Final Report **WFD06**

Review of methods for assessing the hydromorphology of lakes

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Environment Agency

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- The European Water Framework Directive (WFD) was adopted on 22 December 2000. This is a major legislative initiative, intended to resolve the piecemeal approach to European water law which has developed since 1975. The WFD stipulates that surface water bodies such as lakes should achieve good ecological and chemical status (pollutant levels) by 2015. Good ecological status requires hydromorphological conditions supporting <u>at worst</u> 'slight changes' in the composition and abundance of key biological quality elements (phytoplankton, macrophytes and phytobenthos, benthic macroinvertebrates and fish fauna) relative to the appropriate natural reference condition (high ecological status). The two elements of hydromorphology are hydrological regime and morphological conditions, the corresponding hydromorphological quality elements are:

  Hydrological regime: quantity and dynamics of flow, level, residence time, and the resultant connection to groundwaters reflect totally or nearly totally undisturbed conditions.

  Morphological conditions: lake depth variation, quantity and structure of the substrate, and both the structure and condition of the lake shore zone, correspond totally or nearly totally to undisturbed conditions.

  Standing waters designated as Heavily Modified Water Bodies (HMWBs) or Artificial Water Bodies are required to attain Good Ecological Potential by 2015.

- Currently no EU Member States carry out routine assessments of lake hydromorphology. A comprehensive literature review has provided an overview of human pressures on lakes, and the resulting impacts on hydromorphology and biota. A review of methods used to measure the hydromorphological quality attributes of lakes has identified several potential metrics for each. Methods vary in the ease with which they can be adapted for the purposes of the Directive.

- Member states are required to produce a lake typology based on a modelling and/or a reference network of undisturbed water bodies (including development of hydromorphological reference conditions) that define high ecological status. The System A typology is unlikely to prove adequate for UK purposes. A priority need is therefore the development of a UK-specific System B typology, ideally using statistical clustering to determine the most significant optional factors (additional hydrological quality elements) to be to be included beyond the System A obligatory factors.

- A key milestone in the implementation of the WFD is by 2004 to complete a screening exercise to identify significant pressures acting on water bodies and identify those at risk of failing to achieve good ecological status (inclusive of rivers, lakes, transitional and coastal waters). Many of the pressures operating in the catchment of an individual lake can be assessed by direct observation. However, the scale of the exercise required for WFD implementation is such that it will be expedient to use desk-based information sources as far as possible. An outline scheme is presented, which should take advantage of existing databases, exploiting where possible Geographical Information Systems (GIS) query techniques.

- An important conclusion emerging from the review exercise is that both the quantity and quality of existing aquatic ecology data sets are limited. Clearly the regulatory authorities (e.g. the Scottish Environment Protection Agency or the Environment Agency in England and Wales) need to initiate new measurement and monitoring campaigns. There are also fundamental gaps in the knowledge base regarding the inter-relationships between ecology and hydromorphology. In the absence of fuller ecological data sets, more emphasis must be placed on abiotic approaches to both screening and in guiding the necessary programmes of measures needed to raise a failing water body to at least good ecological status. A screening tool is proposed in the form an Abiotic Index based on a combination of the Dundee Hydrological Regime Alteration Method (DHRAM) for standing waters and a newly proposed Lake Habitat Survey (LHS) approach derived from the integration of the Environment Agency's River Habitat Survey (RHS) and the USEPA's Field Operations Manual for Lakes (FOML). Extensive field-testing is required to calibrate such screening tools with ecological data, not only to validate the underlying science, but to ensure that designations and management options are accepted by all stakeholders and user groups.

- In addition to initiating a surveillance (monitoring) exercises, it will be necessary to implement a Programme of Measures to ensure that the hydromorphological quality elements of a standing water body such as a lake are improved to enable the biota to achieve the requirements of good ecological status or good ecological potential in the case of HMWBs. A series of recommendations are made accordingly.

KEY WORDS

Lakes; Hydromorphology; Water Framework Directive; Monitoring; Assessment; Pressures, Impacts; Typology; Reference Conditions; UK.

1. BACKGROUND

1.1 Lakes: their definition, origins and importance

Perhaps the simplest definition is that of Friedman and Sanders (1978, p. 237) who described a lake as, "....a landlocked body of water occupying some kind of basin". According to Kuusisto and Hyvärinen (2000), a lake is a water body that meets the following criteria:

- It fills or partly fills a basin or several connected basins
- It has essentially the same water level throughout, except for short periods when influenced by wind, thick ice cover or large inflows
- Even if located near the sea coast, it does not experience regular intrusion of sea water
- The inflow-to-volume ratio is so small that a considerable portion of suspended sediment is captured
- Its area exceeds a specified value, e.g. 1 ha at mean water level.

There are almost one and a half million lakes (also known as standing waters) of area greater than 0.001 km^2 in Europe, and at least 500,000 natural lakes larger than 0.01 km^2 (Kristiansen and Hansen 1994). Many of them appeared 10,000 – 15,000 years ago, having been formed or reshaped during the Pleistocene glaciation period. They are most abundant in northern Europe, the Nordic countries and the Karelo-Kola part of the Russian Federation, where lakes cover 5-10% of the land surface; and common in Iceland, Ireland and the northwestern parts of the UK. In central Europe, in addition to high-altitude small lakes, some larger lakes are to be found on the margins of the Alps (e.g. Lakes Geneva, Garda, Maggiore and Constance), in the Dinarian Alps (Lakes Ohrid and Prespan) and on the Hungarian plain (Lakes Balaton and Neusiedler). However, natural lakes are few in countries that were little affected by glaciation; such as Portugal, Spain, France, Belgium, southern England, central Germany, the Czech and Slovak Republics, and the central European part of the Russian Federation

Hutchinson (1957) classified lake systems on the basis of mode of formation, listing eleven major processes responsible for building, excavation and damming which produce 76 different types of lake basin (Table 1). The vast majority of British lakes were formed by glacial activity and, as such, fall into Hutchinson's categories 4b (glacial rock basins), 4c (moraine and outwash basins) and 4d (drift basins); although lakes formed due to fluviatile action (category 6b) and associated with shore lines (category 8) are also present.

Table 1 Classification of lake types (after Hutchinson 1957).

Type	Description
1.	Tectonic basins
2.	Lakes associated with volcanic activity
3.	Lakes formed by landslides
4.	Lakes formed by glacial activity:
	(a) Lakes held by ice or by moraine in contact with existing ice
	(b) Glacial rock basins
	(c) Moraine and outwash basins
	(d) Drift basins
5.	Solution basins
6.	Lakes due to fluviatile action:
	(a) Plunge-pool lakes
	(b) Fluviatile dams
	(c) Lakes of mature flood plains
7.	Lake basins formed by wind
8.	Lakes associated with shore lines
9.	Lakes formed by organic accumulation
10.	Lakes produced by the complex behaviour of higher organisms
11.	Lakes produced by meteorite impact

More than 10,000 major reservoirs have been constructed in Europe, and these make up almost one third of the continent's total of 300,000 km^2 of standing waters. The Volga basin alone has a reservoir area of 38,000 km^2 (Mordukhai-Boltovskoi 1979). For Britain, the Building Research Establishment (BRE) dams database contains entries for over 2500 reservoirs (Tedd *et al*. 1992). The total volume of European lakes (excluding the Caspian Sea) is 3,300 km^3, and that of reservoirs 800 km^3 (Kuusisto and Hyvärinen 2000). Estimates based on 1: 25,000 scale Ordnance Survey maps, which include standing waters with surface areas of 4 ha and greater, reveal that the total number of freshwater lakes and reservoirs in Great Britain is 5505, of which 3788 (69%) are in Scotland (Smith and Lyle 1979).

Lakes provide human beings with many "services" (Carpenter and Cottingham 1997) that include water for irrigation, industry, domestic consumption, hydro power, dilution of pollutants, recreation, fishing and general aesthetic appeal. These services may, however, be impaired by inappropriate human impacts on the water bodies themselves and in their catchment areas. It is thus important that lakes are understood within the context of their catchment areas (e.g. Wetzel 1983). By their aesthetic allure and recreational facilities, lakes play an important role in tourism world-wide. This is nowhere better illustrated than in the Lake District National Park of NW England or Loch Ness in Scotland to where thousands of tourists and day-trippers are drawn each year by the scenic beauty of the water bodies themselves. As such, lakes provide a huge tourist draw and thus contribute greatly to the UK economy. It is thus important that their physical and ecological status are conserved since there is evidence to indicate that "degraded lakes represent the loss of substantial economic benefits" (Carpenter and Cottingham 1997, p.11). Whilst a conceptual framework for understanding the interactions of humans and lakes is lacking, severely degraded lakes may be considered as the antithesis of tourist appeal.

1.2 Morphology and hydrology of lakes

A lake thus consists, essentially, of a basin or several connected basins containing water. It offers a range of habitats to living organisms, ranging from the shallow littoral zone at its margin, which may support floating-leafed plants on the one hand and experience wind-generated waves on the other, to the deep profundal where there is insufficient light for photosynthesis (Figure 1). The shape, or morphology, of the basin determines the relative extents of each of these habitats, and influences the physical and chemical conditions within them (Figure 2).

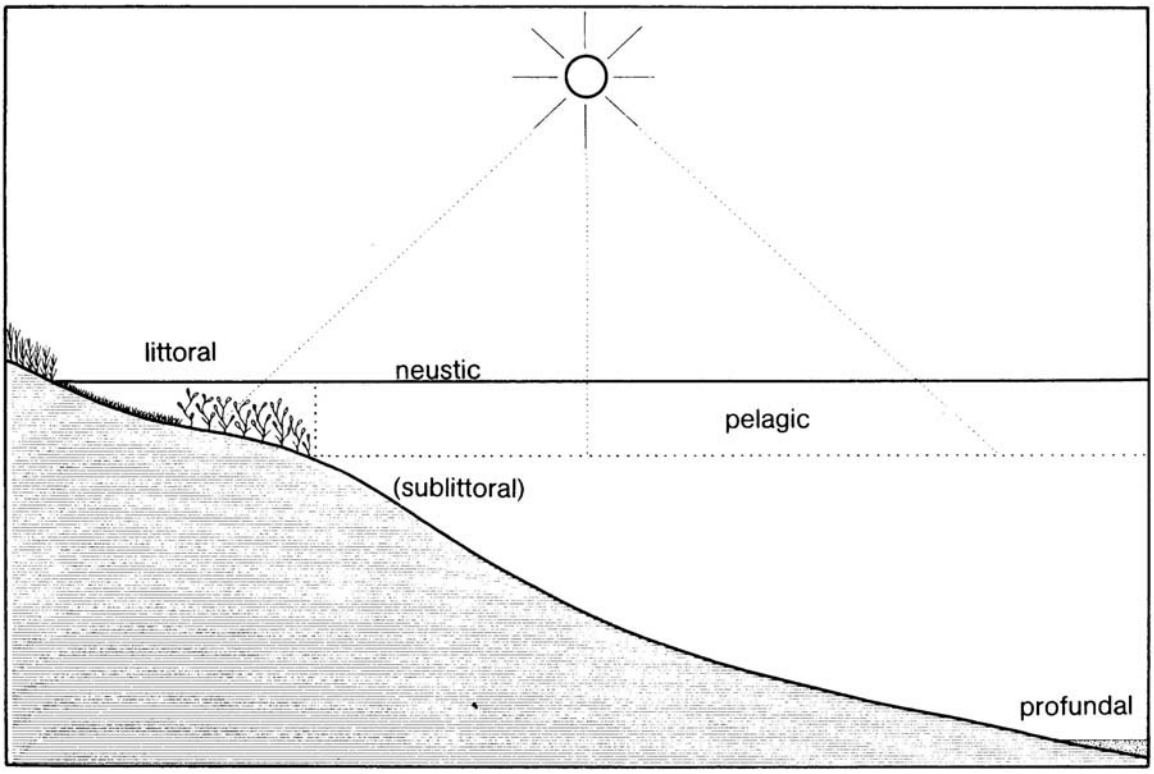

Figure 1 The major habitats found in a typical lake. From Maitland (1990).

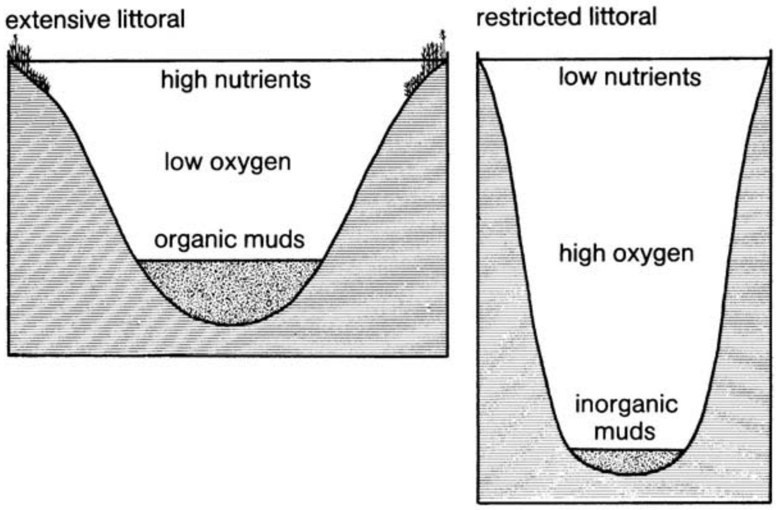

Figure 2 A schematic representation of the main differences between eutrophic (left) and oligotrophic (right) lakes. From Maitland (1990).

Deep lakes in temperate latitudes, such as those of the UK, display an annual thermal cycle (Figure 3) in which the spring period is characterised by isothermal conditions, permitting overturn of the entire water column at a temperature close to that of the maximum density of fresh water (3.94°C). Summer insolation typically leads to stratification of the water column with relatively warm and circulating surface waters (epilimnion) resting upon cooler non-circulating waters (hypolimnion) with a well developed thermocline (the region in which the fall of temperature ≥1°C m^{-1}) in between. Autumn is characterised by a return to isothermal and fully circulating conditions. In winter it is possible for a reverse thermocline to develop as the surface waters become stabilised by further cooling. This thermocline is, however, much less stable than its summer counterpart and can readily be broken down by strong wind action thus producing intermittent isothermal and stratified conditions. Once the surface water temperature falls to 0°C, ice begins to form. This process is usually initiated in shallow bays and protected embayments but it may extend to cover the entire lake surface. With the onset of spring warming the cycle continues (Figure 3).

Various processes serve to infill lake basins, the most obvious being the transport of sediments by influent rivers draining the catchment areas. However, minor components to the sedimentary deposits are derived from wind borne particles (both inorganic silt and organic, such as leaves) and erosion of shores by both wind generated waves and ice activity (e.g. Loch Leven, Kinross). Inorganic sedimentation within a lake is accompanied by the accumulation of organic debris largely derived from the skeletal remains of organisms produced in the lake (e.g. diatoms). Typically there is a zonation from coarse deposits in the littoral zone, which are disturbed by wave activity in the shallow waters, to progressively finer deposits in quiescent, deeper waters that are beyond the base of wind-generated waves.

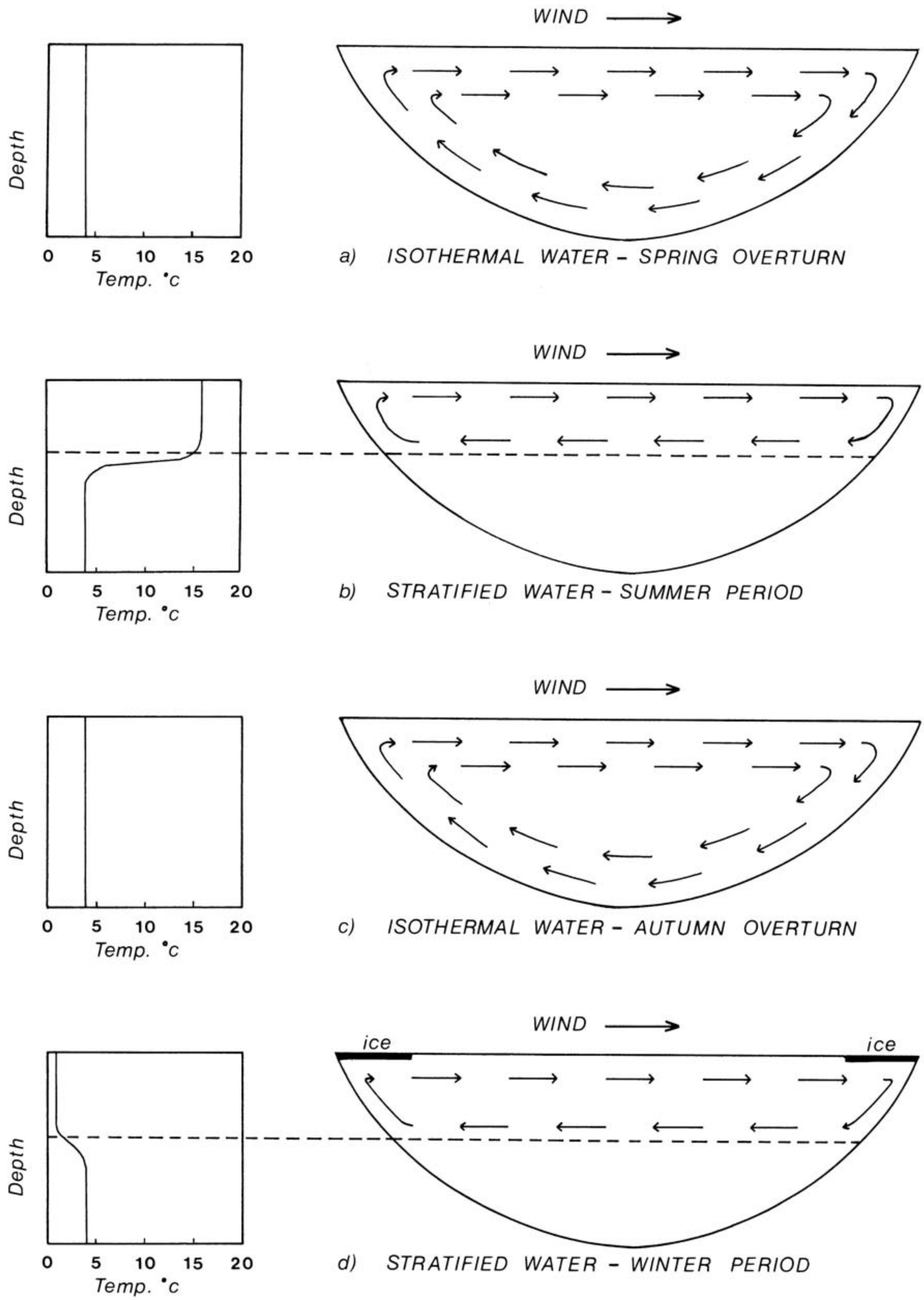

Figure 3 The annual thermal cycle of a typical deep lake in the temperate zone. From Duck (1982).

Many of the processes and forms developed along the shores of lakes are similar to those found on seacoasts (Carter 1988). There are, however, distinctive aspects about lake shores, particularly relating the equilibrium of the shoreline plan to the energy budget, the big difference between lakes and seas being that most lake shores are not subject to tidal rises and falls in water level. The smaller the water body, the more responsive it is to changes in energy input (Carter, 1988) and lakes and lake shore forms tend to be greatly controlled by fetch. Most lake margins, are dominated by forced (i.e. wind generated) waves that are still undergoing active generation right up to the shore. Over their long term development within what are essentially restricted fetches, lakes developed in unconsolidated deposits often assume an elongated or oval shape with the long axis coinciding with the dominant wind direction. At the other extreme, in the deep, strongly elongated rock basins of glaciated terrain (e.g. uplands of Wales, Scotland, English Lake District), lake shape reflects that of the valley from which it was excavated by ice, and shoreline development by wave action is superimposed upon this basic form.

Lakes form integral components of the hydrological cycle and their biota have become adapted to the variety of hydrological regimes that are represented by such water bodies. In the most simplistic of terms they may be viewed as broadened and deepened sections of rivers, though, as Table 1 indicates, fluvial action is not a prerequisite for lake formation. Most important in terms of lake hydrological regime are the quantity and dynamics of flow, i.e. the influent discharge, the effluent discharge and the residence time. The latter, typically expressed as the ratio of the capacity to the mean annual inflow provides an important measure of the period needed to completely replace the water in a lake, a value of great importance to the ecology (e.g. Marsh *et al*. 1993). Changes to the river flow, e.g. by water abstraction, will induce a fall in water level and a decrease in the residence time. Depending on the permeability of the terrain in which a lake has been created, there will be a degree of connectivity between the basin waters and groundwaters. Thus lakes are not only sensitive to activities in their river catchment areas but also to groundwater pollution and abstraction in/from underground areas that may not coincide with the surface catchment.

