	na	na	na	17.5 (-)	8.0 (-)	3	25	na	3	10	10	/ 7
Kilbirnie Loch 26566	na	na	3	9.1	5	0.13	1	5	na	na	61.8 (-)	37.3 (-)	4	56	na	4	11	15	na
Loch Leven 24843	na	na	4.5	25.3	5	0.62	1	3	0.43	1	35.5 (-)	20.2 (-)	4	47	28	4	20	45	na
Loch Lomond 24447	na	na	37	189.9	5	2.1	1	5	1.9	1	3.7 (-)	1.6 (-)	1	5 (N)	2.5 (N)	2	2 to 8 (N)	8 (N)	/ 3 (N)
Loch of the Lowes 23559	na	na	6.2	16.2	5	0.63	1	5	0.62	1	8.6 (-)	3.7 (-)	2	25	na	3	14	14	/ 4
Loch Lubnaig 24459	na	na	13	44.5	5	0.08	2	5	na	na	2.1 (-)	0.7 (-)	1	8	na	2	6	7	6.17 / 3
Lake of Menteith 24919	na	na	6	23.5	5	0.87	1	3	0.75	1	6.3 (-)	2.6 (-)	2	19	na	3	12	11	6.38 / 3
Grasmere 29184	na	na	7.7	21.5	5	0.07	2	5	0.068	2	6.9 (13.4)	2.8 (6.3)	2	19.5	10.6	3	6	na	6.61 / 3
Windermere 29233	na	na	21.3	64	5	0.7	1	5	0.49 (N)	1	10.3 (14.2)	5.2 (7.6)	3	12.4 (N) 20.5 (S)	5.4 (N) 24.6 (S)	3	6	10 (S)	7.00 / 3
Esthwaite Water 29328	na	na	6.4	15.5	5	0.24	1	5	0.27	1	12.8 (20.0)	5.9 (10.2)	3	33	24	3	9	15	6.24 / 5a
Bassenthwaite Lake 28847	na	na	5.3	19	5	0.04	2	3	0.082	2	9.0 (17.1)	3.7 (8.1)	2	21.8	13.4	3	12	20	7.51 / 9
Chew Valley Lake 43096	10.7	27.4	4.27	11.5	5	1.58	1	3	0.71	1	171 (182)	151 (164)	5	215	36	5	23	na	/ 10
Rutland Water 36479	26.1	66.7	10.7	34	5	19.9	1	4	na	na	53.5 (61.4)	43.0 (50.9)	4	15	11	2	28	na	na
Darwell Reservoir 44955	0.61	1.6	6.47	16	1	0.099	1	5	0.095	1	34.7 (52.8)	16.0 (26.6)	3	139	25	5	46	na	na

	Modelled		Measured		Modelled			Measured			Current Modelled (note 1)			Current Measured			Hindcast data (note 2)		
Site name / WBID	Mean depth (m)	Max depth (m)	Mean depth (m)	Max depth (m)	Strat. class	Ret. time (yrs)	Ret. class	Strat. class	Ret. time (yrs)	Ret. class	Mean TP conc (ug/l)	Mean annual chl a (ug/l)	Trophic status class	Mean TP conc (ug/l)	Mean annual chl a (ug/l)	Trophic status class	TP conc - export coefficient models (ug/l)	TP conc - Diatom model (ug/l)	Palmer TRS/ Lake type
Slapton Ley 46472	2.5	6.3	1.55	2.5	4	0.15	1	1	0.047	2	39.8 (58.1)	21.5 (34.0)	4	102	54	5	32	60	8.09 / 9
Crose Mere 35211	3.64	na	na	9.3	5	1.19	1	5	2.25	1	52.0 (74.3)	31.9 (49.4)	4	214	10	5	76	80	8.41 / 8
Barton Broad 35655	na	5.8	1.55	c. 2	4	0.04	2	1	0.05	2	238 (266)	180 (206)	5	65	50	4	120	150	na
Rollesby Broad 35981	na	12.6	2.5	c. 3	5	0.7	1	1	na	na	253 (260)	211 (217)	5	c. 100	18	4 to 5	71	150	na
Malham Tarn 29844	na	na	2.6	4.4	4	0.33	1		0.19	1	11.7 (17.8)	4.9 (8.2)	3	17	8	3	9	na	/ 10B
Coniston Water 29321	na	na	24	56	5	1.04	1	5	0.93	1	5.3 (9.5)	2.3 (4.8)	2	7.62	na	2-3	9	na	6.79 / 2
Priest Pot 29323	4.42	11.3	2.5	3.7	5	0.048	2	5	na	na			3	45	20 to 700	4		na	/ 3

Note 1: These data are based on current P loads modelled using export-coefficients for people and land cover only. Animal data are not available for Scotland. However, animal data are available for England and Wales and the values calculated with the animal component included are given in brackets. The in-lake P and chlorophyll a concentrations were estimated from the modelled P load using OECD regression equations and ranked according to Vollenweider's Trophic classification to give a Trophic status class from 1 to 5 where 1=low and 5=high.