1.3 The Water Framework Directive

The European Water Framework Directive (WFD 2000) was adopted on 22 December 2000. This is a major legislative initiative, intended to resolve the piecemeal approach to European water law which has developed since 1975. The Directive focuses on the management of River Basin Districts, and includes inland (rivers and lakes), transitional (e.g. estuaries) and coastal surface waters and groundwater. For surface waters, Member States are required to protect, enhance and restore all natural water bodies to achieve good surface water status[1] within 15 years. Good ecological status prevails when the total effect of human pressures is insufficient to cause more than slight deviation in the composition and abundance of the flora and fauna from their natural condition.

In contrast to the simplicity of the objective, the prescribed mechanisms for compliance are complex. Water bodies are to be identified and classified into types on the basis of non-biological attributes (WFD Annex II). Type-specific natural hydromorphological and physicochemical conditions and the corresponding biological reference conditions are then to be established. For each water body that is influenced by human activities, the deviation of biological condition from the appropriate reference conditions is to be examined and classified on a scale of ecological status (or potential) with divisions "high" (i.e. no deviation), "good", "moderate", "poor" and "bad". For water bodies falling into the latter three classes, all practical mitigation of physical and chemical impacts is to be applied, ideally restoring them to good ecological status, by the end of 2015. Interim requirements are the characterisation of each river basin district in terms of water body types, the human pressures and impacts acting upon them, and the economics of water use, by 2004; and the establishment of programmes for monitoring water status by the end of 2006.

The work reported here focuses on the hydromorphological status of lakes. The two elements of hydromorphology are hydrological regime and morphological conditions. The corresponding hydromorphological quality elements listed in Annex V of the Directive are:

Hydrological regime: quantity and dynamics of flow, level, residence time, and the resultant connection to groundwaters.

Morphological conditions: lake depth variation, quantity and structure of the substrate, and both the structure and condition of the lake shore zone.

In order to achieve good (hydromorphological) status, the hydromorphological conditions must be consistent with attainment of good ecological status; i.e. the maximum permitted degree of disturbance causes only slight deviation from the natural composition and abundance of biota. Moderate status corresponds to moderate distortion of biota.

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[1] For artificial and heavily modified water bodies, the requirement is to protect and enhance with the aim of achieving good ecological potential and good surface water chemical status within the same period.

2 OBJECTIVES

One aim of the Water Framework Directive (WFD) is that all European lakes that are affected by human activity should achieve good ecological status, or the highest ecological status/potential that is possible given specifically justified human needs.   Given the terms of the Directive (Section 1.3), this target effectively sets requirements that high status for lake hydromorphology can be defined, and that hydromorphological impacts can be assessed in terms of their effects on ecological status. However, it appears that few, if any, Member States carry out routine assessments of lake hydromorphology and that there is a lack of standard methods for this purpose.

In order to begin to address the deficiency, the specific objectives set for this project were:

- To search the (worldwide) published literature on methods for assessing the physical (hydromorphological) features of lakes.
- To review and evaluate existing methods, especially in terms of their relevance and feasibility for use in implementing the WFD.
- To make recommendations for an appropriate methodology for use in the UK and to consider how it is linked with ecological assessment methods required by the WFD.
- To consider the relevance of River Habitat Survey techniques to standing waters and to propose a scoring system for lake shoreline assessment.

3 HYDROMORPHOLOGICAL PRESSURES AND IMPACTS

3.1 Potential pressures and hydromorphological changes

The WFD focuses on minimising the effects (impacts) of alteration of the natural attributes of water bodies due to human activities (pressures). Thus, the effects on hydromorphology that might be associated with water use for different purposes are relevant. A list of pressures and impacts that has been compiled for rivers is shown in Table 2.

Table 2 Pressures and potential impacts on river hydromorphology.

From HMW Paper 5 Version 3 (German & UK Project Managers: Unpublished Guidance Paper).

PRESSURE	IMPACTS
Navigation	Disruption of the river continuum (locks/dams/weirs) Disruption of sediment transport (locks/dams/weirs) Channel maintenance/dredging Channelisation / longitudinal straightening Change in river profile Bank reinforcement/fixation (stone filling, concrete, blocks) Detaching oxbow lakes and wetlands Creation of backwaters through embankments Mechanical damage of aquatic flora caused by passage of ships
Flood protection	Loss of flood plain and wetland Disruption of the river continuum (dams/weirs) Disruption of sediment transport (dams/weirs) Channelisation / longitudinal straightening Change in river profile Bank reinforcement/fixation (stone filling, concrete, blocks) Detaching wetlands and saltmarsh
Hydro-power generation	Disruption of the river continuum (dams/weirs) Disruption of sediment transport (dams/weirs) Change in river profile Channelisation / longitudinal straightening Reduced flow in the river bed (cross-catchment transfer) Change in flow regime (variation in water levels, extreme high and low flows) Mechanical damage of aquatic fauna caused by turbines
Agriculture/forestry	Dams/weirs for irrigation Channelisation / longitudinal straightening Change in river profile Detaching ox-bow lakes and wetlands Land drainage Soil erosion
Water supply	Disruption of the river continuum (dams) Disruption of sediment transport (dams) Channelisation / longitudinal straightening Bank reinforcement/fixation (stone filling, concrete, blocks) Detaching ox-bow lakes and wetlands
Urbanization	Channelisation / longitudinal straightening Change in river profile Bank reinforcement/fixation (stone filling, concrete, blocks) Detaching ox-bow lakes and wetlands Creation of backwaters through embankments Loss of flood plain and wetland (dykes) Land drainage

A similar analysis for lakes has not yet been completed, although it is understood that a comprehensive general overview of pressures and impacts will shortly become available as the EU Common Implementation Guidance on Pressures and Impacts (IMPRESS) and Heavily Modified Water Bodies. The aim of this part of the report is to compile a list of hydromorphological pressures and impacts for lakes, and to link these to effects on biota, largely on the basis of work reported in the international literature.

3.2 Evidence for pressures and hydromorphological changes

3.2.1 Introduction

According to Premazzi and Chiaudani (1992), only two of the six major categories of factors that have been important in degrading the quality of European lakes in recent decades relate to their hydromorphology; namely hydrological and physical changes such as water-level stabilization, and siltation from inadequate erosion control in agricultural activities. However, Kvarnas (2001) identified many differences between the four largest Swedish lakes, Vanern, Vattern, Malaren and Hjalmaren, which can be explained in terms of differences in lake shape, size and the relationship between drainage basin size and lake size. The processes that he considered to be relevant to aquatic organisms were water balance, water residence time, water temperature, water exchange between sub-basins, and other internal water movements. In this Section, the types of impacts on such attributes of lakes (and in particular on the hydromorphological quality elements of the WFD - Section 1.3) that arise from human pressures, and their consequence for biota, are explored. The principal pressures that have emerged are man's use of two resources within lake catchments; namely their land and their water.

3.2.2 Catchment land uses

Since a lake is a sink not only for surface water, but also for solutes and sediments from its catchment, the way in which the land of the entire catchment is used has implications for hydromorphological quality. The sedimentary history of Lake Tahoe, on the boundary of the North American states of California and Nevada, illustrates the consequences of some common pressures. In the late 1800s, most of the coniferous trees in the lake's catchment were felled to shore up the silver mines of the Comstock Lode in Nevada. Sedimentation on the lake bottom then averaged about 430 $gm^{-2}a^{-1}$. When intense mining ceased, the forest re-grew and the annual sedimentation rate dropped to 90 $gm^{-2}a^{-1}$. In 1960, Tahoe hosted the Winter Olympic Games, and this, in turn, stimulated its development as a ski resort. Proliferation of roads, buildings, golf courses, ski runs and parking lots caused an increase in sedimentation rates which reached 270 $gm^{-2}a^{-1}$ in 1970. The great depth, large volume (156 km^3), and long residence time (700 years) of the lake mean that impacts are long-lasting. The results of a 43-year monitoring programme have indicated an increase in algal growth rate of about 5% per year, and a loss of one third of the Secchi Disk transparency (from 30 to 20 m) due to increased densities of both algae and fine suspended sediment particles (Goldman 2002).

The English Lake District, like many parts of Europe, has been used for agriculture for several centuries. Nonetheless, Pickering (2000) noted that there was clear evidence of accelerated accumulation of topsoil in the sediments of Blelham Tarn over the last 30 years, which he associated with an increase in the density of livestock, especially sheep, over that period. For Britain as a whole, large-scale afforestation was probably the largest single land use change of the last century, and in the 1970s was expanding at a rate of about 40,000 ha a^{-1}. Although forestry was generally considered to be a land use giving low sediment yields, a number of studies conducted during the 1980s (e.g. Burt *et al*. 1983, 1984) showed marked increases in the production of suspended sediment following ploughing. The 1.5 km^2 Coalburn catchment (northern England) was drained for afforestation in 1972. The sediment yield during the five years following drainage was equivalent to nearly half a century's load at pre-drainage rates, and in the fifth year the annual yield was still about four times that from the undisturbed catchment (Robinson and Blyth 1982). The development of recreational activities around lakes has also introduced new impacts. Jones and Roberts (1993), cited by Duigan *et al*. (1998), attribute erosion of the shoreline and adjacent paths around Lake Idwal in Wales to the high numbers of hill walkers and climbers using the area. They also report that visitors prise out shoreline rocks to smash the ice cover in winter, adding to erosion problems; that wetland around the lake is vulnerable to damage by trampling; and that the lake itself is subject to direct visitor impacts through its use for power boating and wind surfing. At Slapton Ley in Devon, the effects of live bombs and shells used during United States Army battle training in the winter of 1943-44 are thought to be a causative factor in the disintegration of peat rafts fringing the lake. Also at this site, building of a road in 1856 necessitated replacement of the natural overflow channel with a culvert. This, and the construction and raising of weirs, appears to have caused the water level to rise faster than the peat and sediment surfaces, and consequent retreat of the lake's reed fringe (Morey 1976). A quantified illustration of the potential impact of road construction in accelerating catchment erosion and lacustrine sedimentation rates in Scotland is illustrated by a study of Loch Earn, Perthshire (Duck 1985). In 1982 an unmetalled road was constructed crossing several left bank tributaries of the Ogle Burn, one of the main influents to the loch. As a consequence, at least 1824 t of sediment was deposed over an area of 4.6 ha of loch bed in less than 2 months. This was over 20 times as much material by weight than had passed a gauging station, near the confluence of the loch, during a previous 12-month monitoring period. The mean thickness of the resultant deposit should, under normal circumstances, have taken some 20 to 25 years to accumulate.

Another human pressure on lakes and their catchments is mining. An example with direct consequences for lake ecology is the commercial exploitation of gravel deposits on the bed of Lake Windermere (England), which continued until the early 1970s. Sand and gravel were scooped from the lake bed using a pole and derrick assembly mounted on a fifty-foot sand barge, endangering the gravel beds used as spawning sites by Arctic charr, both directly and indirectly through siltation (Pickering 2000).

Human populations discharge sewage; this also has implications for lake sediments. Granéli (1982) reports that when shallow lakes have been exploited as receivers for insufficiently treated municipal sewage, nutrient-rich sediment deposited during the pollution period continues to cause problems long after the discharge has ceased. The sedimentation rate can increase by at least an order of magnitude, from less than 1mm a^{-1} to over 5 mm a^{-1}. This is due partly to direct deposition of particulate matter from the sewage, but is mostly a consequence of algal blooms. The remains of plankton are only partly mineralised before they reach the sediment surface where anoxic conditions prevent their further degradation and facilitate recycling of phosphorus. Hypertrophic conditions can be expected to continue for decades, until the lake becomes completely filled in or overgrown by macrophytes. Thus, Lake Trummen, a lake of area 1 km^2 and depth 1.1m in southern Sweden, became a “stinking algal soup, bordered by floating mats of unpenetrable macrophytes” (Granéli 1982). Restoration undertaken in the 1970s involved suction dredging around 0.5m of black, P-rich sediment from the floor of the lake and removing dense stands of partly floating emergent macrophytes (*Typha*, *Phragmites*) from its shores. The lake responded immediately with a drastic reduction in the concentrations of P and N, much lower phytoplankton biomasses, and increased transparency. The improvements persisted; after 10 years Lake Trummen was described as “a clean, open lake, used for wind-surfing and sunbathing”. Kelly *et al*. (1984) investigated relationships between concentrations of organic matter, nutrients, heavy metals and organochlorine compounds in surficial sediment samples from 63 Illinois lakes and a range of morphometric variables such as surface area, maximum depth, drainage area, storage capacity, water retention time and mean depth. The hypothesis under investigation was that binding of the substances investigated to clay and/or organic particles occurred in suspension and their settlement should be a function of lake morphology. Retention time emerged as the single most important morphological variable accounting for variance in concentrations of sediment components, notably of organic carbon, lead and mercury.

3.2.3 Water abstraction

In their overview of impacts on European lakes, Premazzi and Cardoso (2000) note not only “that sediments from eroded land can silt up dams, but also that ill-conceived irrigation projects can suck dry irreplaceable groundwater reserves”. Human activities within lake catchments almost inevitably require water. Impacts on lake hydromorphology can be anticipated whether the water is taken directly from the lake, from the rivers that feed it, or – especially in areas with geological strata that can transmit water – from groundwater.

At Lake Bolsena in Italy, water abstraction for drinking, agriculture and tourism has increased to 30 x 10^6 m^3a^{-1} since the late 1960s, increasing the theoretical water renewal time (residence time) from 120 to 300 years. Associated increases in nutrient and pollutant inputs from agriculture and urban sewage are also reported. Despite these impacts, present concentrations of nitrogen and phosphorus do not differ significantly from those observed in the1970s, and water quality remains good within the terms of Italian law. However, this purely chemical approach to monitoring is regarded as insufficient to define fully the trophic condition and evolution of the lake (Moselli *et al*. 2002). Further concerns relating to a new geothermal energy plant at the nearby town of Latera offer an extreme illustration of the hydromorphological issues for lakes in geological settings that allow significant exchange of groundwater with connected aquifers. Super-heated water is raised from a depth of approximately 2000 m, the resulting steam condensed to yield energy, and the effluent returned to the aquifer for re-heating *via* injection wells located 8 km from the production wells. In view of the fractured volcanic geology of the area, exchanges between the salty deep water and the water of the lake are anticipated, especially in the depletion zone around the production wells and in the over-pressurized zone around the injection wells (Bruni 2002).

Various effects of water abstraction on plankton ecology have been described. Parparov *et al*. (2002) considered the ecological consequences of water level lowering by 20m due to increase of outflow in the high mountain Lake Sevan (Armenia) and by 5m due to decrease of inflow in Lake Kinneret (Israel). Although theoretical considerations indicated that over-use of water in these arid regions would alter lake morphometry, they found no significant increase in sediment resuspension in either lake although the nutrient regimes in both had become more favourable for phytoplankton. However, sediment effects have been observed at the Menindee Lakes, an ephemeral arid-zone system located on the Darling River in New South Wales, Australia. The Lakes have been operated as a water storage facility for more than 30 years. This use has modified the natural regime of water level fluctuation, since cycles of wetting and drying are now influenced not only by the timing of inflows, evaporation losses and lake morphometry, but also by the regulation of outflows. Scholz *et al*. (1999) considered that regulation was likely to dampen much of the natural environmental variability of the system. In an attempt to clarify the causes of episodic cyanobacterial blooms and fish kills, they studied the single drying event from August 1997 to 1998. As the water level fell, sediments became increasingly susceptible to re-suspension by wind-generated turbulence, so that both turbidity and salinity increased. Shallower waters were also less buffered against diel fluctuations in temperature, pH and dissolved oxygen. Re-flooding tended to reverse these trends in water quality, to a degree that depended on the relative volumes of residual lake and inflowing water. In lakes where the sediments had been exposed, re-flooding also released a pulse of bioavailable nutrients. Thus, cycles of wetting and drying appeared to facilitate the exchange of nutrients between water and sediments, whilst increases in abundance of blue-green algae were associated with the drying phase.

Some effects on animals have also been reported. Scharf (1997) observed changes in invertebrate communities following emptying of a lake in Lower Saxony. Small residual ponds contained only creeping ostracod species, whilst the most successful coloniser on re-filling was the good swimmer *Physocypria kraepelini*. Pickering (2000) highlights an indirect link between water abstraction and biota at Lake Windermere (England). The lake is used for water supply, and from time to time is subject to drought orders to enable abstraction to continue during extreme dry periods. This, in turn, necessitates dredging to create adequate clearance for boats in shallow areas as the lake level is lowered. The fines thus released tend to re-settle in gravel beds used for spawning by Arctic charr, detracting from their quality for this purpose.

Some of the effects of water abstraction on biota appear to be permanent. Lake Biwa (Japan) was dammed in 1906 and now provides the main source of tap water to Tokyo. In association with a trend towards a drier climate since 1970, Kumagai *et al*. (2002) reported a decline in efflux of 26 x 10^6 m^3a^{-1}. This being a deep lake, they expected the change to extend residence time and to reduce the intensity of vertical mixing, causing anoxia during warm winters. During a period of acute water shortage in the summer of 1994, the water level fell by 1.23 m and the September residence time increased from 2-4 years to approximately 7 years. A persistent change in phytoplankton composition dating from that event was reported by Ishikawa *et al*. (2002). The Myrkdalem Lake in western Norway was permanently drawn down by 1.4 m in 1987, and artificial islands were constructed on the dewatered ground. During the subsequent eight years, major changes in island vegetation were observed. Initial colonisers, such as acrocarpous mosses, were replaced after three years by wetland communities including *Carex rostrata*, *Carex vesicaria*, *Phalaris arundinacea* and *Salix nigricans*. However, since these communities resembled the marginal communities of the lake before drawdown, it appeared that the vascular plant communities had adapted swiftly to the new water level regime (Odland 1997).

3.2.4 Construction of dams and barrages

Needs for more intensive human use of water are usually approached by damming the outlet of a lake, or by damming a river, in order to achieve some degree of temporal control on water availability. Impoundment is often undertaken for water supply or power generation purposes, but may also be carried out at small scale solely to improve opportunities for recreational fishing. Although only a small portion of the lake's shoreline is affected directly, there are usually substantial changes in water level, the range and character of water level fluctuations, and the rate of throughflow; with implications for both hydromorphology and ecology.

3.2.4.1 Changes in water level

Major changes in the vegetation of lakes in west Connemara, Ireland, have been associated with fluctuations in water level coinciding with periods of drier and wetter climate, which appear to exert a much greater influence on plant communities than phosphorus inputs from surrounding agricultural land (van Groenendael *et al.* 1996). Since impoundment can give rise to much more abrupt changes in water level than those caused by climatic shifts, ecological impacts may be anticipated. The dam at Haweswater in the English Lake District was built in order to supplement the Manchester water supply. After its completion in 1941, the total rise in water level was 29 m, maximum depth had increased from 28 to 57 m and mean depth from 10.9 to 23.4 m; and the original basin contained only 16% of the total water volume. The changes are summarised by the depth-area curves shown in Figure 4. At an earlier stage of construction, the water level was raised by around 12 m and the area of the lake approximately doubled (from 138 to 283 ha). The proportion of shallow water also increased so that the average depth declined[2] by just over 9 m. During this period, Frost (1956) observed a general increase in annual growth rates of brown trout, especially during the first year after flooding, which he attributed to the associated enhancement of food availability. Karenge and Kolding (1995) observed a similar and more sustained tendency in Lake Kariba (Africa), where fish catches per unit effort showed high correlation and synchroneity with changes, and in particular rises, in water level; this was attributed to nutrient inputs associated with the supply of water to the lake. Hayes and Anthony (1964) attempted to clarify the interrelationships of physical and biological factors in lakes, and to provide a method for predicting fish production by constructing a series of regressions between a Fish Productivity Index and various more or less independent morphometric variables. They were able to demonstrate relationships of fish productivity with lake depth, as well as with lake area.

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[2] A similar effect has been observed at Loch Tummel in Perthshire, Scotland. Damming for hydro-power purposes led to an increase in maximum depth from 39 to 44 m, but mean depth was reduced from 14.6 to 10.4 m because impoundment created an extensive area of shallow water to the west of the former loch basin (Duck 1982).

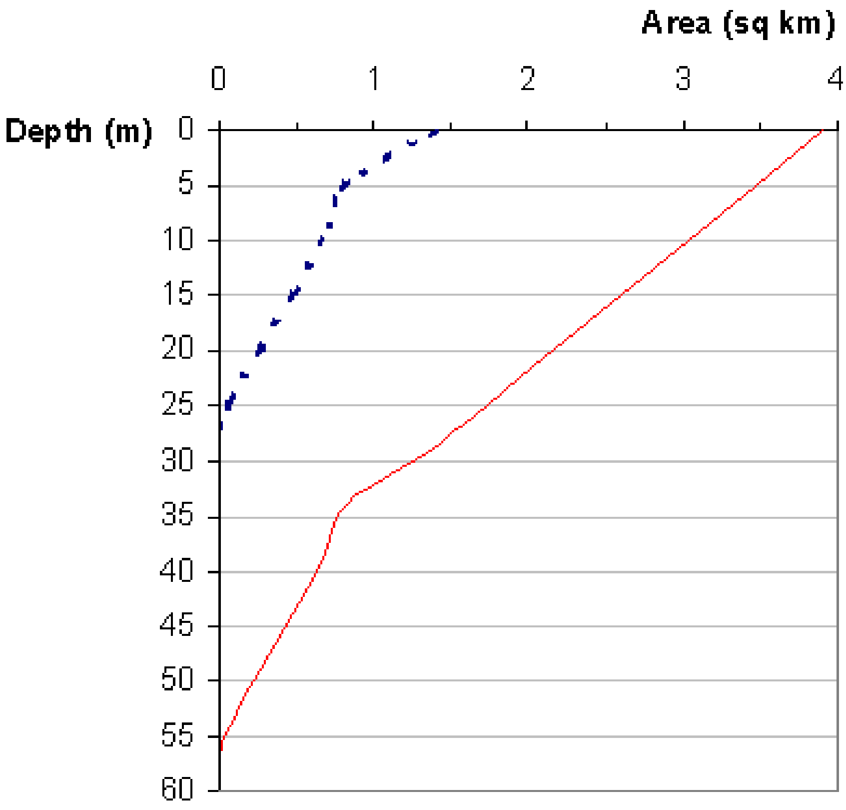

Figure 4 Relationships between contour area and depth (hypsographic curves) for Haweswater in the English Lake District, representing the natural basin (broken blue line) and the basin after dam construction (solid red line). Data from Ramsbottom (1976).

Effects of water level on other biotic groups have also been reported. De Emiliani (1997) compared aspects of phytoplankton community organisation in river and lake habitats in the Parana River system in Argentina. Whilst water level was the main factor controlling phytoplankton biomass in the river, the lake displayed an autogenic successional sequence during the isolation phase and responses to disturbance during flood. The macrophyte *Isoetes lacustris* (Quill-wort) declined rapidly below 3 m depth in Norwegian lakes due to low levels of daily insolation (Rorslett and Johansen 1995). However, in Lake Baciver, Spain, this species survived between depths of 5.8 and 6.1 m ten months after the water level had been raised by 5.5 m, responding to declining irradiance by producing fewer, longer leaves. The following spring, no new growth occurred and this was attributed to low oxygen levels at depth beneath winter ice (Gacia and Ballesteros 1996).

3.2.4.2 Changes in patterns of water level fluctuations

Changes in the character of water level fluctuations usually follow damming, with further direct and indirect consequences for ecology. At Lake Kinneret (Israel), it was already apparent in the 1970s that dam operation routinely stretched water level fluctuations beyond their natural range. Hambright *et al*. (1997) reported that low water levels tended to initiate a chain of physical, chemical and biological changes; the accompanying reduction of hypolimnion volume caused increases in the concentrations of the end products of organic decomposition, which in turn led to fundamental changes in phytoplankton composition and biomass after the autumn turnover.

Hofmann (1998) pointed out that water level fluctuations affect the size of the pelagic zone relative to the size of littoral habitats, and thus may influence the relative abundance of planktonic and littoral cladocerans in lakes. Mezquita and Miracle (1997) found historical evidence in sediment cores for alternation in the composition of chydorid assemblages of Lake La Cruz, Spain, which could be associated with water level variation. Very low and fluctuating water levels or reduced area of shallow water promoted *Pleuroxus laevis*, *Alona guttata* and *Graptoleberis testundinaria*, whereas more constant water level under conditions where a sublittoral zone may develop promoted *Chydorus sphaericus*, *Alona quadrangularis* and *Alona affinis*.

Effects on littoral communities are particularly well reported. The basis for this emphasis was outlined by Wilcox (1995), who noted that water level fluctuations are vital to the wetlands of Lake Huron because they perpetuate the cycling of successional processes and maintain wetland diversity. High lake levels periodically eliminate competitively dominant emergent plants. When levels recede, less competitive species are generally able to grow from seed or propagules, complete at least one life cycle, and replenish the seed bank before being replaced through competitive interactions. Magnitude, frequency, timing and duration are all important characteristics of the fluctuations for biota. Differences in magnitude translate to different depths of water and different habitats. Water level changes with a seasonal frequency are likely to have different effects from those induced by fluctuations with a frequency of a decade or longer; whilst infrequent, unpredictable fluctuations will result in greater diversity than regular annual fluctuations. Seasonal differences in the timing of water level declines will produce different results; low waters in spring allow more seed bank emergence than in summer and water level declines in winter can result in ice-induced sediment erosion. Stable water levels with little fluctuation during the growing season are likely to result in the establishment of stable shoreline plant communities, whilst unstable summer water levels cause variability in the vegetation. The duration of flooding thus becomes a controlling factor.

Hill *et al*. (1998) compared the shoreline vegetation of regulated and unregulated lakes in Nova Scotia. Plant communities of dammed systems were less diverse, contained more exotic species and were generally devoid of rare shoreline herbs; the optimum annual range of water level fluctuations for shoreline vegetation was considered to be 1-2 m. A similar comparison carried out in Finland indicated slightly higher diversity in littoral vegetation at the unregulated Lake Lentua than at the regulated Lake Ontojarvi, but that the difference was statistically insignificant. The authors concluded that the vegetation at Ontojarvi was well adapted to the ecological disturbance caused by water level fluctuations (Hellsten and Riihimaki 1996). Nilsson *et al*. (1997) assessed the long-term effect of water level regulation on riparian plant communities of storage reservoirs and run-of-river impoundments in Sweden. Soon after the onset of regulation, there were few species and sparse vegetation cover, regardless of whether the new water level intersected former upland or riparian vegetation. In the longer term, storage reservoirs maintained only impoverished vegetation; whereas in run-of-river impoundments, some community characteristics deteriorated and others recovered compared to adjacent free-flowing rivers.

Fraisse *et al.* (1997) evaluated macrophyte species for their suitability for re-vegetation of the margins of reservoirs with fluctuating water level. In general, tested species were able to survive both drought and immersion. Growth was more sensitive to substrate type than to water stress conditions, and immersion was a more severe constraint than drought. Eight suitable species were identified. In Norway, revegetation of the shores of reservoirs and impoundments was promoted by light fertiliser dressing but observation highlighted the need for nearby seed banks or refugia. Reducing the designated fluctuation range from 7 m to 1.6 m enabled recolonisation by submerged macrophytes (Rorslett and Johansen 1996). In similar vein, Arai (2001) reported that it was impossible for aquatic macrophytes to grow in Lake Kizaki (Japan) when water levels were reduced to 9 m below normal every winter. Expansion of the Flowering Rush *Butomus umbellatus* to form continuous stands in reservoirs with fluctuating water levels is promoted by low stages (shallow water) following summer drainage (Hroudova *et al.* 1996); whereas the ratio of root to shoot mass of the Bulrush *Scirpus ancistrochaetus* was shown in laboratory experiments to decline as the water level rose from 0 to 10 cm above the soil surface (Lentz and Dunson 1998).

Effects on fauna have also been reported. Hynes and Yadav (1985) reported the results of a 30 year study of the littoral fauna of the impounded Llyn Tegid in north Wales, whilst Humphries (1996) suggested that the influence of changes in water level on macrophytes might play an integral part in determining the abundance, richness and assemblage of invertebrates in a lowland Tasmanian river. A major impact of water level fluctuations on fish ecology operates through their effect on spawning habitat. Clark *et al*. (1998) modelled the effects of water level fluctuation at Brownlee Reservoir, Idaho-Oregon, on the reproductive success of smallmouth bass, *Micropterus dolomieu*. The most significant effect indicated was that of magnitude of water level fluctuations during the peak spawning period on egg-to-dispersal survival. The cyprinid *Thynnichthys thynnoides* spawned during periods of high water level which resulted in flooding of the littoral zone in a Malaysian reservoir (Ali and Kadir 1996). Similarly, in Pomme de Terre and Stockton Lakes, Missouri, intense spawning activity of gizzard shad (*Dorosoma cepedianum*) occurred during rising water levels, creating relatively few weekly cohorts of hatchlings. The distribution and initial abundance of larvae amongst weekly cohorts was also influenced by water level, as well as temperature (Michaletz 1997). Prokes and

Barus (1995) reported survival of fragments of a native population of nase (*Chondrostoma nasus*) after 17-18 years of diurnal water level fluctuations exceeding 10 m, following impoundment of a river section to create the Mohelno reservoir in the Czech Republic. Although the fish could reach full spawning condition, natural reproduction appeared to fail under this water level regime.

Hellsten *et al*. (1996) outlined procedures for setting water level targets to favour biota in lakes regulated for hydropower production in Finland. Ecologically based regulation practices (ERP) were based on underwater light climate and water level fluctuation data which made it possible to calculate the proportion of the frozen littoral to the total littoral area. Another procedure calculated biomass of benthic fauna from data on water level fluctuation and Secchi Disk depth.

Duigan *et al*. (1998) considered that the rate of water level changes was also significant to ecology, since sudden fluctuations do not allow time for flora and fauna to adapt or migrate as environmental conditions alter, and rapid changes in water level could expose fish redds to damage from wave action. McLachlan (1970) reported a related phenomenon in Lake Kariba, central Africa. Since 1963, when filling of Lake Kariba was complete, water level fluctuation has been an annual feature of the lake. Towards the end of the dry season (October/November) the flood gates are opened and the lake level is allowed to fall in order to make way for new water that will arrive from flooding rivers at the onset of the wet season. After re-closure of the gates, the lake level rises gradually until July, and then remains more or less stationary until October. Between 1963 and 1966 the maximum vertical fluctuation was 8 m. During these fluctuations, there were conspicuous cyclic changes at two gradually shelving areas that were exposed only at low water levels. No changes in water chemistry were recorded as the water level fell. At low water, a grass flush developed on the exposed flats and was heavily grazed by game animals. After inundation, grass and dung on the newly inundated flats began to decompose, causing lowered pH and dissolved oxygen values in the water; and marked increases in conductivity and the concentration of K^+. Although transient and restricted to gently shelving areas, this effect was thought to provide a valuable source of nutrients to the lake. Camargo and Esteves (1996) recorded increases in biomass of the macrophyte *Eichhornia azurea* growing in a tropical oxbow lake in response to a flood pulse which imposed substantial increases in nitrogen and phosphorus levels. Nogueira *et al.* (1996) found that floating stands of *Eichhornia azurea* and *Scirpus cubensis* were enriched by nutrients washed from flooded areas adjacent to the lake at high water levels, and thereafter derived nutrients released by decomposition of old plants directly from the water. By this means, maintenance of high biomass of the stands during the entire hydrological cycle was possible in a closed system with episodic flooding.

In Scotland, Smith *et al*. (1987) found that littoral macrophytes and zoobenthos communities were impoverished in lochs and reservoirs where regular water level changes occurred, even if their amplitude was quite small, as well as under conditions of large annual water level fluctuations. They concluded that rich littoral communities similar to those of lochs with natural water level regimes occurred in regulated lochs which had an annual water level range of less than 5 m and where weekly changes in water level were not greater than 0.5 m for 85-100% of the time. Impoverished communities occurred where either or both of these criteria was not met. Fluctuations of much greater magnitude may occur, for example as a result of the damming of large lochs for hydro-power generation. The waters of Loch Quoich are held back by a 38 m high rockfill dam which is the largest in Scotland (SHE undated). This is the main storage reservoir of the Garry/Moriston development, and discharges eastwards through Quoich power station and Loch Garry to Invergarry power station on Loch Oich, which lies in the Great Glen southwest of Loch Ness. Figure 5 compares the 1933 and 1993 annual hydrographs for Loch Quoich, showing that the annual water level range has increased from around 2 m to around 20 m as a result of impoundment. A similar comparison for the unimpounded Loch Oich is shown in Figure 6. In this case, it is noteworthy that there is a clear difference between the 1931 and 1991 hydrographs in that the latter oscillates much more rapidly than the former; presumably reflecting the effects of storage, compensation releases and power generation upstream.

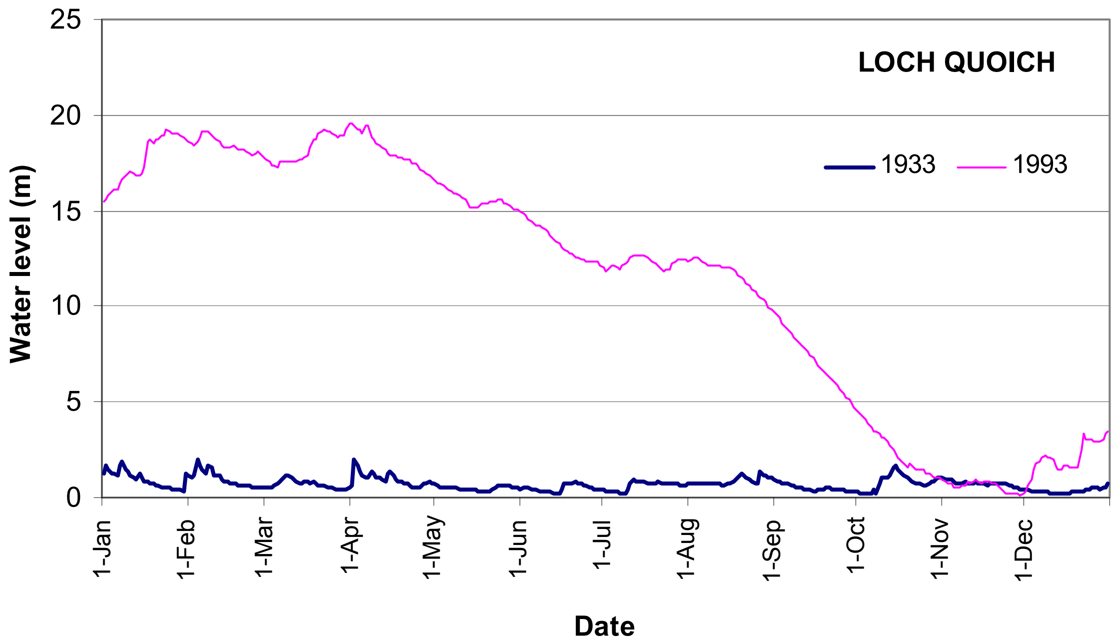

Figure 5 Comparison of annual hydrographs for Loch Quoich, Scotland, for 1933 (before damming for hydro-power generation) and 1993.

Water level records for the two years are not related to the same datum level.

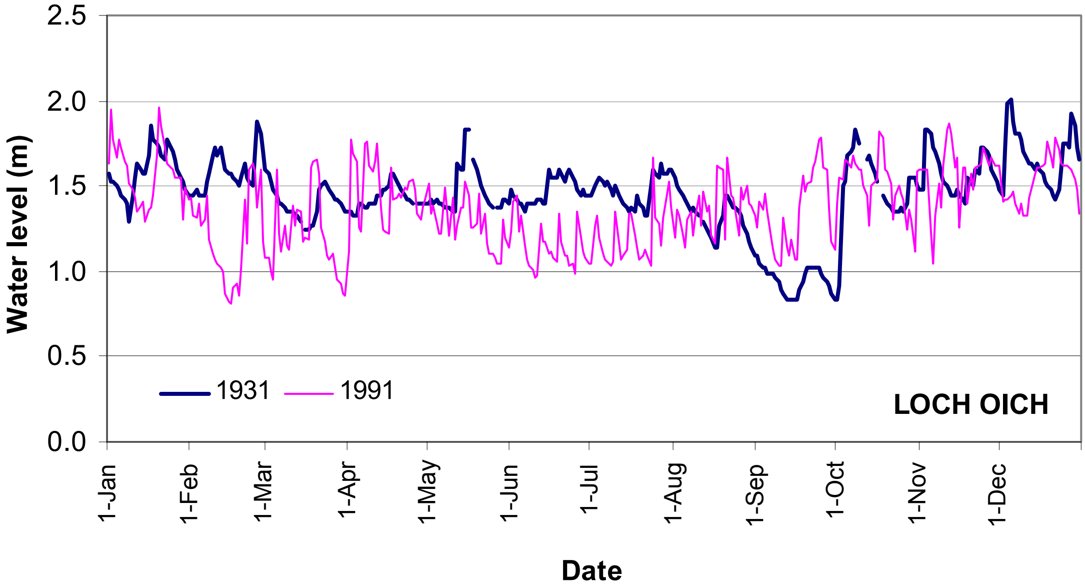

Figure 6 Comparison of annual hydrographs for Loch Oich, Scotland, for 1931 (before hydro-power generation) and 1991.

Datums have been adjusted so that 50%ile values coincide.

3.2.4.3 Changes in rate of throughflow

At Lough Inchiquin (Co. Clare, Ireland) Allott (1990) considered that washout became an important selective factor for phytoplankton when the instantaneous residence time (IRT) fell below 20 days. In the much larger Lake Kinneret (Israel), on the other hand, Gophen (2002) showed that the total biomass of phytoplankton was low under long (>5 years) monthly residence time and high when residence time was short (<1 year), and associated this with attendant variations in nutrient input rates. Dokulil and Teubner (2002) reported that phytoplankton communities in highly flushed Austrian and German lakes were more resilient to perturbations than those in shallow groundwater seepage lakes, whilst water quality was the most important controlling factor in run-of-river lakes.

Jørgensen (2002) proposed that the dynamics of the relationship between water and nutrient residence times and biota could actually be used to manage plankton population dynamics in reservoirs. If a shorter residence time was applied just before the spring or summer bloom of phytoplankton and/or just before the spawning period of planktiverous fish, a significant reduction in primary production could be achieved. Thus, control of seasonal residence time could be a cost effective means of controlling eutrophication. On the other hand, Boavida *et al*. (2002) found no significant relationship between eutrophication and residence time in more than a dozen reservoirs on the River Tejo in Portugal and suggested that the manipulation of residence time might be a less useful tool for reservoir management than was originally imagined.

James *et al*. (2002) investigated the influence of hydro-electric power generation on the biota of two lakes on the central volcanic plateau of North Island, New Zealand. Lakes Rotoaira and Taupo have been used to provide storage for hydro-electric schemes since the late 1970s. Water is diverted from other catchments into Lake Rotoaira and eventually through Lake Taupo to the Waikato River and its 9 power stations. The diversion has altered the residence time in Lake Rotoaira from 247 days to an average of 28 days (actually 2 basins with residence times of 32 and 5.7 days) and in Lake Taupo from 13 to 11 years. Mean phytoplankton biomass had not changed significantly but the frequency of major algal blooms had declined and the assemblage had shifted towards domination by diatoms. The main change in abundance of zooplankton groups was an increase in the rotifer component. The authors suggested that this was a response to the change in residence time as these taxa are "R" selected, i.e. they have high growth rates, can respond rapidly to changes in food concentrations and have short generation times (days). Changes to the physical habitat structure (oxygen and temperature) through new diversion inputs and underflows were also important to the spatial distribution and productivity of plankton, and these effects might potentially offset the impact of shorter residence time.