Note 2: The export coefficient models of Johnes *et al* (1996) for England and Wales and the PLUS model for Scotland (Ferrier *et al*, 1997) were used to hindcast TP concentrations. The TP concentration hindcast from diatom transfer functions (Bennion *et al*, 1996a) is given where available.

7. GEOREFERENCED INVENTORY

7.1 Introduction

There have been several attempts during the last 100 years to describe the extent and distribution of standing waters in Scotland (Murray and Pullar, 1910; Lyle and Smith, 1994) and Great Britain as a whole (e.g. Smith and Lyle, 1979; Barr *et al*, 1994; Fuller *et al* 1994; Haines-Young *et al*, 2000). Many of these surveys have been based on stratified random sampling techniques or remote sensing. The Smith and Lyle survey, which was based on a visual inspection of 1:250,000 paper maps from Ordnance Survey (OS), remains the most comprehensive account so far. At this scale however, the lower level for inclusion is about 4 hectares and this, coupled with the fact the survey data are not held digitally, meant that it was necessary to start with a fresh approach.

7.2 Data Source

In choosing the data source for the inventory the main consideration was the degree of detail needed. The basic requirements were for an outline of the water body from which the coordinates of its centroid, surface area and perimeter could be derived. It was decided at an early stage to concentrate on water bodies with a surface area of at least 1 hectare. OS Land-Form PANORAMA® contour data at 1:50,000 contains features representing contours, spot heights, breaklines, coastline, lakes, and ridge and form lines as seen on the 1:50,000 Landranger paper map series. Data capture took place in 1983. Each lake outline has an associated elevation attribute (to the nearest metre) and all line objects have a quoted spatial accuracy of 3m root mean square error (RMSE) (Ordnance Survey, 2001). A visual inspection of the data indicates that water bodies with surface areas as small as 0.5 ha are accurately represented and although smaller water bodies do exist in the dataset (the smallest being 0.02 ha), their representation is somewhat generalised. However, the dataset remains relatively manageable in terms of computer processing whereas data at a larger scale (such as OS Land-Line®) would have introduced problems of data processing and unnecessary complexity.

The main drawback of using PANORAMA is that it is a 'static' dataset, i.e. OS do not update this product, and so the database reflects the state of Britain's water bodies in 1983. Sample tests with new web-based 1:50,000 maps indicate that approximately 4% of the water bodies in the database have changed shape or are now missing – mainly in areas around quarries, docks, industrial works and extractive industries, urban areas and dunes. A large proportion of these 'missing' lakes are probably due to mistakes in the original dataset (i.e. land parcels or contour lines being incorrectly coded as water) and cartographic errors on the new map. Also, any reservoirs or alterations to water level which have taken place since 1983 will not be included.

During the course of this project the Countryside Council for Wales independently developed a GIS layer of lake outlines based on more recent OS data. This is largely identical to the data used for this survey except for the addition of several hundred smaller (<1 ha) water bodies, the enlargement of two reservoirs (Llyn Gwynant and Marchlyn Mawr), the addition of a new reservoir (Cwm Reidol) and 31 additional water bodies between 1 and 10 ha surface area. Interestingly, comparison between the two datasets reveals that some 85 water bodies in the original dataset no longer exist, 25 of which are larger than 1 ha.

7.3 Data Processing

Each of the 812 20 km square PANORAMA tiles was processed individually to extract the lake features using 3 SPARC Ultra-5 workstations and ESRI software. Tiles were converted to ArcInfo coverages using ESRI's MapManager software and subsequently lake features were extracted automatically and converted to polygons using custom scripts in ArcInfo (AML). Each lake polygon was then assigned a pair of geometric centroid coordinates (to the nearest metre) and basic physical parameters (surface area in hectares, altitude and perimeter both to nearest metre, number of islands).

The data were error-checked using a variety of methods, both automatic and manual. Lake features that did not form whole polygons were closed automatically using an iterative process where snapping distance was gradually increased from 2 m to 10 m. Open polygons with gaps larger than 10m were edited manually with reference to the paper map, resulting in more than 700 additional water bodies. The process of converting to polygons occasionally produced slivers (very small polygons adjacent to 'real' polygons) and these were searched for automatically (by size) but checked visually against the map. Some 300 polygons were rejected as being slivers. It was noticed that the original dataset contained large rivers (coded as lakes and split into sections) appearing as long chains of adjacent rectangular polygons. These were removed manually, resulting in the loss of a further 2200 polygons. The final number of polygons in the database was 46570, of which 43738 were lakes and the remaining 2832 were islands.