3.2.4.4 Effects on sediment dynamics

Wilcox (1995) notes that lake level changes greatly affect sedimentology, both through net erosion and net deposition at specific sites and through changes in transport mechanisms. Waves from storms that occur during periods of high lake levels can erode materials not accessible at low stages and increase the load of sediment transported in the littoral drift. At low lake levels, sediments are exposed and thus susceptible to transport by wind. Some of these effects also appear elsewhere in the literature. Lake Blåsjőn, in northern Sweden, has been influenced since 1947 by artificial water level fluctuations with an annual amplitude of 6 m from 1949 to 1957 and 13 m since 1957, the latter regime exposing approximately 22% (8.8 km^2) of the total bottom area of the lake during winter. In consequence, freezing of sediments and fauna occurs, and parts of the profundal zone come under the influence of abnormally low winter temperatures. Grimås (1962) reported powerful erosion of the littoral zone during periods of drawdown, and that spring meltwater was an important factor. Sampling of bottom sediments indicated addition of fine sediments to the 6m drawdown zone and their removal from the newly exposed 6-13 m zone, and export of minerogenic material (sand) from the new littoral to the gyttja (organic-rich) zone below the drawdown limit. Landslides in the bottom deposits were also observed. Kumon (2001) studied sediments in Lake Kizaki in Japan. The lake operates as a hydro-power system which reduces the water level by 2.4 m. The distribution of bottom sediments showed a distinct pattern, with the finest (clayey) sediments covering the central part of the basin below 20m depth, and progressively coarser sediments (silt, sand and gravel) arranged in zones parallel to the shoreline. Abraham *et al*. (1999) speculated that the distribution of sediment types within reservoirs may differ from those of natural lakes because reservoirs have a component of riverine hydrodynamics, and greater drainage area to surface area ratio. They studied sediment distributions in seven Texas reservoirs, and found sand and gravel-size sediments in the deeper regions of some of them. This was inconsistent with the classical morphometry (water depth, slope) controlled sediment distribution pattern of natural lakes, with coarser sediments in shallower regions and finer sediments in deeper regions. They concluded that the distribution of sediment types in reservoirs cannot be defined or predicted merely by morphometric variables but needs to be evaluated in terms of the contributing sources of sediment. Butcher *et al*. (1992, 1993) reported the discolouration of water supplies from reservoirs in the southern Pennines (England) arising from trapping of peat eroded from the surrounding moorland.

3.2.5 Shoreline modification

Pieczyńska (1976) points out that the littoral zone is a highly differentiated environment, mainly due to the distribution of macrophytes, and that the zone that is largely controlled by water level fluctuations is especially distinct. The littoral communities are strongly related to one another due to the mechanical exchange caused by wave action, but on the other hand can function independently. Thus the littoral zone contains subsystems which are self-regulated and variously connected with the neighbouring ones, so that the shore zone is highly sensitive to changes in shoreline structure, water level, and the pattern of water level fluctuations associated with human activities. Thus, *ad hoc* attempts to protect individual sections of shoreline from erosion by current and wave action can simply shift the problem to another down-drift location, as reported for Loch Lomond by Hansom and McGlashan (2000). Moreover, when the water level is drawn down, the shoreline may be exposed to wind erosion; at Lake Bolsena in central Italy (see Section 3.2.3 for pressures), Fantucci-Montefiascone (2002) reported loss of 1-1.2 m of soil, often exposing 70-80% of the root systems of *Populus nigra* trees.

Direct modification of the shoreline is undertaken for a variety of reasons; for example in association with buildings, roads and railway lines (artificial embankments,bridges and reinforcement), to prevent erosion, and to enable access to the water (quays, harbours and jetties). Such activities alter not only the nature of the substrate, perhaps replacing soft sediments with hard substrates such as brick or concrete, but also the profile of the shoreline. Damming imposes a similar effect but on a very short section of the shore; although the implications for the whole lake are far-reaching in that the level of the entire shoreline is thus raised by anything up to several metres.

3.3 Overview of pressures and hydromorphological changes

Tables 3 and 4 summarise the principal human pressures on lakes and their catchments identified in Section 3.2, the resulting impacts on the WFD hydromorphological quality elements and, where available, on biota.

Table 3 Summary of human pressures on lakes, and the resulting impacts on hydromorphology and biota.

PRESSURES	ACTIVITY	IMPACTS ON LAKE HYDROMORPHOLOGY	IMPACTS ON BIOTA
Agriculture	Clearing natural forest; increase in sheep stocks	Increase in sedimentation rate; change in composition of sediment load	Decrease in photosynthetic rates; degradation of lake bottom habitats
Forestry; timber harvesting	Ploughing, drainage, harvesting	Increase in suspended sediment production and lake sedimentation rate	Decrease in photosynthetic rates due to increased turbidity
Military activities	Army training using live ammunition	Disintegration of shoreline peat rafts	Loss of shoreline communities
Recreation	Hill walking, power boating, angling	Erosion of shoreline and paths; trampling of wetland	Loss of shoreline communities
Road building	Construction; culverting of lake outflow	Accelerated catchment erosion and lake sedimentation rates	Retreat of reed fringe; decrease in photosynthetic rates
Urbanization	Urban development Sewage discharge	Increase in sedimentation rate and suspended sediments Increase in sedimentation rate due to increased deposition of persistent algal remains	Increase in algal growth rate Emergent macrophytes (*Typha, Phragmites*) favoured
Mineral exploitation	Mining; gravel extraction from lake bed	Changes in sediment deposition and distribution patterns	Degradation of fish spawning grounds
Navigation	Dredging	Increase in water depth and turbidity	Siltation of fish spawning grounds
Upstream water use	Change in inflow rate	Change in water level	Phytoplankton favoured
Water supply	Direct water abstraction from lake Groundwater abstraction	Increase in residence time Change in rates of exchange between lake and groundwater; change in water quality (e.g. salinity)	Changes in plankton populations; increases in frequency of algal blooms
Hydro-power generation (water supply)	Water diversions Damming	Reduction in residence time See Table 4	Decline in frequency of algal blooms; changes in plankton populations See Table 4

Table 4 Summary of effects of damming on lake hydromorphology and biota.

IMPACTS ON LAKE HYDROMORPHOLOGY	IMPACTS ON BIOTA
Increase in area and depth	Increased fish productivity
Change in outflow rate leading to change in water level	Phytoplankton favoured
Permanent changes in water level, maximum and mean depths	Succession in marginal plant communities
Rise in water level	Reduced growth of submerged macrophytes
Low water levels (reduced hypolimnion volume)	Changes in phytoplankton populations; cyanobacterial blooms.
Change in character and rate of water level fluctuations (leading to changes in relative sizes of littoral and pelagic zones and changes in sediment deposition patterns)	Changes in littoral macrophyte and zoobenthos populations; changes in invertebrate communities; changes in fish spawning success
Altered residence time	Changes in phytoplankton populations: <20 days flushed out; <1 year high biomass and populations resilient; >5 years low biomass

In general, pressures operating on the catchment's land area influence lake hydromorphology by altering sediment loads, whilst those focusing on use of the water itself affect hydrology as well as morphology. Changes in individual WFD hydromorphological quality elements rarely occur in isolation, and some of the effects on biota operate indirectly by influencing other physical and chemical factors such as light levels (and thereby photosynthetic rates), temperature and water chemistry.

4. ASSESSMENT METHODS FOR LAKE HYDROMORPHOLOGY

4.1 Introduction

This Section reviews information given in the literature on methods that have been used to measure the hydromorphological attributes of lakes, in order to provide a basis for their evaluation for WFD purposes. Where appropriate, the material is organised according to the hydromorphological conditions specifically listed by the Directive (Section 1.3). However, some approaches that cover combinations of these conditions are described separately.

4.2 Hydrographic survey

Lake morphometry involves a detailed analysis of the form of the lake and estimation of the total water volume. The hydrographic chart gives an accurate depiction of the shoreline, the positions of islands and bars, and a sufficient coverage of the water area to accurately locate and record depth soundings. Once depth contours have been constructed at regular intervals, the hydrographic chart becomes a bathymetric chart which details the spatial variation in depth of the lake (Petts and Foster 1985). Håkanson (1978, 1981) gives a detailed description of the approach and indicates how data collection can be optimised.

At the turn of the last century, Grant Wilson (1888) completed bathymetric surveys of the chief lochs of Perthshire (Earn, Rannoch, Tay and Tummel), Scotland. Perhaps stimulated by Grant Wilson's pioneering work (Duck 1990) Sir John Murray directed a survey of 562 Scottish lochs, including all the major water bodies of Scotland, between 1897 and 1909 (Murray and Pullar 1910). The Murray and Pullar surveys were conducted from rowing boats along traverses between known end points. Water depths were determined by means of a lead-line running through a winch system which recorded on a dial the length of line paid out. Uniform spacing of soundings was achieved by measuring the depth after every 30 pulls by the oarsman; and the locations of soundings were fixed by sextant in some situations and in others by direct lines of sight on prominent shoreline features (Duck and McManus 1985). Similarly, the the first bathymetric maps for Llyn Idwal and Llyn Cwellyn in Snowdonia, Wales, were constructed in 1902 from a series of soundings made using a colour-coded cord attached to a 5 lb lead weight (Duigan *et al*. 1998). The bathymetric charts produced using such methods form an important baseline with which to compare contemporary observations. However, depths measured using the lead-line method are subject to over-estimation. For example, the sounding line may fall at an angle as the boat drifts in the wind; or the weight may sink into soft sediments on the loch bed, such as the gelatinous mud that occupies the centres of loch basins in Scotland (Duck 1982).

Modern hydrographic survey techniques afford substantial improvements in speed, precision and detail. The electronic echo-sounder yields a continuous record of water depth beneath a motor-propelled survey vessel, whilst a variety of methods are used to fix the locations of soundings. Panosso *et al*. (1995) carried out a bathymetric survey of Lake Batata, an Amazon floodplain lake in Brazil, as part of an environmental impact assessment of disposal of bauxite tailings. The survey was carried out at low water level in December 1992, using a high-frequency (208 kHz) echo sounder and completing 63 transects running approximately perpendicular to the longest axis of the lake. Allott (1990) hand-drew bathymetric maps for five lakes in Co. Clare, Ireland[3] from depth data gathered by making multiple (8 to 20 depending upon the size of the loch) transects between identifiable landmarks taken from enlargements of published 1:10,000 scale ("six-inch") maps, and recording depth with a "Seascribe" echo sounder at constant intervals of time. The depth measurements were made during dry, calm weather in 1985 when water levels were low; lake levels were not referenced to Ordnance Datum. The bathymetric maps of 13 Scottish lochs[4] presented by Duck and McManus (1985) and Lowe *et al*. (1991a) were produced using Kelvin Hughes MS 26 and Lowrance X-15M echo sounders, which permitted marks corresponding with position fixes to be electronically inscribed on the echograms. In most of these surveys, position fixing to within 2m was achieved using a Motorola Mini-Ranger Mk.III system which measured the distance of the vessel from two VHF transmitters at known stations onshore simultaneously up to 10 times per second. The bathymetric resurvey of Loch Muick, Aberdeenshire (Lowe *et al*. 1991a,b), produced by recording echo-sounder coupled with radio position fixing, is believed to have resulted in the most detailed bathymetric chart so far produced for a loch in Scotland. Today, differential geographical positioning systems (DGPS) are used to provide positional accuracy at the centimetre scale.

Once constructed, the bathymetric chart can be used to derive hypsographic curves, which illustrate elements of the form of the lake basin. The hypsographic (depth-area) curve is constructed by plotting depth on the negative y-axis and cumulative area on the positive x-axis (e.g. Lowe *et al*. 1991a; see also Figure 4); the percentage hypsographic curve shows percentage cumulative area versus depth; and the relative hypsographic curve shows both cumulative area and depth as percentages. Such a curve provides an illustration of the form of the basin and is the basis for the definition of the lake form concept (Håkanson, 1977b). The mean lake form, denoted by $f(\bar{x})$, signifies that there is a 50% chance for an unknown lake to have a relative hypsographic curve above

[3] Loughs Inchiquin, Ballycullinan (north and south basins), Cullaun, Dromore, and Black.

[4] The water bodies mapped were Backwater Reservoir and Lochs Benachally, Butterstone, Drumellie, Earn, Lindores, Lintrathen, Lubnaig, Tay and Tummel (Duck and McManus 1985), and Lochs Lee, Muick and Callater (Lowe *et al*. 1991a).

(i.e. on the convex side) or below (i.e. on the concave side) of the f($\bar{x}$) curve. The statistical deviation forms corresponding to ± 0.5, ± 1.0, ± 1.5, ± 2.0 and ± 3.0 standard deviations are denoted f(± 0.5), f(± 1.0) etc. A schematic bathymetric description of four different lake forms is given in Figure 7. A lake with a relative hypsographic curve of the type f(-3.0) has one, or more, spatially limited deep hole(s) but is generally very shallow. By contrast, a lake of the type f(3.0) is trough like with steeply inclined walls and a flat, spatially-dominant bottom. Terminology and class limits are illustrated in Figure 8 and Table 5. The latter also includes a listing of the probability of occurrence of the various lake forms.

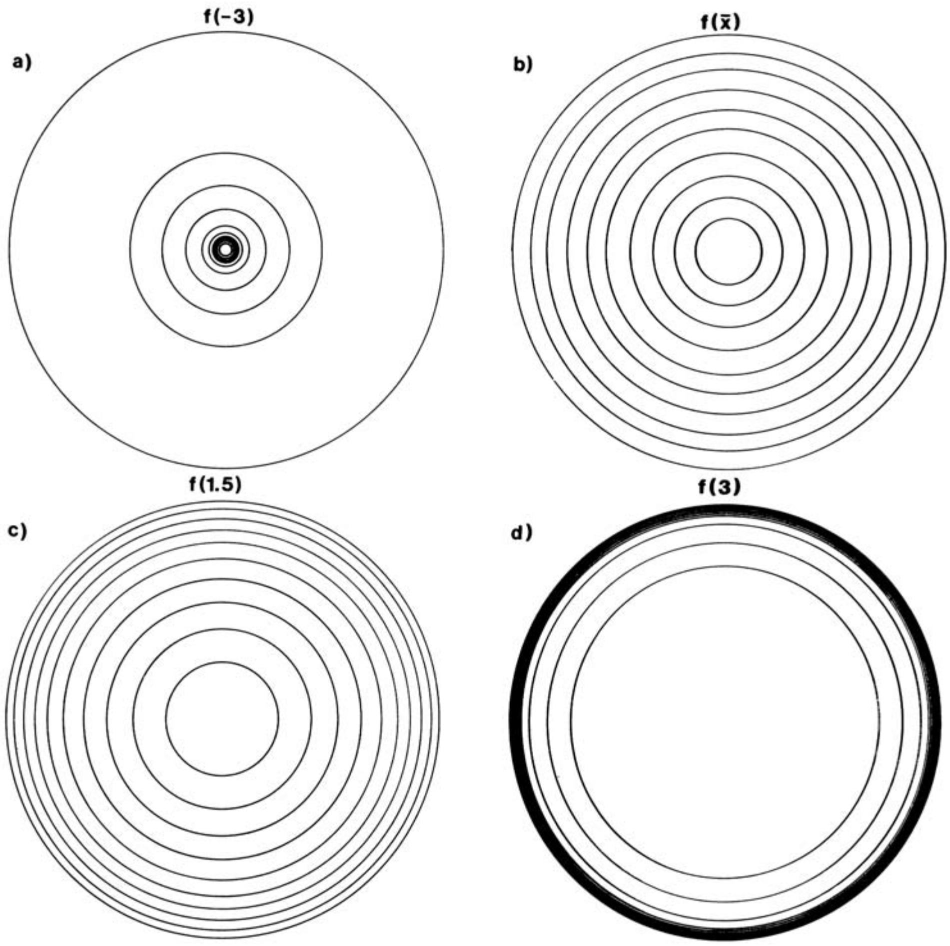

Figure 7 Schematic bathymetrical interpretation of four statistical lake forms, from Håkanson (1981).

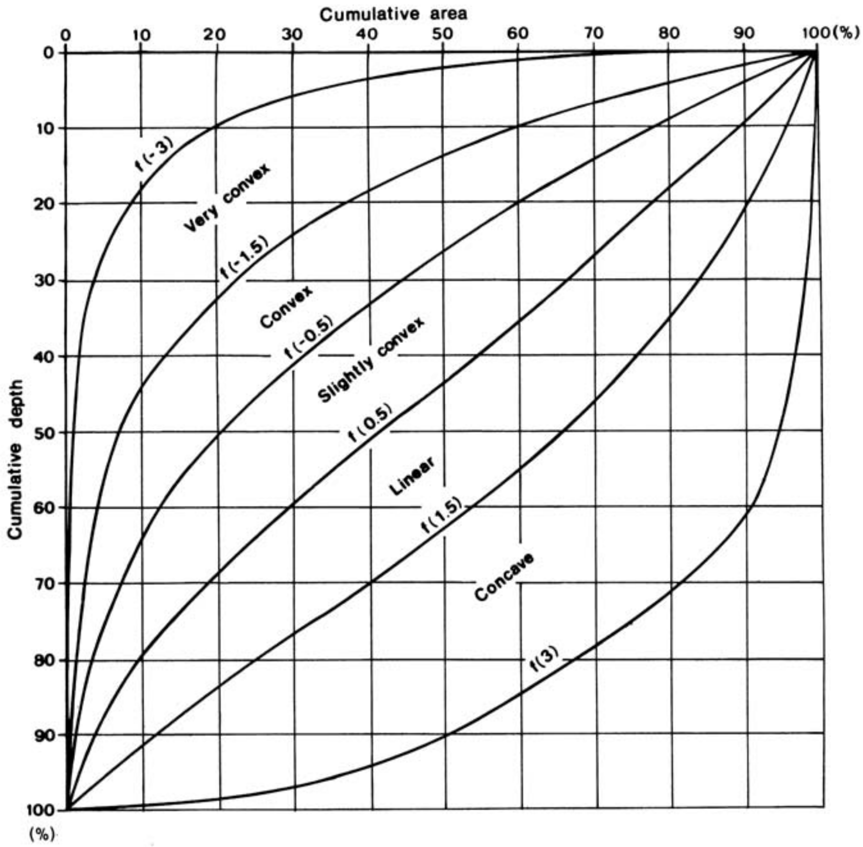

Figure 8 Terminology and class limits for the classification system of lake forms, from Håkanson (1981).

Table 5 Terminology, class limits and probability of occurrence of the various lake forms, modified from Håkanson (1981).

Class Limits	Lake Form Name	Probability (%)
f(-3.0) – f(-1.5)	Very convex	6.5
f(-1.5) – f(-0.5)	Convex	24.2
f(-0.5) – f(0.5)	Slightly convex	38.3
f(0.5) – f(1.5)	Linear	24.2
f(1.5) – f(3.0)	Concave	6.5

The bathymetric chart and hypsographic analysis can, in turn, be used to derive a range of "morphometrical parameters" of the lake (Table 6). Håkanson (1981) gives detailed manual methods for determining these parameters but many of them might now be determined using GIS techniques.

Table 6 Morphometric information that can be derived from bathymetric charts, after Håkanson (1981).

Parameter	Symbol, formula	Description
Maximum length	L_{max}	Length in km of the line (which may be curved) connecting the two most remote points on the shoreline. Descriptive, of limited limnological use.
Maximum effective length	L_e	Length in km of the straight line connecting the two most distant points on the shoreline over which wind and waves may act without interruptions from land or islands. Important in limnological and hydrological contexts, e.g. internal seiches.
Effective length	L_s	Length in km of the straight line from an arbitrary position on the lake to the most distant point on the shoreline without crossing land or islands
Effective fetch	L_f	A more representative measure than L_s of how wind governs waves, taking into account several wind directions. Derived using a transparent overlay. Important in relation to beach morphology and bottom sediment dynamics.
Maximum width	B_{max}	Length in km of the straight line perpendicular to maximum length which connects the two most remote extremities on the shoreline without crossing land (may cross islands). Primarily of descriptive value.
Maximum effective width	B_e	Length in km of the straight line perpendicular to maximum effective length which connects the two most distant points on the shoreline without crossing land or islands.
Mean width	$B_{mean} = a / L_{max}$	Ratio of lake area to maximum length.
Maximum depth	D_{max}	The greatest known depth of the lake in m.
Mean depth	$D_{mean} = 1000\ V / a$	The quotient of lake volume (V in km^3) to lake area (a in km^2), expressed in m.
Median depth	D_{50}	Derived from the hypsographic curve; 50% of the lake area lies below, and 50% above, D_{50}. Can be used to determine roughness of the lake bottom.
Quartile depths	D_{25} , D_{75}	25% of the lake area lies below D_{25}; 75% of the lake area lies below D_{75}.
Relative depth	$D_r = (D_{max} \sqrt{\pi}) / (20 \sqrt{a})$	The ratio of maximum depth to mean diameter of the lake
Direction of major axis		The general compass direction of L_{max}
Shoreline length	l_o	Length of shoreline in km, measured on the bathymetric map.
Contour-line length	l_i	
Total length (normalized) of contours	L*	Used to determine lake bottom roughness R
Total lake area	A	The area in km^2 of the lake including all islands, islets and rocks within the limits of the shoreline.
Lake area	a	The area in km^2 of the water surface
Volume	V	Derived using linear or parabolic interpolation between depth contours.
Slope; mean slope; median slope	α ; α_{mean} ; α_{50}	The slope for a station in the lake, derived from the echogram. Derived for the entire lake area from normalised contour lengths. Signifies that 50% of the lake area is steeper, and 50% less steep.
Shore development	$F = l_o / (2\sqrt{(\pi A)})$	The ratio of shoreline length to the circumference of a circle of the same area.
Lake bottom roughness	$R=(0.165(l_c+2)\sum l_i)/(D_{50}\sqrt{a})$ where l_c is the contour interval and $\sum l_i$ is the sum of lengths of all contours	A measure of the degree of irregularity of the whole lake floor.
Form roughness	$R_f = (0.165\ (l_c+2)\ \sum l_i) / a$	Used to quantitatively compare topographical irregularity between different parts of lake floor.
Volume development	V_d	Quotient of lake volume (= a x D_{mean}) to the volume of a cone with base area a and height D_{max}.
Insulosity	$I_n = 100A_i / A$	The percentage of total lake area occupied by islands.
Slope curve		Plot of slope (y-axis) against cumulative area (x-axis)
Hypsographic curves / volume curves		Plots of depth (negative y-axis) against cumulative area / volume; either or both variables may be expressed as absolute values or percentages, for different purposes.
Lake form		Defined by the relative hypsographic curve.

Håkanson (1981) evaluated all of the parameters listed in Table 6 for Lake Vanern (Sweden), and other authors have evaluated sub-sets for various purposes. Gunkel *et al.* (1984) calculated a shoreline development ratio of 1.5 for the nearly circular Eau Galle Lake in Wisconsin. Allott (1990) derived area, perimeter, mean depth etc., and reed coverage from his bathymetric maps, field notes and air photographs. Areas, perimeters and lengths were measured on digitised drawings of the lakes using Autocad (Autodesk Ltd) and a TDS LC series digitiser. Volumes were estimated by measuring the area under hypsographic curves, again using Autocad. Of particular note is his comment that mean depth can be highly sensitive to the decision taken as to whether or not reed beds should be included in the lake area. Panosso *et al*. (1995) used their survey data to construct a bathymetric map, and to calculate total lake area (A), volume (V) and shoreline length (l_o). They then derived eight of the morphometric parameters listed in Table 3 (F, D_{max}, D_r, D_{mean}, V_d, L_e, B_e, L_f) and the relative hypsographic curve. This enabled them to derive the variations in area and shoreline length that corresponded to the observed seasonal range of water level fluctuations. For Lake Batata (mean water depth 2.19 m), the seasonal water level range of around 7 m caused the area of the lake to vary from 18.02 to 30.17 km^2, with correspondingly large changes in shoreline length. Lowe (1993) attempted to quantify the geomorphological variations within Loch Muick in northeastern Scotland by using bathymetric data to map the distribution of form roughness (R_f in Table 6). The results (Figure 9) were influenced by the size of the base map squares used in the calculation, but did indicate differences in R_f between four zones identified from the bathymetric chart. Moving eastwards from the soutwestern end of the loch, these were a smooth basin (low R_f), an area of mounds and hollows (highest R_f), an area with six broken ridges (high R_f) and an area of minor mounds and hollows with amplitude <2 m (relatively low R_f).

Thus, bathymetric maps yield comprehensive data on the size and shape of the lake basin. Moreover, once the bathymetric chart has been constructed, it can be used not only to derive morphometrical parameters of the lake but also to gain insights into thermal stratification and turnover processes, which in part control the efficiency with which the lake traps inflowing sediments (Petts and Foster 1985; see also Section 4.7). Within Britain, fairly comprehensive exploration of freshwater lakes has been achieved for Scotland (Murray and Pullar 1910) and for the Cumbrian Lake District (Ramsbottom 1976). In order to quantify changes due to human pressures, however, repeat survey is necessary to enable comparisons with the baseline. There have been few re-surveys of Scottish lochs, with the notable exceptions of Loch Leven (Kirby 1971) and Loch Morlich (Brown and O'Sullivan 1975) in addition to those listed in Footnote 4 of this report. Repeat surveys appear to be even scarcer for lakes elsewhere in the British Isles; although Duigan *et al*. (1998) report two re-surveys of Lake Idwal in Wales (Ferrar 1961, Brathay Exploration Group 1971) following the 1902 baseline work. For Ireland, there is scope to utilise information from the unpublished dataset on lake morphology, lake retention times and catchment land use pressures collected by Irvine and Mills (K. Irvine, pers comm.).

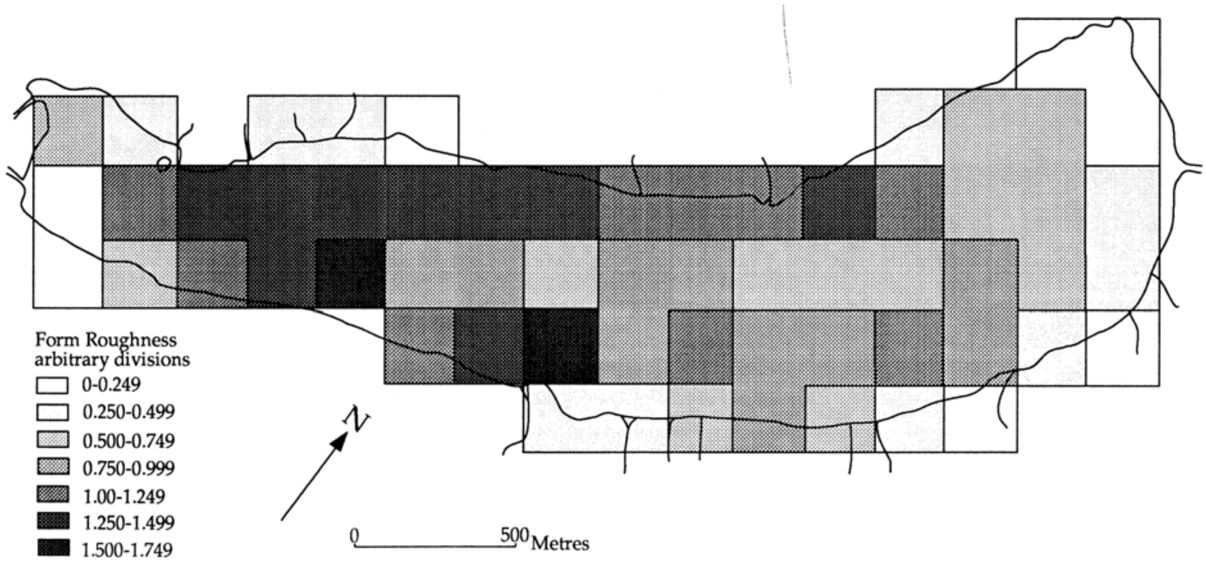

Figure 9 Map of Håkanson's Form Roughness (R_f) for Loch Muick, from Lowe (1993).

4.3 Predictive limnology

Håkanson and Lindström (1997) point out that only a sample of even the 83,000 lakes in Sweden, let alone the world population, can be investigated in detail, so that there is considerable interest in using data collected for the sample to derive empirical models that can be used to predict otherwise inaccessible characteristics of other lakes. For lake morphology, an early contribution can be found in the work of Gorham (1958), who used the Murray and Pullar (1910) data to examine inter-relationships between drainage area, lake surface area, length, mean breadth, mean depth and maximum depth for 262 rock basins and 137 basins lying in or dammed by glacial drift (Figure 10). Significantly in the present context, he derived regression lines that relate mean depth to lake area for these two classes of lochs. The relationship was very clear (r = 0.68) for the rock basins, but much less so (r = 0.24) for the drift basins. George and Maitland (1984) revisited this approach. They identified 1577 bodies of standing water in Shetland from maps, and classified them on the basis of altitude, area, inflow and outflow streams, distance from the sea, highest point in catchment, catchment area and geology. Groups of lochs were then selected at random for field survey, and 65 were visited. Basic physical characteristics including area, catchment area, altitude, mean and maximum depths and retention time were recorded, and inter-relationships between loch dimensions were explored. The slope of the depth/area relationship for the Shetland lochs was similar to that quoted by Gorham (1958) for Scottish rock basins, and was shown to hold even for small pools. However, the data indicated that lochs formed in Shetland drift tended to be shallower than average and the rate of subsequent sediment accumulation was relatively low.

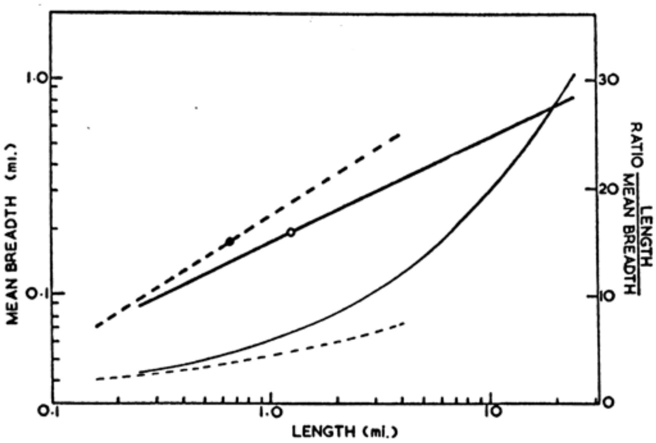

Fig. 1. The relation between length and mean breadth in Scottish lakes. The heavy solid line represents rock basins and the heavy dashed line drift basins, with the circles marking the log means. The lighter lines represent the ratio of length to mean breadth.

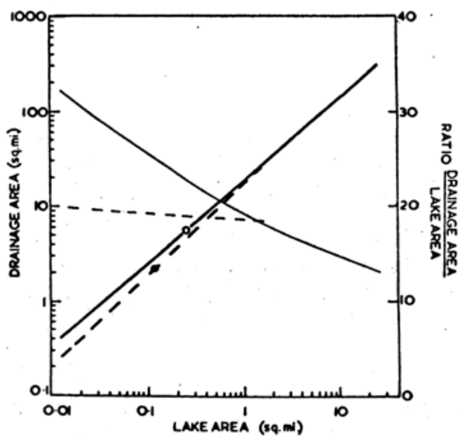

Fig. 2. The relation between drainage area and lake area. The heavy solid line represents rock basins, heavy dashed line drift basins, and circles log means. Ratios are given by lighter lines.

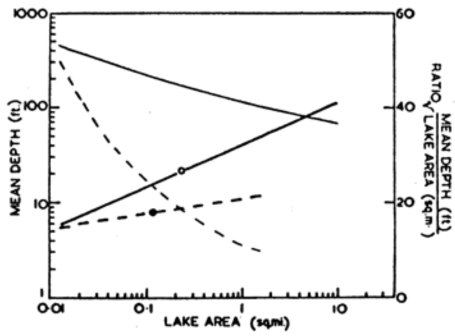

Fig. 4. The relation between mean depth and lake area. The heavy solid line represents rock basins, heavy dashed line drift basins, and circles log means. Ratios are given by lighter lines.

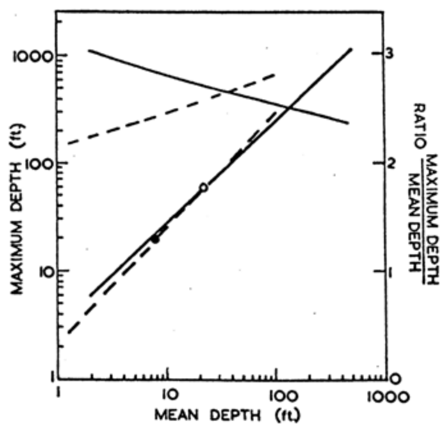

Fig. 6. The relation between maximum and mean depth. The heavy solid line represents rock basins, heavy dashed line drift basins, and circles log means. Ratios are given by lighter lines.

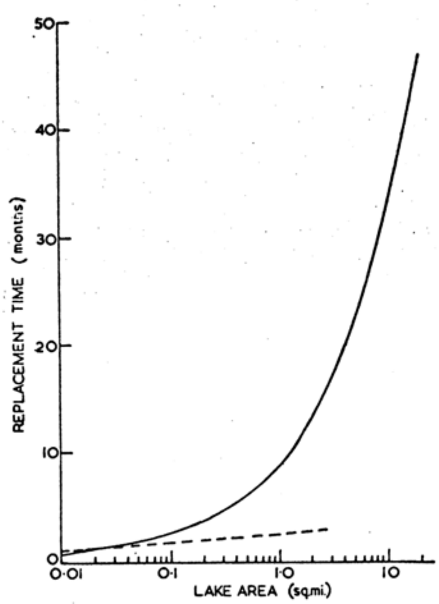

Fig. 8. The time required for complete water replacement within a lake, as a function of lake area. The solid line represents rock basins, the dashed line drift basins.

Figure 10 Some hydromorphological relationships derived by Gorham (1958) from the bathymetric data of Murray and Pullar (1910).

Håkanson (1997) and Håkanson and Lindstrőm (1997) used three registers of data for Swedish lakes to investigate possibilities for building empirical predictive models. They contend that the results should be widely applicable, since glacial lakes are the most common lake type on Earth, and the Swedish examples cover a wide range of geographical, geological and climatological characteristics. This work may well be relevant to the lakes of Scotland, the English Lake District and the Welsh uplands, in view of their similar origins; most of these fall into Hutchinson's categories 4b (glacial rock basins), 4c (moraine and outwash basins) and 4d (drift basins) (Table 1).

Håkanson and Lindström (1997) presented comprehensive datasets for a battery of practically useful standard lake variables from more than 900 Swedish lakes. The use of 12 water variables (pH, total-P, colour, hardness etc.), 13 catchment area characteristics (bedrocks, soils etc.) and 17 lake morphometric features (size and form parameters) in compiling empirical predictive models was demonstrated. Amongst other variables, Håkanson (1997) determined a range of standard morphometric quantities from bathymetric maps, such as V, a, A, D_{mean}, B_{mean}, D_r, F (Table 6) and dynamic ratio ($D_R = (\sqrt{\text{area}})/D_r$), applied transformations to yield approximately normal frequency distributions where appropriate, and used a simple statistical analysis to test inter-relationships. Two relatively independent clusters of morphometric parameters were identified; those indicating size (e.g. volume and area) and those related to form (e.g. relative depth and dynamic ratio). A useful outcome of this work is a method by which mean depth, maximum depth and other morphometric parameters can be predicted using information that can be obtained from topographical maps (Table 7).

Similar approaches have been developed independently in America, giving rise to some additional morphometric parameters with relevance to ecology. Riera *et al*. (2000) set out to test the degree to which a lake's landscape position constrains the expression of limnological features and imposes a characteristic spatial pattern in the Northern Highland Lake District of north-central Wisconsin. The concept of lake order was employed to reflect the type and strength of the connections between each lake and the surface drainage network. For lakes with both surface inlets and outlet, lake order was defined as the order (Strahler 1964) of the stream that drained the lake, derived from 1:100,000 scale maps. Headwater lakes (without inlets) were assigned lake order 0. Lakes connected to the surface drainage network by temporary streams or streams of very low flow were assigned lake order –1. Those connected to the drainage system by a wetland without channelized flow were assigned order –2, and closed-basin lakes that were not connected to the drainage network by surface water were assigned order –3. Thus, lake order was expressed as a metric based solely on geographical information. It was strongly related to lake size and shape, concentrations of major ions and three biological variables (chlorophyll-a concentration, crayfish abundance and fish richness). In particular, lake area, shoreline length and the shoreline development factor[5] $SDF = P/ (2\sqrt{(\pi A)})$ where P is lake

[5] Equivalent to Håkanson's shore development parameter.

perimeter and A is lake area, increased with lake order. Lakes high in the landscape tended to be numerous, small and circular; whilst lowland lakes were less common, large, and tended to have convoluted shorelines. Hondzo and Stefan (1996) explored the Minnesota Lakes Fisheries Database, which contains lake survey data on 22 physical variables and all common fish species for 3,002 lakes. They ascertained that nine primary variables explained 80% of the variability amongst lakes; namely surface area A_s, volume, maximum depth H_{max}, alkalinity, Secchi Disk depth, lake shape, shoreline complexity, percent littoral area and length of growing season. They then divided the lakes into three classes according to lake geometry ratio, $A_s^{0.25}/H_{max}$. At lake geometry ratios above 8 the lakes were well-mixed or polymictic. At values below 2 they were seasonally stratified or dimictic and had low dissolved concentrations near the bottom in summer. There was a transition region between the two values.

Table 7 Definitions and formulae for lake morphometric parameters, after Håkanson (1997).

Parameter (units)	Abbreviation	Derivation
Lake area (km^2)	A	From topographical maps
Altitudinal range of drainage area (m)	dh	From topographical maps
Drainage area (km^2)	ADA	From topographical maps
Relief of drainage area (dimensionless)	RDA	RDA = dh / (√ADA)
Lake volume (km^3)	V	Log(1000*V) = 0.134 + 1.224*log(A) + 0.332*log(RDA)
Mean depth (m)	D_{mean}	D_{mean} = 1000 * V/A
Maximum depth (m)	D_{max}	$\mathrm{Log}(D_{max}) = -4.202 + 4.558*(1000*V)^{0.1} - 1.008*\log(A)$
Relative depth (dimensionless)	D_{rel}	$D_{rel} = (D_{max}*\sqrt{\pi}) / (20*\sqrt{A})$
Dynamic ratio (dimensionless)	D_R	$D_R = (\sqrt{A}) / D_{mean}$
Volume development (dimensionless)	V_d	$V_d = 3*D_{mean} / D_{max}$
Shoreline length (km)	l_o	From topographical maps
Shore development (dimensionless)	F	$F = l_o / (2*\sqrt{(\pi*A)})$
Specific runoff (m^3/m^2 per year)	SR	From hydrological measurements/topographical maps
Theoretical water discharge (m^3/year)	Q	Q = ADA*SR
Theoretical retention time (yr)	T	T = V/Q
Areas of erosion and transportation (%)	BET[6]	$BET = 25 * D_R * 41^{0.061/D_R}$ (if A>1 km^2)
Areas of accumulation (%)	BA	BA = 100 - BET

[6] The bottom dynamic parameters are: BET (the percentage of the lake bottom where erosion and transportation of fine sediments occurs) and BA (the percentage of the lake bottom where fine sediments accumulate continuously). For lakes in 5 area classes less than 1 km^2, a series of water depths delimiting BET from BA is given.

4.4 Quantity and structure of the substrate

Changes in the rate of sediment input to lake basins usually arise from changes in catchment land use (Section 3.2.2). Basin-scale soil erosion models are being constructed to address erosion problems in the catchment of Lake Vico, central Italy. The rate of sedimentation was assessed for model validation through repeat bathymetric survey, using data collected by the Italian Institute of Hydrology in 1968 as a baseline (Leone *et al*. 2002). Where baseline data are not available, acoustic survey methods may be employed in some situations to obtain information on sub-bottom sediments, and thus to gain insights into sedimentation rates. However, Kumon (2001) reports that an acoustic survey in Lake Kizaki in Japan, carried out using a Uniboom (EG&G: Model 230, 700-14,000kHz), provided unsatisfactory information because sediment density decreased in the downward direction. Thus it was necessary to supplement the acoustic survey data by extracting three cores 2-3 m long using a Mackereth piston corer. One or two ^{14}C ages were determined within each core; and profiles of apparent density and organic carbon and nitrogen concentrations were used to trace the long-term history of the lake, revealing evidence of ancient floods. The Mackereth corer was also used by Halcrow Water (2001) to extract sediment samples from English storage reservoirs.

Various coring devices have been used to obtain material for assessment of sedimentation rates. Studies of long-term sedimentation in the 3-6 m deep lake basins at Slapton Ley Nature Reserve, Devon, are reported by Morey (1976). A previous study had employed a Livingstone corer which limited the length of the core that could be taken. In this survey, use of a Hiller borer in conjunction with carbon dating enabled penetration of the full depth of sediments and reconstruction of lake development over a 3,000 year period. The reasons for more recent, man-made changes in processes affecting the lake (Section 3.2.2) were, however, inferred by other means. Alternatives to carbon dating techniques are available for sedimentation events associated with relatively recent human pressures. Brakke (1984) worked on the 2,036 ha Lake Whatcom in the Puget Sound Lowlands of Washington State. The lake became the principal water supply for the city of Bellingham in 1892 and other major uses of the catchment were coal mining until the 1920s and logging until the 1950s. A diversion system to transport water from the Nooksack River was completed in 1962. Sediment samples were dated by ^{137}Cs and ^{210}Pb methods. The 100-year average sedimentation rate based on ^{210}Pb was 0.50-0.53 cm a^{-1}, but the rate rose to 1.0 cm a^{-1} when calculated over the most recent 30 years. Plots of depth versus ^{137}Cs dates indicated an acceleration of sedimentation rates since 1962 which was attributed to the diversion inputs and increased land surface disturbance within the catchment. Layering of sediment and thick clay lenses indicated periods of rapid sedimentation in the past; although the effect of a major storm in the winter of 1983 was detectable as an increase in sedimentation rate only in the basin farthest upstream because the sills separating the basins blocked transport down-lake. Present sediment deposition rates can be measured using sediment traps (e.g. Bennion *et al*. undated).