Additional parameters were derived for each lake polygon. OS-style grid references, geographic coordinates, distance to sea, shoreline development index (a measure of shoreline complexity) and length and bearing of line of maximum fetch were all computed using Microsoft Excel, ArcView and ArcInfo. Attribute data were managed in a Microsoft Access97 database and linked to the GIS using a unique identification code. The lake centroids were used in a series of overlays to identify co-occurrence with a range of national datasets.

Measured depth data for approximately 5% of the water bodies >1 ha were collected from a wide range of sources (including Murray and Pullar, 1910) and used in a simple multiple regression model to predict mean and maximum lake depths, for the calculation of volume and retention time. The basic model for predicting maximum lake depth was developed using lake easting, northing, surface area, altitude and shoreline development index (from TBL_LD and TBL_SDI). Actual maximum depth values were collated for 824 water bodies (see TBL_DP). Multiple regression analysis was carried out on the above parameters and maximum depth for lakes where the latter was known. England, Scotland and Wales were treated separately due to the different physical nature of water bodies in each country. The relationships were used to predict maximum depth for the remaining water bodies > 1ha in England, Scotland and Wales (TBL_MDP). The predictive power of these relationships is not strong and the models all underestimate significantly at the lower end of the depth range (< 5m). A better model would also take account of the surrounding relief and lake shape as an indicator of lake type (e.g. corrie, glacial, lowland etc).

Mean depths (TBL_MDP) (where an actual mean depth was not known) were predicted using a simple relationship between mean and max depth (obtained by analysis of the training data where both mean and max depth were known, n = 597, TBL_DP). This relationship is shown in Figure 8.

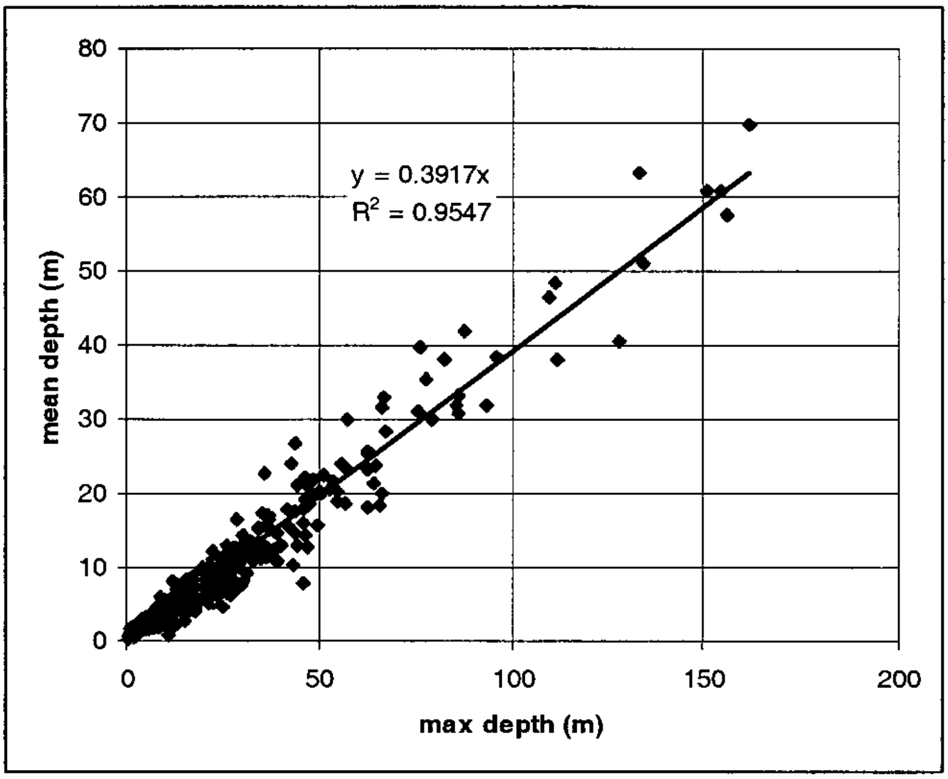

Figure 8 Scatterplot showing the relationship between measured maximum lake depth and measured mean lake depth in the training set of lakes

7.4 Catchment Delineation

Catchment areas were derived for all water bodies with a surface area larger than 1 hectare. The lake polygons (n = 14353) were extracted and processed with a flow grid derived from the Institute of Hydrology digital terrain model (DTM) (Morris and Flavin, 1990) to generate catchment polygons. This 50 metre resolution DTM is based on digitised contours from the Ordnance Survey 1:50,000 map (PANORAMA) but has been adjusted to conform to a digitised stream network for greater accuracy.