Gunkel *et al* (1984) carried out a full core-based study of sedimentation processes in Eau Galle Lake, a small flood control reservoir in central Wisconsin, which was created in 1968. Sediment core samples were collected at 35 stations distributed across the area of the lake using a single-barrel Wildco Core Sampler fitted with polyethylene liners. This sampler provided a means for identifying surficial sediments and maintaining sample integrity. Two samples were collected at each station; one for particle size analysis and the other for interstitial water and sediment chemistry analysis. Upon retrieval, samples were sealed and stored vertically at 4° C in the dark for transfer to a field laboratory for processing. Field processing for particle size analysis involved removing the top 10 cm from the core, gently mixing it for several minutes, then placing it in a 35 ml plastic vial, sealing and shipping on ice by air express to the base laboratory. Particle size analyses were performed using a Micro Trac Particle Size Analyzer (Leeds and Northrop, North Wales, Pa.) which measures 13 particle size fractions between 1.9 µm and 176 µm. No significant correlation between sediment median particle size and distance from the influent river was apparent, but particle size distribution did appear to be related to the local energy environment, as described by Håkanson (1977a). The characteristically turbulent nature of the shallow (high energy) areas within the 3.5 m depth of mixing during summer stratification was reflected by relatively uniform distribution of particle volume amongst the 13 particle size classes. In deeper, low energy sediments, the size distribution was skewed towards the smaller size classes, suggesting preferential deposition (termed “focusing”) of small particles in the deep areas of the reservoir. Thus, conditions in the turbulent shallow waters appeared to discourage the permanent deposition of fine particulates, and sediment accumulation occurred principally in deeper, low-energy parts of the lake. In Loch Tummel, Scotland, Duck (1986) demonstrated that the distribution of bottom sediments in terms of texture (mean grain size and sorting) is similar to that of many lakes in that it conforms to an inshore – offshore progradation associated with declining energy as water depth increases.

In 1994, the United States Geological Survey (USGS) began a 3-year multidisciplinary evaluation of the geology, geomorphology, coastal processes, and environmental quality of the Pontchartrain Basin in southeastern Louisiana. The primary issues stimulating this work were wetland loss, sediment contamination and shoreline erosion causing subsidence and loss of diversity in vegetation. In order to address the issues associated with sediment quality and shoreline dynamics of the lake, it was necessary to understand the geological evolution of the region as well as recent changes in the characteristics of the lake bottom and subsurface. To develop this understanding, a variety of field techniques were employed (Table 8).

Remote sensing geophysical techniques provided a non-invasive, multi-dimensional survey of the lake bottom and subsurface delivering data for geologic framework interpretations, computer models of lake bottom and water column dynamics, and identification of features such as relic barriers, beach trends, fault lines and man-made structures. Sub-surface sampling techniques such as vibracore, borehole drilling, and box cores were used to directly sample the sediments at depths and resolutions dependent on the type of investigation. Sediments obtained by these techniques yielded information on the Quaternary geological framework, regional sedimentation patterns, downcore geochronology, palynology, and sediment contamination history. Finally, surficial sediment sampling, such as grab and underwater sampling, was used to investigate spatial and temporal variations in sedimentation and contaminant distribution.

Table 8 Field investigation methods used in the Lake Pontchartrain Basin study, from Manheim and Hayes (2002).

FIELD INVESTIGATION	TECHNIQUE	TASK OBJECTIVES
Geophysical Surveys	Seismic profiling (>650 line-km)	Data interpretation for geological framework; modelling
	Side-scan sonar surveys	Geomorphology
	Bathymetric surveys (3 surveys, >100 km)	Geomorphology; modelling temporal change
Sediment Sampling	Vibracores (102)	High resolution sedimentation patterns; post-Pleistocene geological framework
	Boreholes (>100)	Regional sedimentation patterns; Pleistocene geological framework
	Box cores (>80)	Downcore geochronology; contaminant history; palynological studies
	Grab samples (>100)	Regional surficial contaminant survey
	Direct underwater surficial sediment sampling (2 surveys, 800 sites each)	Regional surficial contaminant survey
Others: Oceanographic and atmospheric flux and circulation measurements	Wind measurements Current measurements Turbidity measurements Satellite imagery Tide gauge	Circulation modelling; shoreline mapping

Two critical processes related to sediment transport were the resuspension of sediments due to wind-generated storm waves and the transport of resuspended material during strong wind events. These processes were studied using a combination of in-situ data, numerical modelling, and remote sensing. There were two deployments of moored instrumentation, the first in March-June 1995 and the second in January-May 1998. During the 1995 deployment, continuous wave and turbidity measurements (as well as salinity and temperature records) were collected at two depths at each of three sites: north lake, central lake, and south lake. These data indicated that turbidity was highly correlated with bottom currents generated by wind waves. The potential for sediment resuspension was studied using a wave prediction model HISWA (HIndcasting Shallow water WAves, Holthuijsen *et al*. 1989), which simulates local generation of waves by wind and shallower effects on waves (refraction, shoaling, bottom friction, and breaking). Long-term wind measurements were then used to determine the spatial and temporal variability of wave- induced currents at the bottom. Excellent agreement was obtained between the predictions of the wave model and the 1995 wave observations. Satellite imagery collected daily by the NOAA Advanced Very High Resolution (approximately 1 km) Radiometer (AVHRR) on NOAA polar-orbiting weather satellites include measurements of sea surface temperature (SST), water reflectance, and false-colour infrared imagery. The water reflectance measurements were converted to provisional estimates of suspended sediment concentration (seston) and diffuse attenuation coefficient (*K*) based on algorithms developed for the area. An investigation of seasonal relationships between turbidity and bottom stress (predicted from the wave model) throughout the lake was established, using five years' sea-surface reflectance data to indicate turbidity, and monthly water property data (obtained by sampling) for ground truthing (Manheim and Hayes 2002).

4.5 Water level

Direct measurement of lake water levels is relatively straightforward, and the existence of some long datasets is reported in the literature; although methods are not usually described. For Lake Tanganyika (32,600 km^2), water level records date from 1846 and enabled Crul (1995) to trace some events in the lake's history. The annual mean level increased from 777.6m in 1846 to 783.6 m in 1878, and then the lake overflowed. By 1884, the level had fallen to 775m and reached minima of 772.5m in 1894 and 1902. Systematic recording began in 1909, indicating seasonal fluctuations of around 0.8 m. The lowest level of 773m was recorded in 1929, after which the level rose until 1939 before dropping steadily to another minimum in 1950. It rose by more than 2m in the early 1960s, in 1965 reaching its highest level since 1878, at 776.5m. For Lake Malawi (28,800 km^2), systematic records date from 1894; here the fluctuations can be related to changes in the degree to which the lake's outlet was blocked. Long records also exist for the north American Great Lakes, where water levels have been logged systematically by the US and Canadian governments since 1860 (NOAA 1992). Wilcox (1995) presented monthly lake level elevations for Lake Michigan-Huron for the period 1860-1993, derived from these records and subsequent updates. Recording at the hydrometric station on Lake Peipsi, Estonia, began in March 1921. The data reveal cyclical variations in water level related to climate (Jaani 2001).

There are water level records for very few – perhaps between 15 and 20 – unimpounded lakes in Scotland, and fewer than 10 of these are represented within the national hydrological data archive held in Dundee. On the other hand, the requirements of the Reservoirs Act have ensured that good water level data are available for impacted lakes. Recording is conducted largely by Scottish Water (SW), Scottish and Southern Energy (SSE) and Scottish Power (SP), who operate more than 90% of the principal reservoirs, and routinely record daily water levels in their operating logs. In many cases, these records cover periods of several decades but rarely pre-date impoundment. With the advent of electronic logging devices, data can now be generated at much finer time intervals, but they are not always archived. SSE still record and permanently archive daily water levels; in addition, each "significant change" (which may well be significant for biota) is logged and this information is retained for one year. SP hold long-term hourly records for most of their reservoirs, whilst SW have long-term daily data plus hourly records dating from the 1980s. It is anticipated that similar responses to the availability of evolving technology for water level monitoring have been adopted by reservoir operators throughout the UK.

Indeed, conventional methods for recording water levels, such as stage posts, have now generally been superseded by devices incorporating electronic pressure transducers which enable direct remote measurement of the water level at frequent intervals. However, where information on seasonal maximum and minimum levels only is required, an inexpensive mechanical alternative is offered by the principle described by Bragg *et al*. (1994), which has been adapted for recording the range of water level fluctuations at Balgavies Loch in Scotland (H.A.P. Ingram, pers. comm.).

Useful summaries of water level fluctuations are provided by level duration curves. The data from Figures 2 and 3 are presented in this form in Figures 11 and 12.

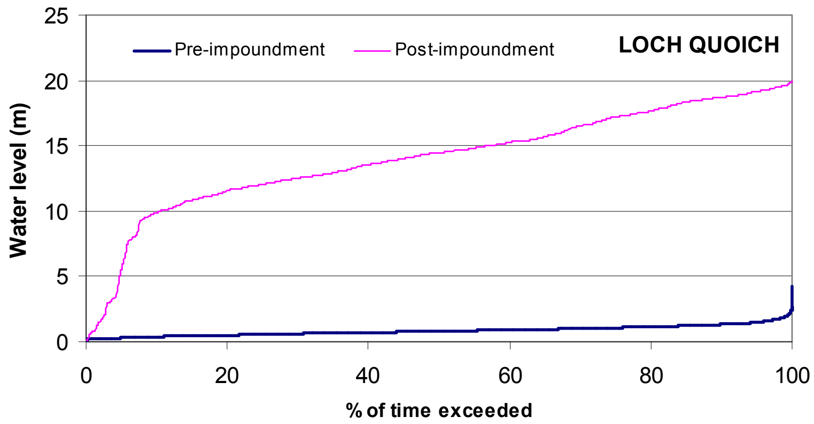

Figure 11 Comparison of water level duration curves for Loch Quoich, Scotland, for 1933 (before damming for hydro-power generation) and 1993. Water level records for the two years are not related to the same datum level.

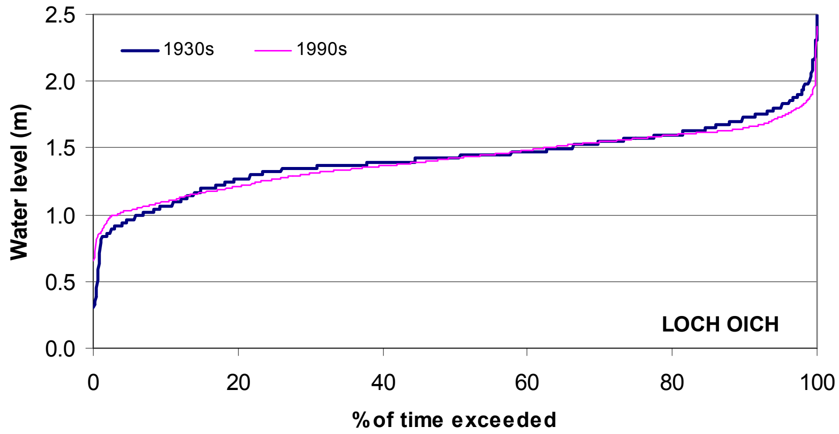

Figure 12 Comparison of water level duration curves for Loch Oich, Scotland, for 1931 (before the catchment was used for hydro-power generation) and 1991. Datums have been adjusted so that 50%ile values coincide.

The information that is extracted from water level records varies with the purpose for which it is being used. Jaani (2001) explored issues related to computing the average water level for Lake Peipsi. Since the water level can vary greatly, the use of reconstructed records in deriving mean water level values was not favoured; and it was noted that the computed long-term average is highly dependent on the period chosen. Muzik (1998) studied the effect of river flow regulation on water levels in Lake Athabasca in Canada. Maximum water level in the lake normally occurred in July. The change in lake water level regime associated with the commencement of flow regulation in 1970 was illustrated by plotting a series of July levels from 1960 to 1999, and quantified by comparing the mean and standard deviation of July levels recorded in 19 years before 1970 with the same statistics calculated for 15 post-regulation years. Hill *et al*. (1998, see also Section 3.2.4.2) compared the variability of the water level regimes of lakes and reservoirs. Regulation rendered the hydrological regimes of different lakes either hypovariable or hypervariable in comparison to unregulated systems, for both within-year and among-year fluctuations in water level. The optimum operation regime for shoreline vegetation was defined as one which allowed manipulation of within-year water level variation by 1-2 m whilst ensuring that between-year variation (standard deviation of summer levels) was less than 25% of within-year variation.

Water level data may also be derived by modelling. White (1973) considered the potential consequences of management of the Kafue River in Zambia for hydroelectric purposes on the flood regime of the Kafue Flats and its consequent influence on the suitability of the area for cattle, game and fish. The areas of the Flats that were inundated naturally were calculated from water level data and contour maps, and these were compared with the results of simple mathematical models for various water management scenarios. Hydrological simulation models were also used to predict drawdown in the English Lakes Windermere and Ullswater resulting from abstraction under drought orders issued in 1995/6. The models were used to explore and define different mitigation conditions to protect the environment, and in particular the fisheries in rivers fed by the lakes, as the drought continued; and eventually to examine the impact of relaxing the restrictions on abstraction. The practical outcome for Lake Windermere was that abstraction was permitted so long as the flow in the River Leven exceeded 45×10^{6} $l\ d^{-1}$, which was the minimum discharge required to ensure survival of migratory salmonids. However, it is possible that such modelling could be extended to consider the impact on other biota, e.g. lake margin plant communities, and thus to clarify the trade-off between protecting lake and river habitats (Smithers and Durie 1998, Pickering 2000).

Some indirect approaches to estimating water levels are also available. Wilcox (1995) noted that water level changes for Lakes Michigan and Huron are recorded in the late-Holocene geological record, in the form of chronosequences of beach ridges that formed as different stages of the general decline in water level over the past 4000 years. Harper *et al*. (1986) derived information on water level history for Lake Poukawa, a shallow hardwater lake situated on calcareous lake silt overlying peat and alluvium in central Hawke's Bay, New Zealand, from the sediment record. Four 6 m cores of sediment showed the presence of two tephra layers (Taupo and Waimihia) aged at c*.* 2000 and 2500 calendar years respectively. The diatom flora of the cores was examined for indications of changes in lake morphology and to assess the effects of tephra deposition. Increased abundance of small *Fragilaria* spp. appeared to indicate periods when the lake was less extensive, c. 3700-2500 and c*.* 2800-3000 years ago. In the recent past, increased abundance of *Fragilaria* spp. in lake sediment near the present southern margin was related to artificial drainage that had taken place since 1931 AD. The occurrence of marine sponge spicules in the cores probably indicated that rates of erosion in the catchment were low before 2500 BP and high during the last 100 years. Estimated diatom numbers increased immediately above the tephra layers, but no conclusion could be reached as to whether this reflected increased growth or simply better preservation of frustules. Duck *et al.* (1998) reviewed and assessed a range of signals found in physical records that have been used to infer the occurrence of historical lake-level changes, listed in Table 9. These authors concluded that multiple lines of mutually consistent evidence are always necessary, first to confirm that a change in water level actually occurred, and secondly to distinguish between climatic and non-climatic causes.

The Dundee Hydrological Regime Assessment Method incorporates a method for calculating the degree of anthropogenic impact on the water level fluctuations in Scottish lakes (Black *et al.* 2000b; 2002b). The DHRAM score translates into one of five classes, ranging from 'unimpacted condition' to 'severely impacted condition'. Central to the procedure is the concept of a natural neighbour (analogue site) which is used as a baseline against which to measure alteration.

Table 9 Types of physical evidence that may indicate historical changes in lake level, after Duck *et al.* (1998).

Type of evidence	Description and interpretation
Coarse minerogenic layers	Relatively thick and coarse-grained minerogenic layers within sequences of lake sediments, due to horizontal displacement of the littoral zone.
Coarse organic layers	Composed of shallow water or terrestrial biota mixed into deeper water laminites.
Sediment stratigraphy	Changes in lithostratigraphy, e.g. gyttja overlying peat.
Depositional hiatuses	Visible on prepared core surfaces or inferred from missing zones in microfossil, palaeomagnetic, mineral magnetic etc. profiles.
Exposed horizons	Evidence that a sediment layer within a deep water lacustrine sequence was at one time exposed to the atmosphere; e.g. desiccation and frost cracks, iron oxide-rich horizons.
Wave-cut benches and terraces	May be detected above and below the present water level.
Chemical precipitates	Changes in mineralogy, geochemistry and isotopic compositions of chemical precipitates reflecting fluctuations in the composition of the lake waters at the time of their formation.
Quality of varve/lamination preservation	Zones of poorly-preserved varves within a core sequence of well-laminated sediments indicating a period of bioturbation under shallow water conditions.
Archaeological evidence	Remains indicating that people once lived on dry land on a horizon that is now below lake water level.

4.6 Structure and condition of the shore zone

On soft shores, effects of man-induced changes on sediment dynamics may be discernible as specific types of patterning in the sediment surface. These reflect operation of the mechanism of migrating bed forms, e.g. sand ripples moving ashore, which can function as a method for adjusting a bottom that is not in equilibrium with flow conditions, perhaps due to a change in lake level (Duane *et al*. 1975). In more extreme cases, erosion occurs. Studying shoreline erosion at Loch Lomond (Scotland), Hansom and McGlashan (2000) made a detailed map of the distribution of natural shore types (sand/gravel and boulder beaches, rock, till and vegetated shore) and artificial protection. They then divided the shoreline into a series of sediment cells, which are parts of the coast between which there is no longshore exchange of coarse sediments (sand and gravel) except during extreme events. The cells were proposed as the basis for an overall shore zone management strategy. Fantucci-Montefiascone (2002) proposed the use of dendrochronological methods to date and estimate rates of wind erosion at different points on the shoreline of Lake Bolsena in central Italy, since the exposure of the root systems of *Populus nigra* trees induced growth suppression and changes in wood structure that could be detected by such techniques.

The UK River Habitat Survey (RHS), developed by the Environment Agency of England and Wales, provides a systematic framework for the collection and analysis of data on the physical structure of river channels and for assessing habitat quality (Raven *et al.* 1997, Fox *et al*. 1998). It has been applied across the UK and over 5000 sites exist within the EA reference site database (Raven *et al.* 2000).

Table 10 Summary of RHS survey data (after Fox *et al*. 1998)

BACKGROUND AND MAP-DERIVED DATA

General information
Date of survey
River name
Catchment name
OS six-figure grid reference
Altitude
Valley slope
Solid geology code
Drift geology code
Mean annual flow
Distance from source
Height of source
Site planform

FIELD SURVEY

SPOT CHECK

Channel data
Predominant substrate:
  bedrock / boulders / cobbles / gravel or pebbles / sand / silt / clay / artificial / not visible
Deposition features
Vegetation types and extent
Predominant flow type:
  free fall / chute / broken standing wave / chaotic / rippled / upwelling / smooth boundary turbulent / no perceptible flow / no flow (dry)
Modifications

Bank data
Substrate
Erosion and deposition features
Modifications
Bank face vegetation structure
Banktop land use

SWEEP-UP

Channel data
Braiding/side channels
Shading of channel
Trees:
  boughs overhanging channel / underwater roots / fallen trees
Debris:
  dams / coarse woody / leafy
Extent of:
  waterfalls / cascades / rapids / riffles / runs / boils / glides / pools / marginal deadwater
Waterfalls > 5 m high
Number of riffles / pools
Artificial features:
  culverts / weirs / foot bridges / road bridges / outfalls / fords

Bank data
Shape
Modifications
Flood embankments
Extent of bankside trees
Exposed bankside roots
Number of point bars
Extent of side bars

Other site data
Valley shape
Adjacent land uses:
  broadleaved woodland / coniferous plantation / orchard / moorland or heath / scrub/ tall herb or rank vegetation / rough pasture / improved or semi-improved grassland / tilled land / wetland / open water / suburban or urban development
Site dimensions:
  bank-top height and width / water width and depth / embankment heights
Special floodplain features:
  artificial or natural open water . water meadow / fen / bog/ carr / marsh / flush
Notable nuisance species:
  Giant hogweed / Himalayan balsam / Japanese knotweed

RHS was developed in response to the need for a nationally applicable classification of rivers based on their habitat quality. Four related outputs were envisaged:

a) standard field survey method (Fox *et al*. 1998)

b) computer database of national reference network of UK sites

c) classification of river types based on a predictive model of physical structure

d) a scheme for assessing habitat quality.

The standard survey covers a 500m length of river corridor, 100 m wide. Within this stretch, 10 spot checks and a 'sweep-up' survey are conducted. The full set of features recorded is summarised in

Table 10. The data can be used to derive the Habitat Quality Assessment (HQA) score, which provides an assessment of habitat features that are considered important in conservation terms, regardless of river type and naturalness (Raven *et al*. 1998a); and the Habitat Modification Score (HMS) which reflects the degree to which the natural stream channel and its banks have been altered (Table 11). Both of these scoring systems are currently being revised by the Environment Agency (England).

Table 11 Rules for derivation of the Habitat Modification Score (HMS) from RHS data.

The HMS score for a site is the total of all the component scores in the categories listed below.

Modifications at spot-checks	Score per spot-check
Reinforcement to banks	2
Reinforcement to bed	2
Resectioned bank or bed	1
Two-stage bank modification	1
Embankment	1
Culvert	8
Dam, weir, ford	2
Bank poached by livestock	< 3 spot-checks: 1 3–5 spot-checks: 1 ≥ 6 spot-checks: 2

Modification present but not recorded at spot-checks	One bank (or channel)	Both banks
Artificial bed material	1	-
Reinforced whole bank	2	3
Reinforced top or bottom of bank	1	2
Resectioned bank	1	2
Embankment	1	1
Set-back embankment	1	1
Two-stage channel	1	3
Weed-cutting	1	-
Bank-mowing	1	1
Culvert	8 for each	-
Dam, weir, ford	2 for each	-

Scores for features in site as a whole	One	Two or more	Site
Footbridge	0	0	
Roadbridge	1	2	
Enhancements such as groynes	1	2	
Site partly affected by flow control			1
Site extensively* affected by flow control			2
Partly realigned channel**			5
Extensively* or wholly realigned channel**			10

* Extensively means at least one-third of channel length; ** Information from map.

4.7 Quantity and dynamics of flow

Especially for large lakes, patterns of water movement are complex and related to basin form. Beeton and Saylor (1995) identified three major forces driving currents in Lake Huron: hydraulic flow-through of water entering from tributary streams; wind acting on the water surface to generate waves and storm surges, and to propel currents; and horizontal pressure differences caused by wave motions, thermal forcing and long-lasting spatial variations in thermocline depth. They also identified complex flows within and between Lakes Huron and Michigan that resulted from the semidiurnal tide and the various seiche[7] modes of both lakes.

Dumont *et al*. (1973) investigated through-flow at Lake Ifni, a high-mountain lake (maximum depth 65 m) in Morocco without direct inlets and outlets. Routine profiles of water temperature showed a sharp increase in water temperature from 6.6 to 10^{o} C at 60m depth. From this, the authors inferred the existence of a strong bottom current between the deep inlet and outlet, which must be fast enough to prevent warm water from ascending through the water column and mixing with the superficial layers. Carmack *et al*. (1987) studied the dynamics of flow under winter ice on the 201 km^2 Lake Laberge, Yukon. Two different survey patterns were established. To obtain detailed information on ice regime and water mass structure, a local transverse section comprising 11 stations was set up and visited by snowmobile at intervals of 1-2 weeks. Information on circulation and mixing was derived from measurements at 21 stations distributed across the lake and visited by ski-plane at intervals of one month. At each survey station, a 0.2m diameter hole was drilled through the ice and a vertical profile of temperature and conductivity obtained using an Applied Microsystems Model-12 conductivity-temperature-depth (CTD) probe. Solar radiation, and various attributes of the ice and snow cover, were also measured. The data collected enabled the authors to describe the flow pattern in some detail. The lake is frozen from late December to early June, during which time wind and surface heat exchange become negligible, and river through-flow is the main source of turbulent mixing. The river enters the lake as a turbulent jet near 0^{o}C, spreading as a buoyant plume within the upper 15-20m of the water column. Coriolis forces influence the flow so that it is most intense along the eastern margin of the lake although frictional forces are responsible for broadening of the current downlake. Upwelling and increased flow velocities at the outlet support an area of open water and thin ice (outlet polynya).

The overall rate of throughflow of a lake is susceptible to modification through alteration of the hydrology of the rivers or streams that feed it. The Dundee Hydrological Regime Assessment Method

[7] Seiches are stationary waves that are formed in a lake as a result of external forces, e.g. wind or changes in atmospheric pressure.

(DHRAM) incorporates a method to quantify the degree to which the flow regime of a river, expressed in terms of variables that are significant to ecology (monthly discharge characteristics, magnitude and duration of annual extreme discharge conditions, frequency and duration of high/low flow pulses), departs from the natural condition (Black *et al.* 2000b; 2002b).

Seiches play an important role in the movement and mixing of the waters of Lake Peipsi (Estonia). They were detected when a limnograph was erected in Mustvee. Here, current measurements have been conducted from both aircraft (surface water currents) and boats. Between 1971 and 1977, submerged current recorders were also used. These recorders were installed on rigid bases, 0.8-1.0 m from the lake floor. Data from 139 of these recorders, deployed at 66 stations, are presented by Filatova and Kvon (2001). Currents in Lake Kizaki (Japan) were studied through routine observations of temperature at depths of 0, 1, 4, 8, 14, 20, 22 and 26 m at the deepest point near the lake centre, the data being collected by data loggers (Kishino *et al*. 2001). Relationships between wind and water movements were investigated by studying the temperature distribution at different times of day when winds of different directions prevailed, in conjunction with measurements made with floats and a current cross-drag. The distribution of fine bottom sediments indicated the existence of an anticlockwise circulation resulting from the temperature distribution that prevailed during the summer stagnation. Another study employed an ultrasonic current meter in shallow water and a current drag further from the shore, and indicated the presence of a density current caused by cold inflow water from one of the rivers feeding the lake. A model flume was used to investigate the combined effects of wind and mountains around the lake in creating currents capable of moving small paper floats, whose movement was tracked using a video camera. The interaction of wind and catchment relief, in combination with Coriolis forces, was confirmed as the reason that circulation in the lake was always in an anticlockwise direction.

The dam at Lake Volta, a man-made lake in Ghana, was closed in May 1964, creating a lake 400 km long with a surface area of 7000 km^2. Its complicated shape means that different weather effects operate according to locality, principally driven by wind. Viner (1970) identified relationships between the lake's morphometry, the degree of stratification, and the composition of phyto- and zooplankton communities which he associated with local climatic variations. Allott (1990) attempted to formalise the relationship between lake morphometry and mixing behaviour in temperate oceanic lakes, with particular reference to the role of water-column stability in the selection of phytoplankton assemblages. He performed an ordination of 35 British and Irish lakes, described in terms of their lengths (L) and maximum depths (D), and thus separated them into Groups I and II (stratifying) and Group III (non-stratifying) (Figure 13). A Group III lake (low D:L ratio) would tend to have a deeply circulated water column, given adequate depth; a high degree of contact between water and sediment; and a relatively poor light climate.

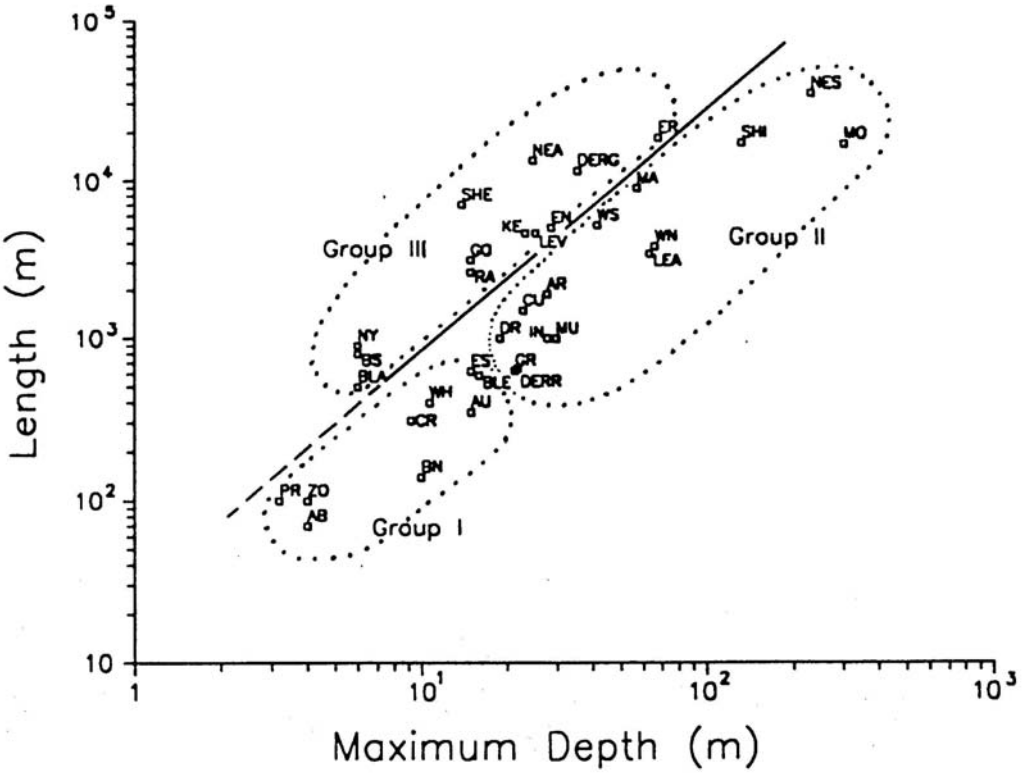

Figure 13 Ordination of 35 British and Irish lakes, from Allott (1990).

The line separates stratifying from non-stratifying lakes in years of average weather conditions. The dashed part of the line shows the range of length and depth where local shelter is of importance in determining whether or not the lake will stratify. Key to lake codes:

Group I		**Group II**		**Group III**	
LAKE	**CODE**	**LAKE**	**CODE**	**LAKE**	**CODE**
Abbott's Pond	AB	Leane	LEA	Ballycullinan (S)	BS
Ballycullinan (N)	BN	Arrow	AR	Nynydd	NY
Zoo	ZO	Cullaun	CU	Ramor (W)	RA
Derravaragh	DERR	Windermere (N)	WN	Gowna	GO
Augher	AU	Windermere (S)	WS	Leven	LEV
Grasmere	GR	Mask	MA	Key	KE
Crosmere	CR	Black	BLA	Ennell	EN
Priests Pot	PR	Ness	NES	Sheelin	SHE
Muckno (SE)	MU	Shiel	SHI	Derg (S)	DERG
White	WH	Morar	MO	Erne	ER 1
Esthwaite	ES			Neagh	NEA 3
Inchiquin	IN				
Blelham	BLE				
Dromore	DR				

In Group II lakes, conditions for phytoplankton would be predominantly those of the metalimnion (thermocline), with low light levels and more stable physical conditions although with some turbulence. Group I lakes could be expected to stabilise quickly after the spring circulation period. For a subset of 12 Irish lakes he concluded that morphometry, through its influence on the timing and nature of stratification, was important in determining seasonal changes in phytoplankton.

Patterson *et al*. (1995) reported that satellite-derived night time surface temperature data (NOAA-II) provided accurate, timely and reliable information on the surface temperature structure of Lake Malawi in southern-central Africa, and explored the potential use of such information in developing an understanding of subsurface temperature structure and thus of real limnological events. These authors found that the satellite image contained substantial evidence of the three-dimensional structure of the lake in terms of the epilimnetic wedge. Temperatures derived from a series of satellite images, in combination with surface wind data, were used to predict the likelihood of mixing of the epi- and hypolimnion. Ephemeral hydrological phenomena, such as upwelling of colder water associated with high productivity of phytoplankton and fish larvae, could also be detected.

4.8 Residence time

Residence time indicates how long it would take for all the water in a lake to be replaced, and may be calculated as the ratio of capacity to inflow rate. For Cameron Reservoir in Fife, Al-Jibburi and McManus (1993) derived residence times of approximately 180 days in summer, 4 days during peak storm events, and 38 days on average. Marsh *et al*. (1993) defined residence time as "lake volume divided by the rate of river inflow assuming complete mixing", whilst other authors have calculated the quotient of lake volume and yearly outflow (e.g. Allott 1990, Cordella 2002) or annual rainfall (Glen and Hurley 2002).

It is often necessary to adopt an indirect approach for the estimation of the rates of flow through lakes, because their outflows are not gauged. In this situation the runoff into a lake from its catchment may be calculated using a water budget relationship:

$$E = P + I + U - R +/- S$$

Where: E = evapotranspiration
P = total precipitation
I = surface inflow
U = underground outflow
R = surface runoff
S = change in storage (both surface and subsurface).

If surface inflow, underground outflow (see Section 4.9) and storage changes are assumed to be negligible, thus:

$R = P – E$

Using long term averages of annual precipitation and evapotranspiration, Duck (1982) calculated the theoretical average residence time of four Scottish lochs as the quotient of the basin volume and the average runoff from the catchment (Table 12).

The residence time values of Table 12 are averages; the actual water renewal times will vary throughout the year according to seasonal changes in runoff. In addition, the water exchange zone is different in different seasons according to the thermal structure of the water column and degree of ice cover (cf. Kajosaari 1966). Nevertheless, such values are useful for broad comparative purposes. For example, "theoretical" (average) water residence times were calculated as the ratio of lake volume and annual discharge for the EU project EMERGE (European Mountain Lake Ecosystems: Regionalisation, diaGnostics and socio-economic Evaluation). This study included lakes in six European mountain regions, from the Pyrenees to central Norway. Residence times for all but one of them fell within the range 1 - 7 months; the exception being Lake Redó in the Pyrenees, whose large volume resulted in a residence time of 4 years (Nickus *et al*. 2002).

Table 12: Catchment areas, long average annual precipitation and evapotranspiration, average runoff, basin volumes and average residence times of Lochs Butterstone, Marlee, Earn and Tummel (Duck 1982).

Loch	Catchment area (km^2)	Long average annual precipitation (mm)	Annual evapotrans -piration (mm)	Average runoff (m^3 day^{-1})	Basin volume (m^3)	Average residence time (days)
Butterstone	21.6	980	480	2.96×10^4	1.51×10^6	51
Marlee	60.2	787	380	6.71×10^4	6.28×10^6	94
Earn	236.7	1792	350	9.31×10^5	4.08×10^8	438
Tummel	1336.4	1599	330	4.65×10^6	5.78×10^7	12

Allott (1990) calculated instantaneous residence times (IRT) for Lough Inchiquin, Co. Clare, by dividing lake volume by daily discharge at the outlet. The IRT values varied widely around the annual mean values (Table 13; see also Section 3.2.4.3).

Table 13 Instantaneous residence for Lough Inchiquin, Co. Clare, after Allott (1990).

	Mean residence time (days)	Standard deviation	Number of days that discharge was measured	median	min	max
1981	128	200	341	47	10.5	1548
1982	126	164	335	50	10.3	516
1985	43	28	112	35	10.5	129
All years	115	172	172	46	10.3	1548

Glen and Hurley (2002) adopted a slightly different approach to the calculation of residence time. They used daily rainfall to calculate the time required to flush the lake volume from a specified start date (yielding the 'forward' residence time), or to a specified end date (yielding the 'backward' residence time), and generated curves showing how the 'forward' and 'backward' values varied through the year. The backward residence time provides a useful measure of the impact of an extreme event, whereas the forward residence time is more appropriate for estimating the persistence of a pollution incident.

Calculations of residence time usually assume uniform flow and mixing conditions throughout the basin. The actual residence time is strongly influenced by internal physical processes such as wind, thermal stratification, basin irregularity and freezing (Ambrosetti *et al*. 2002, Paganelli 2002). Kajosaari (1966) employed a tracer technique to study the resulting temporal variations in "detention period[8]" of the Ruovesi Lake system in Finland. The tracer was waste liquid from a sulphite pulp mill discharging upstream of the lake, and its concentration was monitored at the lake's inlet and outlet. The fluctuations in tracer concentration at the outlet showed reasonable agreement with the results of calculations based on a model incorporating estimates of seasonal variations in the extent of the water exchange zone and in the intensity of horizontal mixing. More recently, tracer techniques have been used to investigate spatial variations in residence times of large European lakes within the EU 5th Framework project EUROLAKES. This work focuses on large-volume lakes (2,600 - 88,900 x 10^6 m^3) with water depths greater than 145 m and mean residence times of 2 -12 years. Of particular interest are Lakes Constance and Geneva, Loch Lomond and the Lac du Bourget; all of which are important for water abstraction and have been subject to intensive management. The pathways taken by water particles have been calculated using three-dimensional model results and, where available, the results of radioactive tracer measurements. Thus, residence times have been estimated for near-bottom layers, different lake basins, epilimnion, metalimnion (thermocline) and hypolimnion. The concept of water mass lifetime, defined as the period during which at least half of a marked water mass remains in the same condition, is introduced with the objective of using it to

[8] "Detention period" was defined as the quotient of the basin volume and the rate of flow, and is thus directly equivalent to residence time.

interpret physical processes in biological terms. It is envisaged that the results will be used to define two-dimensional or coupled one-dimensional box models for lakes of different shapes (Duwe 2002).

4.9 Connection to groundwaters

Vanek (1985) noted that few lakes are truly isolated from the groundwater system ("perched"), with an unsaturated zone beneath the lake floor, and that the occurrence of perched lakes in glacial terrains had never been proved. Thus, most lakes in humid areas form integral parts of dynamic groundwater flow systems, functioning as "discharge", "recharge" or "flow-through" lakes (Figure 14). The groundwater-lake relationship may be assessed by direct measurement of the seepage flux through the bottom sediments, by using various environmental tracers, through study of the water balance, or using Darcy's Law. An important characteristic is the ratio of groundwater inflow or outflow to total inflow or outflow, on the basis of which lakes can be divided into two groups; those which are groundwater dominated and those which are surface water dominated. In general, the permeability characteristics of the soils surrounding the lake are much more important in determining the degree of hydraulic connection between lake and groundwater than are the thickness, permeability and distribution of sediments within the lake. Moreover, theoretical considerations indicate that groundwater seepage will be most intense in near-shore areas, decreasing exponentially towards the centre (Figure 15) so that groundwater-lake communication is generally more pronounced when lake level is high. In some cases, it has been observed that maximum seepage rates occur through the steepest parts of the lake bottom.

Thus, the degree of connectivity between lake and ground- waters is most strongly influenced by the permeability of the solid and/or drift geology in which the lake basin has developed, and to a lesser degree by basin form. Materials that allow water to pass through them easily are said to be permeable whereas those that permit water to pass only with difficulty, or not at all, are impermeable. It is important to note that a rock or soil may be highly porous but relatively impermeable (e.g. clay or shale), either because the pores are not connected or because they are so small that groundwater can be forced through them only with difficulty. Conversely, a rock that has no voids except for occasional open cracks (e.g. joints, faults) will have a low porosity, and will be a poor store of groundwater. However, because groundwater will be able to pass easily through the fissures, the permeability will be high. Many igneous and metamorphic rock varieties, i.e. rocks not intuitively thought of as aquifers, are characterised by fissure systems that can transmit large volumes of groundwater. An example is found at Lake Bolsena, Italy, where underwater observations indicate that the lake is fed by underwater springs and there is a consistent outflow through fractured magmatic rock. Thus, doubt is cast upon the accuracy of estimates of the lake's retention time based on discharge measurements in the effluent river (Fioravanti 2002).