The lake outline was used to select grid cells from the flow grid, and the cell with the greatest value (i.e. maximum flow) was selected as the pour point. ArcView's Spatial Analyst Watershed function was used to generate a catchment outline from the pour point, which was saved as a polygon. The catchment polygons were subsequently processed to calculate their area, perimeter and lake to catchment ratio. Catchment polygons were then used in the GIS to extract data from national datasets.

The catchment overlay process for each dataset took one of two forms depending on the data type. A catchment-weighted procedure was used for overlay with gridded maps of distributed data (such as acid deposition and P load) whereby a mean value is found by calculating the proportion of each gridded data cell overlaid by the catchment polygon. For datasets containing categorical data in discreet units (such as geology and land cover) the proportion of each category was calculated as an actual area (in hectares) and percentage of catchment. (Note: many of the national datasets did not cover the Isle of Man and so these were excluded from the risk prioritisation exercise.)

7.5 Data Types

The inventory consists of two components: i) GIS coverages of lake centroids and catchment boundaries (available as ArcView shape files or MapInfo files) and ii) an Access database containing all derived attribute data, referenced by water body ID. The attribute data are summarised in Table 6 and documented fully in Appendix 1, along with details of the available queries. All data and documentation are currently available for download from a secure server (http://ecrc.geog.ucl.ac.uk/gblakes). The database can be downloaded in either Microsoft Access97 or Access2000 formats. Information on data coverage and quality are given in Appendix 2.

Table 6 List of data available in the lakes inventory

Data available for lake centroids	Data available for catchments
Agency (EA/SEPA) Region co-occurrence	LCM90 Landcover class (Fuller *et al*, 1994)
1995-97 Acid Deposition (CEH)	Drift Geology (1:625,000)
Freshwater Sensitivity (CEH)	Solid Geology (1:625,000)
Protected areas co-occurrence (includes National Park, Forest Park, National Nature Reserve (NNR), RAMSAR , Special Area of Conservation (SAC), Special Protection Area (SPA), Site of Special Scientific Interest (SSSI))	1995-97 Acid Deposition (CEH) Freshwater Sensitivity (Hornung *et al*, 1995) Animal stocking density (MAFF) Modelled hindcast P load (Johnes *et al*, 2000) Modelled current P load 1991 Population - SURPOP91 (Bracken and Martin, 1995)
EN Character Area co-occurrence	
EN Natural Area co-occurrence	Mean annual runoff (CEH)
OS Landranger Map sheet	

The inventory contains 43,738 water bodies in England, Scotland, Wales and Isle of Man. A breakdown of distribution by surface area and country is given in Table 7. The majority of water bodies in each country have a surface area smaller than 1 hectare with less than 10% having a surface area larger than 10 hectares. The total surface area of standing waters in the inventory is 213,911 hectares, covering approximately 1% of the land surface of Great Britain.

Table 7 The distribution of lakes by surface area (ha) and country

	≤1 ha*	>1 to ≤5 ha	>5 to ≤10 ha	>10 to ≤50 ha	>50 to ≤100 ha	>100 ha	Total
England	10765	4233	710	625	64	51	16448
Scotland	17748	5273	1195	1205	168	171	25760
Wales	894	394	88	90	10	17	1493
Isle of Man	26	9	0	2	0	0	37

* the dataset contains no water bodies < 0.02 ha and the number between 0.02 and 0.2 are almost certainly under-represented

In their survey of Scottish lochs Smith and Lyle (1979) grouped water bodies larger than 25 hectares into logarithmic area classes to investigate the relationships between numbers of lochs, accumulated area and volume. They found that there was a natural order in the frequency of occurrence based on surface area, which is confirmed by the present study. The relationship between numbers of water bodies and accumulated areas for logarithmic area classes is shown in Figure 9a and shows that although the number of water bodies increase as the logarithmic area class decreases, the accumulated area decreases, something which Lyle and Smith (1994) predicted but were unable to demonstrate with their dataset.

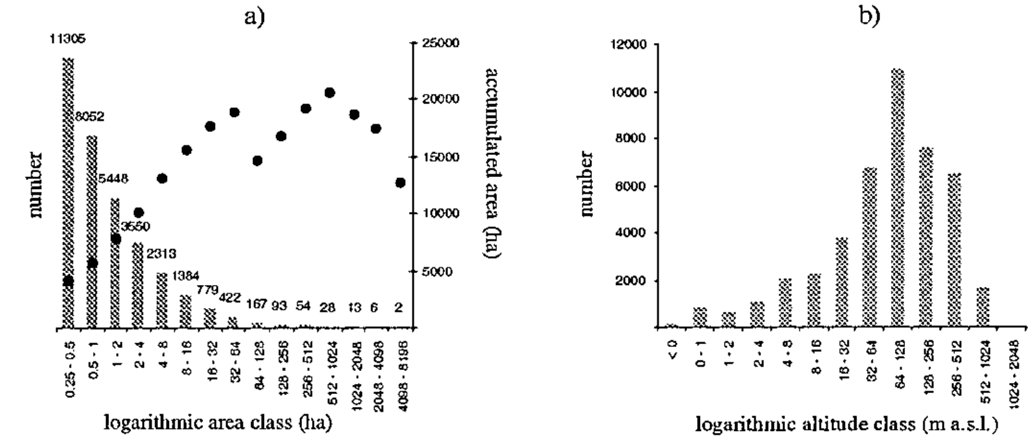

Figure 9 a Numbers of water bodies (grey bars) and accumulated areas (black dots) for logarithmic area classes;
b Numbers of water bodies for logarithmic altitude classes

Table 8 and Figure 9b show the distribution of water bodies by altitude and country and by logarithmic altitude class, respectively. Here there are two different distributions influenced by topography: England with the majority of its water bodies at lower altitudes and Scotland and Wales with the majority at slightly higher altitudes. In terms of the Water Framework Directive 'System A' ecotype altitide classes, 75.8% of water bodies (by number) occur in the lowland ecotype (<200 m), 23.8% in the mid-altitude ecotype (200-800 m) and the remaining 0.4% in the highland ecotype (>800 m).

Table 8 Numbers of water bodies by country and altitude (metres above sea level)

	<10	10 to <50	50 to <100	100 to <300	300 to <500	500 to <750	≥750
England	2686	4826	4757	3866	245	66	2
Scotland	1828	4651	4481	9001	4205	1327	267
Wales	183	180	213	468	345	102	2
Isle of Man	4	21	2	10	0	0	0

7.6 Meta-data

The inventory was linked to external databases using a meta-data system. Table TBL_MD in the inventory database contains a list of water body IDs with a meta-data code. This code refers to external databases such as the JNCC Standing Waters database, which contains macrophyte and some water chemistry data or the CLAG Critical Loads database wich contains water chemistry and critical load calculations. Another table (KEY_MD) contains details about the meta-datasets such as availability, type of data, published references etc. There are more than 8900 entries in the meta-data table; the majority of these refer to the JNCC and CLAG meta-datasets, although there are currently 17 meta-datasets included. The database also contains a table with summary water chemistry data from some of these external databases (TBL_SUMM). There are currently 470 entries for 399 water bodies including data on pH, conductivity, total phosphorus (TP) and alkalinity, many of which are annual means. It is hoped that both meta-data and summary data can be added in the future as and when data become available.

During the lake naming exercise, there was the opportunity to gather additional information from features on the 1:50,000 map, e.g. whether or not the lake is in a quarry or whether the catchment is forested. Despite its subjectivity, such information was entered into a Microsoft Access2000 database. Unfortunately time restrictions meant that the additional information fields were incomplete at the time of writing and for this reason the Access database has not been incorporated into the main database. The data are provided as an additional output of the project as an Access2000 database on CD-ROM and details of the data fields are given in the Project Record (Bennion *et al.*, 2003).

7.7 Lake Typology

The WFD requires that Member States characterise lakes into ecotypes according to one of two methodologies, either system A or B, which differentiate lakes according to a set of key descriptors. In both systems, typology needs to include, altitude, depth, size and geology. This project has collated information required to develop such a lake typology and, although not one of the original aims, a preliminary exploratory analysis of the data was performed during Phase 2. The lakes >1 ha were classified into broad types using a neural network which essentially finds the optimal way of mapping data points into a specified number of clusters. Six variables were initially used as descriptors: the System B obligatory criteria set out in WFD Annex II (altitude, size, depth, solid and drift geology) as well as one optional factor, freshwater sensitivity (as a surrogate for acid neutralising capacity). Latitude and longitude were not included in the analysis as they added nothing other than to tell us that there are lakes in England, Scotland and Wales.

The data analysis identified five broad clusters of sites: i) lakes which are large, deep, lie on siliceous geology and are highly sensitive to acidification - predominantly in the Scottish Highlands, southern Wales, Cumbria, and the Pennines with a few in south-west England, ii) lakes which are high, small, relatively deep, and highly sensitive to acidification with no peat in their catchments – in similar regions to those in (i) but differ in that they are at higher altitudes and are generally smaller, have less peat and higher percentage of calcareous geology in their catchments, iii) lakes of intermediate altitude, size and depth, with low sensitivity to acidification and low % peat - predominantly in the Midlands and northern England, south-west England, central and northern Wales, and central Scotland, iv) lakes which are lowland, small and shallow with low sensitivity to acidification - predominantly in lowland areas of south-east and eastern England, and southern Wales, v) lakes which are generally high, of intermediate size, relatively deep, and highly sensitive to acidification with high % peat – predominantly in upland areas of south-west England, Wales, the Pennines, Cumbria and Scotland, especially the far north-east. The lakes, however, formed a continuum rather than discrete lake types and it was agreed that more clusters were required to produce a workable typology.

In an attempt to improve upon the first analysis and to introduce more ecologically relevant descriptors, the analysis was subsequently re-run with the addition of Stratification Class and Fetch and with the number of specified clusters increased to 10. The results are given in the Project Record (Bennion *et al.*, 2003). In summary, this second analysis improved upon the first but there were still concerns over whether a typology based on essentially physical descriptors had any ecological meaning. Furthermore, errors associated with the depth model resulted in lakes potentially being placed into the wrong class as the modelled depth data were used to derive a number of the descriptors such as maximum lake depth and Stratification Class. Further work is required, therefore, to develop a lake typology for the Great Britain ecoregion but once a system has been agreed, it could be introduced into the risk prioritisation protocol. For example, the importance assessment could be stratified by lake type to ensure full representation of all key ecotypes at Risk Tier 2.

8. SUMMARY AND RECOMMENDATIONS

This project has successfully developed and refined a three-tier, risk-based prioritisation system for lakes with respect to acidification and eutrophication and developed a georeferenced inventory of standing waters in Great Britain containing morphometric, use-related and summary meta-data. Application of the risk protocol to 30 lakes illustrates that the schemes for both eutrophication and acidification produce reliable risk assessments in most cases.

There are, however, a number of limitations and areas for improvement which should be addressed in future.

i) Although not included in our test lake assessments, it is vital that local knowledge is incorporated into the prioritisation exercise at Risk Tiers 2 and 3 so that lakes with special local significance, which would not be identified with the normal Tier 1 assessment, can be incorporated into the Tier 2 assessment and if prioritised, the Risk Tier 3 assessment.

ii) In the eutrophication scheme, modelled P loads currently exclude animal data owing to the absence of livestock data in a suitable format for Scotland. This results in potential underestimates of P loads for many water bodies. We recommend that animal data are incorporated into the calculations once they become available for Scotland. Further, where point sources of nutrients from consented discharges are known, for example fish cage units, we recommend that these also be included.

iii) There are reasonably large errors associated with the lake depth models used to derive mean and maximum depth for lakes where measured data are lacking. We recommend that the depth models are further developed and refined, and efforts are made to collect more measured depth data in future.

iv) In several cases catchment-derived attribute data for certain lakes were suspect, leading to an incorrect risk assessment. Closer inspection revealed that the catchment delineation process had failed to produce an accurate watershed for the lake concerned. The majority of these 'errors' occur when a small water body is close to a large river. The cell that gets selected as the pour point for the catchment is the one with the highest accumulated flow and if a lake cell coincides with a river cell then the river catchment will actually be computed. In the risk assessment protocol this leads to a small water body being erroneously attributed large nutrient and acid loads. Another type of error that may occur is poor catchment delineation in areas of low relief – such as in the Fens. The vertical resolution of the DTM is insufficient in these cases to allow the accurate mapping of a lakes catchment. A confounding factor in these areas is that lake catchments are often determined by man-made drainage features, which are not represented in the DTM. Clearly, these lowland water bodies represent a challenge. Higher resolution digital surface models (DSM's) from LiDAR data could be used as a means to more accurately delineate their catchments.We recommend that catchments are checked locally where possible and that a method for revising and updating catchments where necessary, is considered.

v) The inventory does not currently allow heavily modified waters to be identified. For WFD purposes, we recommend that a method for separating these from other water bodies is considered in future. For example, it would be possible to identify lakes with a long straight side, which probably highlights a dam, and check at least the largest ones against a map. Additionally, the county councils keep a register of all water bodies which have dams and store water above the ordnance datum, as well as registers of flooded quarries and gravel extractions.

vi) Currently the importance assessment considers only one of the major statutory designations (in addition to conservation staus), i.e. Bathing Waters Directive. We advise that further statutory designations be added in future as data become available, particularly with regard to the Surface Water Abstraction Directive and the Fisheries Directive.

vii) A scoring system to assess the relative importance of sites requires further development. A simple count of the number of importance factors attributed to each lake is proposed. In order to do this, however, one would need to ensure that there was no double counting. New work would require making some rules about how to add scores together.

viii) The Wederburn depth is a good starting point for modelling stratification class and thus for assessing sensitivity to restoration in the eutrophication protocol. However, we recommend that the modelled data are validated against measured values and that the class boundaries are modified accordingly. A further class could be added for shallow lakes where sediment is continually resuspended, following a different equation.

ix) Further work, using data from low and medium P loaded lakes with high retention times, is required to clarify the criteria for passing lakes through the second sensitivity assesment of eutrophication risk at Risk Tier 1.

x) Since rehabilitation management is most effective for deep lakes, the method assumes that rehabilitation of shallow lakes with high risk of eutrophication damage is not an option to be followed. Further work should be carried out to define the selection criteria at this point more clearly, since rehabilitiation can work in these systems but recovery may take decades to be achieved. Indeed one might argue that restoration at such sites should receive urgent priority because recovery may be slow.

xi) The inventory provides an invaluable resource for assisting with the characterisation of river basins in Great Britain and highlighting the range of pressures that occur in various lake typologies. Whilst this project involved a preliminary analysis of the data, a lake typology clearly urgently requires further development.

xii) This project does not attempt to quantify relationships between pressure and response. However, there is clearly scope to build on the scheme developed here to establish such relationships. These could be used to set site- or type- specific boundaries for assessments of pressure which have a quantified link to various levels of ecological quality.

xiii) Chapter 7 introduced some of the problems arising from the use of PANORAMA data as the inventory data source. A new OS dataset, still in development during the early stages of this project, is now available called MasterMap – the definitive digital map database for the UK, developed through the Digital National Framework (DNF) project. Potentially, this dataset could provide detailed data on the location of water bodies, including those smaller than 0.0025ha (5m x 5m), but data costs could be prohibitive. The use of MasterMap for mapping water bodies needs to be investigated further.

xiv) The data in the database will be continually increased and updated. A mechanism for storing and updating the data must be instigated.

xv) Access to the inventory is currently restricted to project partners via the website (file download). Users will require a good working knowledge of Microsoft Access as there are no graphical user interfaces and only a few ready-made queries. A prototype web-based query interface has been tested and seems to be a good method for making data available whilst ensuring it is current. This could be easily expanded to meet the needs of users and the public; indeed summary data should be made available to the public in any case. However, such a system would need maintaining and managing and the Agency must consider how this is to be done.

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GLOSSARY OF TERMS AND ABBREVIATIONS

Acid neutralising capacity (ANC). Ability of a natural water to buffer the effects of loading of strong acid ions, usually from atmospheric sources, thus preventing severe decrease in pH.

Acidification. Reduction in pH value (increase in hydrogen ion concentration) in a natural water.

Acid sensitive. Waters which have a naturally low pH and low concentrations of base cations and thus a low potential acid neutralising capacity.

Algae. General term applied to photosynthetic organisms that are generally aquatic, may be microscopic or very large (e.g. seaweeds), and may be floating or attached.

ArcView. GIS software package from ESRI.

Baseline state. A reference condition of an ecosystem with which the current condition can be compared and hence the degree of deviation or change determined.

Biodiversity (Biological diversity). The variety of life, as indicated by the number of species present.

Biomass. Total quantity or weight of organisms in a given area or volume - e.g. algal biomass.

Blue-green algae (cyanobacteria). Group of largely microscopic, photosynthetic organisms with a bacterial structure, but containing chlorophyll a and a photosynthetic biochemistry unlike other bacteria but similar to that of other algae and higher plants.

Catchment. Area drained by a river or a river system.

Chlorophyll a. The major photosynthetic pigment of algae and plants.

Diatoms. Group of brown or yellow coloured algae commonly found in natural waters. The cell wall is made of polymerised silicate which is readily preserved in sediments when the organic part of the organism decays.

Diffuse source. Supplies of nutrients or other pollutants that come from a myriad of small-sized locations.

Ecotype. A water body type as defined using either system A or system B descriptors identified in the Water Framework Directive.

Environmental risk. A combination of the probability of occurrence of a defined hazard and the magnitude of the consequences of the occurrence; that is in simple terms, the likelihood of suffering harm from a hazard.

Eutrophic. A description of water which is rich in nutrients and is highly productive.

Eutrophication. The enrichment of water, by inorganic plant nutrients, which results in the stimulation of an array of symptomatic changes. These include the increased production of algae and/or other aquatic plants, affecting the quality of the water and disturbing the balance of organisms present within it. Such changes may be undesirable and interfere with water uses (Environment Agency, 2000).

Export coefficient model. Technique for calculating nutrient loadings and concentrations in a stream or lake from a knowledge of land use, numbers of stock and number of people in the catchment, stream discharge and the rates at which the nutrients are leached or excreted from the various sources.

Fetch. Distance (from shore to shore in a given direction) of open water surface over which the wind can blow uninterrupted to create waves.

Harm. The damage or adverse effect resulting from a hazard.

Hazard. A property or situation that in particular circumstances could lead to harm.

Hindcasting. The process of estimating the state of a waterbody at a given point in the past, in the absence of appropriate baseline water quality data. This is achieved by considering natural catchment characteristics e.g. morphology, geology and soil type, and historic records of land-use, or by the assessment of past diatom communities preserved in the lake sediment.

Hypertrophic. A description of water which is extremely nutrient-enriched, and typically affected by heavy growth of algae and other water plants.

Importance. The value (both non-monetary and monetary) which society in general attaches to a lake in respect to its chemical and ecological quality.

Inventory of standing waters. A list of all lakes or reservoirs (fresh standing waters) in Great Britain contained in the 1:50 000 Ordnance Survey Panorama digital dataset (1993) along with basic physical data.

Lake. Any standing water body contained in the 1:50 000 Ordnance Survey Panorama digital dataset. Catchment boundaries and related data for standing waters of less than 1 hectare are not included within the inventory.

Limiting Nutrient. Nutrient in an ecosystem which is in short supply relative to demand, and can thus inhibit efficient and productive ecological development.

Macrophyte. Any plants large enough to be seen with the naked eye, including all higher aquatic plants, together with macroscopic algal species that typically form mats or dense growths.

Mesotrophic. A description of water which is of medium nutrient status and medium biological productivity (between oligotrophic and eutrophic).

MIMAS. Manchester Information and Associated Services - national data centre providing the UK higher education, further education and research community with networked access to key data.

National Biodiversity Network. A union of likeminded organisations that are collaborating to create an information network of biodiversity data that is accessible through the Internet.

National Nature Reserve (NNR). Land declared under the National Parks and Access to the Countryside Act 1949 or Wildlife and Countryside Act (1981).

Nutrient. Substance providing nourishment for plants (or animals) e.g nitrogen, phosphorus, silicon, potassium, etc.

Nutrient export coefficient. A measure of the nutrient loss from a specific land use, typically measured as kg $ha^{-1}yr^{-1}$

Oligotrophic. A description of water which has a low nutrient status and low biological productivity.

Orthophosphate. A fraction of phosphorus, often approximately equated to Soluble Reactive Phosphorus, as measured by the molybdenum blue assay on a filtered sample. (If the determination is carried out on an unfiltered sample, the fraction measured is Total Reactive Phosphorus).

OS. Ordnance Survey, UK National Mapping Agency.

Palaeolimnology. The science that studies lake histories based on analysis of biological, chemical and physical characteristics of lake sediments.

PANORAMA. Ordnance Survey's Digital Height Dataset with data available as vectorised contours (at 10m vertical intervals).

Phytoplankton. Community of largely microscopic algae suspended or floating in natural waters. Most species are denser than water and tend to sink, but are maintained in suspension by wind-generated water currents.

Point source. Supplies of nutrients or other pollutants that come from discrete, identifiable, comparatively large origins (e.g sewage treatment works).

Pristine state. Nature of an ecosystem that is not influenced by any human activity, or at least by technologically sophisticated activity.

PROTECH. A universal model of phytoplankton dynamics in lakes based on fundamental ecological and physiological equations. It is able to test lake system sensitivity and quantify the impacts of change.

RAMSAR site. Land listed as a Wetland of International Importance under the Convention on Wetlands of International Importance Especially as Waterfowl Habitat (the Ramsar Convention) 1973.

Retention time. The period on average in which a parcel of water is retained in a lake. Retention time is the reciprocal of replacement rate, also called hydraulic flushing rate.

Sensitivity. The degree to which a lake responds to external factors such as exposure to, or removal of, a hazard.

Site of Special Scientific Interest (SSSI). An area given a statutory designation by English Nature or the Countryside Council for Wales (under the Wildlife and Countryside Act, 1981) because it is particularly important, on account of its nature conservation value.

Special Area of Conservation (SAC). An area designated for protection as part of the Natura 2000 network in the 1992 EC Habitats Directive (92/43/EEC), because it supports rare, endangered or vulnerable natural habitats and species of plants and animals.

Special Protection Area (SPA). Land classified under Directive 79/409 on the Conservation of Wild Birds.

SURPOP. Population estimates for 200 m cells derived from the 1981 Census of Population in England, Wales and Scotland, and the 1991 Census in England, Wales, Scotland and Northern Ireland.

SWAD. Surface Water Abstraction Directive.

Total Phosphorus. The sum of dissolved and particulate phosphorus (water) fractions.

Transfer function. A predictive equation based on the relationship between modern biological assemblages and contemporary environmental data for a set of lakes. It is used to infer a selected environmental variable from fossil assemblages in sediment cores.

Trophic state. The category of a water in relation to the process of eutrophication, typically assessed on the basis of nutrient and chlorophyll concentrations, and transparency. Waters have traditionally been classified into five trophic states: ultra-oligotrophic; oligotrophic; mesotrophic; eutrophic; and hypertrophic (see individual definitions).

Ultra-oligotrophic. A description of water with extremely low nutrient availability for the growth of algae or other plants.

Water Framework Directive (WFD). Directive of the European Parliament and of the Council 2000/60/EC Establishing a Framework for Community Action in the Field of Water Policy (European Union, 2000).

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