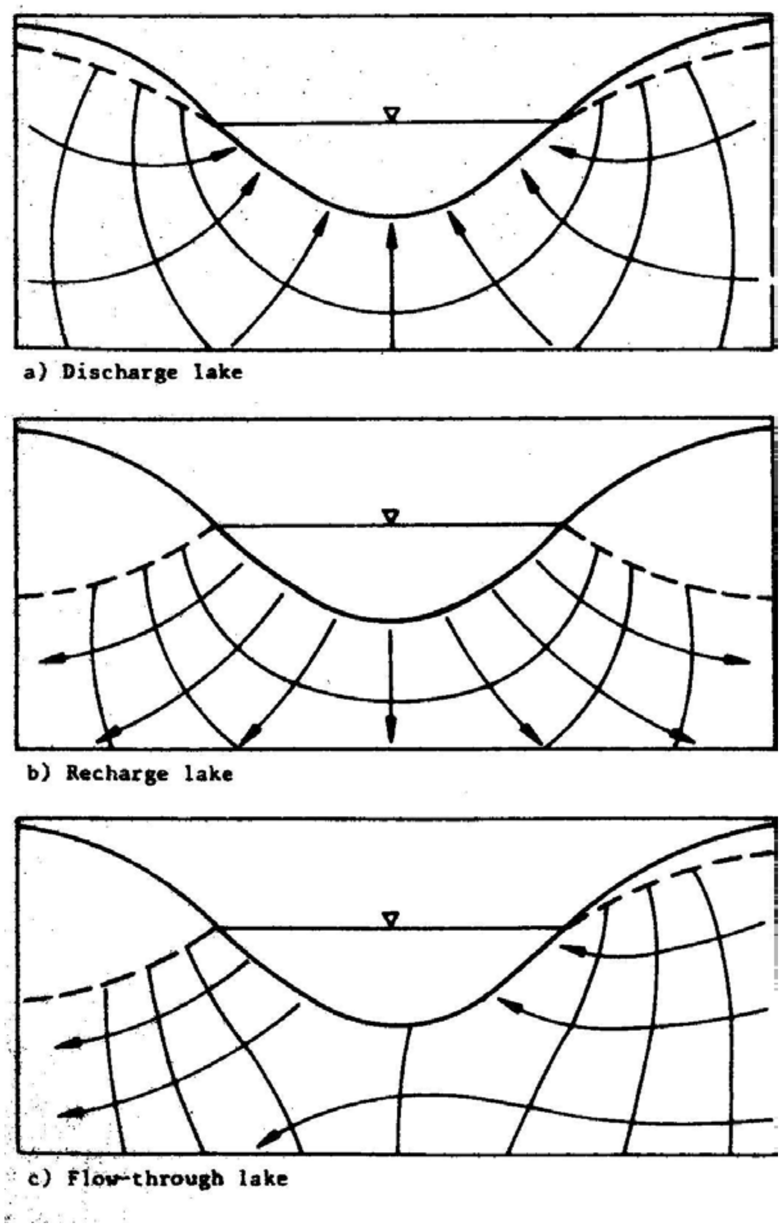

Figure 14 Basic configurations of groundwater flow systems around lakes, from Vanek (1985).
The water table is indicated by broken lines, the open water surface by inverted triangles, and the direction of groundwater seepage by the arrowheads on flow lines.

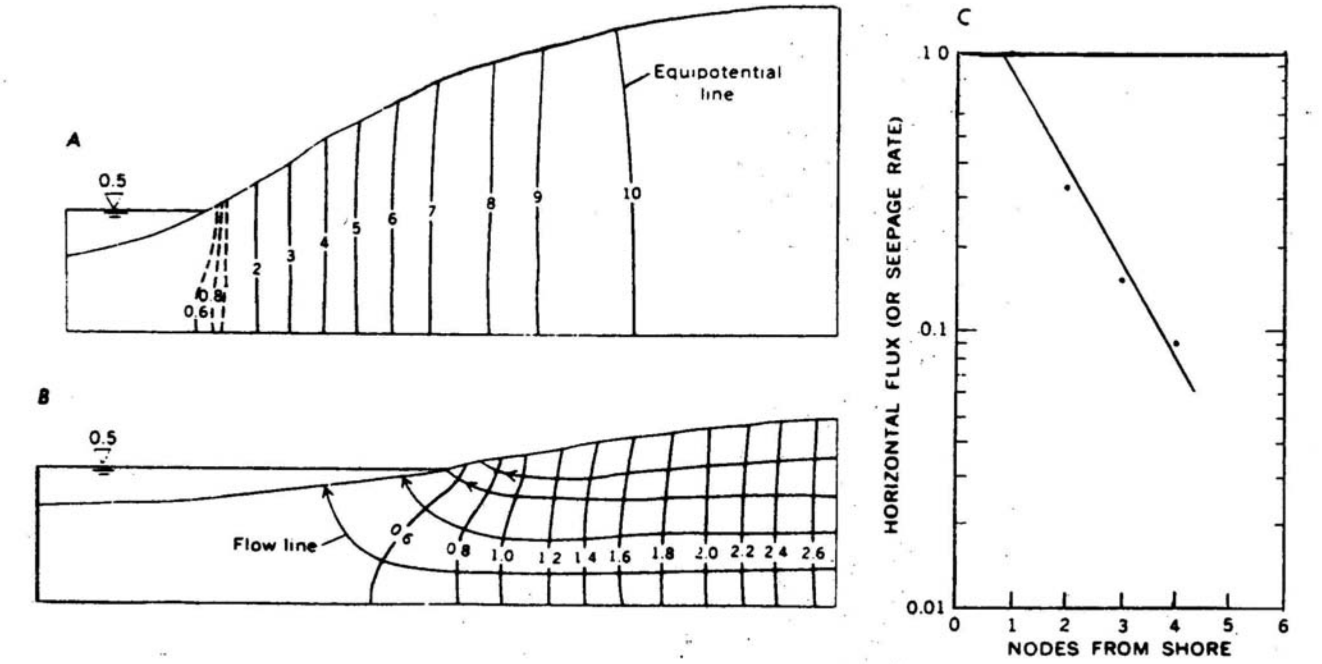

Figure 15 A typical vertical-section model showing the seepage pattern at the margin of a lake, from Vanek (1985).

A: distribution of hydraulic potential; B: closer view of near-shore section showing crowding of flow lines; C: relationship between seepage rate and distance from shore.

In terms of the System A typology of the WFD (Table 19), siliceous rocks are likely to be characterised by varying degrees of permeability. This group includes, at one extreme, highly porous and permeable sands, gravels and sandstones and, at the other extreme, crystalline rocks with little or no permeability. However, should the latter be fissured or highly weathered, then their permeability may well be high and could result in as high a degree of lake to groundwater connectivity as that for a basin developed in sandstone. Similarly, calcareous rocks will show a range of permeability values but it may be assumed that, in general, they will show higher values than siliceous rock types and especially so in karst terrain. Organic rock types (taken to refer to peat) are also difficult to characterise in terms of their permeability; first because the ease with which water is transmitted changes by 3-5 orders of magnitude within 0.5 m of the surface of a living peatland (Ingram and Bragg 1984; Bragg 1995), and secondly because sub-surface permeability measurements give equivocal results due to elastic storage effects (Rycroft *et al.* 1975a,b; Hemond and Goldman 1985). However, the types of lakes developed within peat basins are likely to be shallow, and a high degree of connectivity between lake and peat pore waters is to be anticipated; Ivanov (1981) gives detailed consideration to the processes of water exchange between “soil” and lakes in peaty landscapes.

The above serves to highlight the unhelpfulness of the WFD's simple division of geological types into three categories in terms of lake to groundwater connectivity. A more productive approach might be adapted from the method used by Zhang (undated) to map the sensitivity of groundwater to pollution, in which separate permeability indices were derived for surficial and subsurface deposits. Four groups of surficial deposits were distinguished. Group 1 included those with coarse texture and high permeability, such as alluvium, aeolian sand, outwash, terrace deposits and ice contact deposits, whilst tills were placed in the lowest-permeability Group 4, or in Group 3 if coarse grained. Peat deposits were assigned with consideration of the substratum; if they overlay till, the combination was placed in the low permeability group appropriate to the till; but if they overlay a substratum with higher permeability than peat, such as outwash, the combination was placed in a lower group because the peat was deemed to reduce the overall vertical permeability. Subsurface permeability was assessed by a weighted scoring procedure. Each lithologic type represented in archived well records for the region was assigned a weight between 0 and 1 on the basis of estimated permeability, as follows:

0.0: boulder, cobble, gravel, pebbles, sand, silt, soil;
0.2: hardpan, loam, marl, sandstone, saprolite, wood;
0.3: mud, peat, regolith, siltstone;
0.5: coal, drift, fill, granite, quartzite;
0.8: schist, slate, till;
1.0: clay, shale.

For each well, the thickness of each type of deposit recorded within 50 feet (15.24 m) of the ground surface was multiplied by the appropriate weighting factor, and the results were summed to yield a subsurface permeability score in the range 0 – 50; for example, a well log with clay recorded for the entire upper 50 feet would receive a score of 50, while a log with sand and gravel only in the uppermost 50 feet would score 0. The scores were considered in three classes: <20, 20-40 and >40. Those in the last class were typically for locations with almost homogeneous, low permeability till without buried sand and gravel lenses within the 50 foot zone, and would be expected to have the greatest natural protection against infiltrating contaminants. The surface and subsurface scores were then combined to arrive at the pollution sensitivity category (Very High, High, Moderate or Low) for the well location.

4.10 Habitat measurement

The United States Environmental Protection Agency (USEPA) has developed comprehensive monitoring, bioassessment and biocriteria programmes for lakes and reservoirs, recognising that these are interrelated and critical components of the total US freshwater resource. Two schemes are of particular significance in the context of this review. The first is the Surface Waters Field Operations Manual for Lakes (FOML) developed as part of the national Environmental Monitoring and Assessment Program (EMAP) (Baker *et al*. 1997). The FOML provides protocols for data collection on water quality, ecological variables and physical structure. The second is the Habitat Measurement Programme, from the Office of Wetlands, Oceans and Watersheds, which involves both catchment and in-lake observations and has two purposes. First, it helps in placing each lake into a classification category. Secondly, it can help to identify anthropogenic disturbances and exposure that might be responsible for biological degradation (USEPA 1998). Therefore, two kinds of variables are measured:

- **Classification variables**: those attributes that are intrinsic to the system and relatively unaffected by human activities, e.g. geology, soils, lake and catchment morphology. The classification variables assist in placing the lake into one of the categories for which reference conditions have been determined. It is then possible to determine the deviation of attributes of the test lake from reference conditions, for both habitat and biological indicators.

- **Assessment variables**: those attributes which are either direct indicators of human activity, e.g. land use and discharges; or influenced by human activity, e.g. most water quality variables.

Catchment metrics are obtained to assess whether catchment conditions might account for observed ecological status. Several operations may impact lake habitat through sediment loading, nutrient loading, contaminant loading, hydrological changes, and direct habitat alteration through removal of wetlands. Most measures of morphology and land use can be obtained from maps and GIS databases. The field sampling programme includes in-lake physical and chemical measurements, as well as a shore zone habitat survey generating metrics derivative of the FOML (cf. Baker *et al*. 1997) as summarised in Tables 14-16.

Table 14 Catchment and basin habitat measurement and metrics (USEPA 1998).

Measurements	Additional metrics	Calculation	Indicator
LAKE AND BASIN MORPHOLOGY			
Catchment drainage area		Estimated from map contours	Hydrology
Lake surface area		Map	
	Catchment: Lake area ratio	Catchment area / lake area	Sediment, nutrients
Shoreline length	Shoreline development ratio		Effect of riparian zone
Lake volume		Estimated from basin contours	
Maximum depth		Measurement	Stratification potential
	Mean depth	Volume / surface area	
	Mean basin slope		
Lake outflow	Retention time	Volume / outflow	Eutrophication potential
LAND USE			
% forest or natural vegetation			Sediment, nutrients, hydrology
% agriculture	GIS database		Sediment, nutrients, contaminants
% urban and residential			Sediment, nutrients, contaminants, hydrology
	Catchment impervious surface	Estimate from land use	Sediment, contaminants, hydrology
Population density		US Census, state or county	Sediment, nutrients, contaminants, hydrology
Discharges		USEPA NPDES database	Nutrients, contaminants
Road density		Maps, GIS	Sediment, contaminants, hydrology

Table 15 Physical and chemical measurements and metrics (USEPA 1998).

Measurements	Metrics	Calculation	Indicator
T profile	Epilimnion temperature Hypolimnion temperature Metalimnion depth	Mean from temperature profile Mean from temperature profile Inflection point of temp. profile	
DO profile	Epilimnion DO Hypolimnion DO Oxycline depth Hypoxic volume	Mean from DO profile Mean from DO profile Depth where DO falls to >2mgL^{-1} Volume of water with DO<2mgL^{-1} (annual or seasonal mean)	 DO problems DO problems
Secchi Depth (SD)	TSI(SD)=60-14.41 ln(SD)		Transparency
Total N	TSI(N)=54.45+14.43 ln(TN)		N enrichment
Total P	TSI(P)=4.15+14.42 ln(TP) N:P ratio	 N conc. / P conc. (molar)	P enrichment
Silica			Depletion
Acid Neutralizing Capacity	ANC		Sensitivity to acidification
pH	pH		Acidity
Total Dissolved Solids	TDS		Dissolved minerals

TSI = Trophic State Index

Table 16 Lakeshore habitat measurements and metrics (USEPA 1998).

Habitat Measurement	Mean % Cover	Indicator
Bank Measurement - Rocky (%) - Soil (%) - Vegetation (%) - Other (%)	Mean % cover from shorezone habitat transects	Bank stability
Bank Erosion (0 – 4)	0 = none; 4 = severe erosion	
Riparian Vegetation Measurements - Canopy (% cover) - Understorey (% cover) - Ground Cover (% cover)		Disturbance
Human Influence Measurements Buildings - In-lake structures - Roads, railroads - Agriculture - Lawn - Dump or landfill	Influence score (mean score of transects) Presence / absence	Human influence

4.11 Overview of methods for WFD hydromorphological quality elements

The hydromorphological features of lakes have been assessed by many authors, using a wide range of approaches. The principal methods identified for measuring the hydromorphological quality elements defined by the WFD are listed in Tables 17 and 18. Several potential metrics have been identified for each attribute; for example, there are five different methods for calculation of residence time, and water level may be measured over a range of time intervals. There are fewer methods with inbuilt facility to assess the degree to which the quality elements deviate from the natural condition, in line with the focus of the Directive; and the methods vary in the ease with which they could be adapted for this purpose.

Table 17 Summary of methods for measuring hydrological quality elements of lakes.

SEE SECTION	METRIC	METHOD
QUANTITY AND DYNAMICS OF FLOW		
4.7	Distribution of currents	Profiles of water temperature and conductivity Current cross-drag Model flume studies
4.7	Surface currents	Floats (airborne or boat survey) Ultrasonic current meter
4.7	Sub-surface currents	Submerged current recorders
4.7	Tendency to stratify	Calculation using morphological and meteorological attributes Remote sensing of surface temperature
4.7	Surface inflow and outflow rates	Flow gauging
4.7	Modification of flow regime of feeding and effluent watercourses	DHRAM for running waters
LEVEL		
4.5	Daily water levels	Stage posts, limnographs etc.
4.5	Hourly water levels	Electronic pressure transducers
4.5	Period water level range	Maximum-minimum recorders
4.5	Level duration curves	Calculation from water level records
4.5	Average water level	Calculation from water level records
4.5	Flood prediction	Hydrological simulation models
4.5	Human impact score for water level regime	DHRAM for standing waters
4.5	Historical changes in level	Stratigraphical/archaeological techniques
RESIDENCE TIME		
4.8	Theoretical average residence time	Calculation (volume / annual net rainfall, inflow or outflow)
4.8	Instantaneous residence time	Calculation (volume/daily discharge)
4.8	Forward/backward residence times	Calculation (volume/∑daily rainfall)
4.8	Actual residence time	Tracer techniques, modelling
CONNECTION TO GROUNDWATERS		
4.9	Rate of water exchange between lake and groundwater	Seepage flux measurements Tracer techniques Water balance calculations Darcy's Law
4.9	Inferred connectivity based on nature of local geology and superficial deposits	Examination of geological maps (solid and drift) Borehole samples

Table 18 Summary of methods for measuring morphological quality elements of lakes.

SEE SECTION	METRIC	METHOD
DEPTH VARIATION		
4.2 4.2	Bathymetric chart	Existing data Hydrographic survey
4.2 4.3	Mean and maximum depths	Analysis of hydrographic data Calculation from cartographic data
4.2	Median and quartile depths	Analysis of bathymetric data
4.2	Bottom roughness, form roughness	Analysis of bathymetric data
4.2	Hypsographic curve (lake form)	Analysis of bathymetric data
4.2	Depth changes through time	Repeat measurements
QUANTITY AND STRUCTURE OF SUBSTRATE		
4.4	Basin-scale erosion	Modelling
4.4	Rate of sedimentation	Repeat bathymetric survey Acoustic survey Coring and dating (^{14}C, ^{137}Cs, ^{210}Pb)
4.4	Sediment structure and distribution	Particle size analysis (cores or surface samples)
4.4	Current nature of sediment and rate of deposition	Sediment traps
STRUCTURE AND CONDITION OF SHORE ZONE		
4.6	Man-induced changes in sediment dynamics	Observation of migrating bed forms
4.6	Pattern of shoreline erosion	Definition of shoreline sediment cells from maps and observations (direct or remote i.e. air photographs*)
4.6	Wind erosion rate	Dendrochronology
4.6	Presence of artificial structures	River Habitat Survey approach; direct or remote observation*
4.10	Lakeshore habitat	USEPA approaches

* A review of the application of remote sensing methods for the implementation of the WFD is currently being undertaken by SEPA (D. Corbelli pers. com.).

5. EVALUATION OF METHODS FOR WFD PURPOSES

5.1 Introduction

The purpose of this section is to evaluate the methods reviewed in terms of their relevance to implementation of the WFD, with a view to formulating recommendations for a methodology suitable for use in the UK. Pertinent sections of the Directive are outlined below.

Article 5: Each Member State shall ensure that for each river basin district, or for the portion of an international river basin district falling within its territory, an analysis of its characteristics and a review of the impact of human activity on the status of surface waters and on groundwater is undertaken according to the technical specifications set out in Annex II (and an economic analysis of water use is undertaken according to the technical specifications set out in Annex III), to be completed at the latest by 22 December 2004. The analysis and reviews shall be reviewed and if necessary updated at the latest by 22 December 2013 and every six years thereafter.

Annex II: Characterisation of lakes and related surface water body types consists of:

1. Identification as lake, or as an artificial or heavily modified surface water body resembling a lake more closely than a river, transitional or coastal water.
2. Assignation of each water body to a Type.
3. Establishment of hydromorphological (and physicochemical) reference conditions for each Type at high ecological status, based on either spatial or modelling approaches or a combination.
4. Establishment of biological reference conditions for each Type; through development of a reference network of sites at high status if a spatial approach is employed, and/or by modelling using predictive or hindcasting methods (e.g. employing historical and palaeological data).
5. Collection of information on land use patterns (urban, industrial, agricultural, fisheries, forests) and the type and magnitude of significant anthropogenic pressures to which water bodies are likely to be subject; including point and diffuse source pollution, water abstraction, flow regulation, morphological alterations, and other causes of significant anthropogenic impacts.
6. Assessment of the susceptibility of the surface water status of lakes to these pressures, and the likelihood that they will fail to meet the environmental quality objectives set out in Article 4 (essentially, good ecological status or potential by 22 December 2015).
7. Further characterisation relevant to optimising the design of programmes for monitoring (Article 8) and application of measures (Article 11) to prevent deterioration of, to enhance and to restore those water bodies deemed to be at risk of failing the environmental quality objectives (Articles 1, 4; Annex V).

The material is presented in three sub-sections, focusing on different aspects of WFD implementation, as indicated below.

Section of this report	Sections of Directive	Outline
5.2	Article 5 / Annex II, 1.3	Characterisation of River Basin Districts; establishment of type specific reference conditions; development of hydromorphological reference conditions.
5.3	Annex II, 1.4/5	Assessment and reporting of pressures and impacts upon hydromorphology; aid the identification of pressures on hydromoprhology and the risk assessment of current activities / proposed developments (e.g. river engineering works).
5.4	Articles 1, 4 / Annex V (environmental objectives)	Prevent deterioration / restore to good status for hydromorphological quality elements supporting biological quality elements at good/moderate status.
	Article 8 (monitoring of surface water status)	Contribution to surveillance / operational monitoring for hydromorphological quality elements.
	Article 11(i) (programme of measures)	Measures to ensure hydromorphological conditions of the bodies of water are consistent with required ecological status.

5.2 Typology and reference conditions

5.2.1 Rationale

The lakes in each River Basin District are to be differentiated according to type, as described in Annex II of the Directive. Types may be defined using the full set of factors given for “System A” or using the obligatory factors plus any number of the optional factors given for “System B” (Table 19). The Directive indicates that a non-biotic typology should first be established; then physical and, later, biological reference conditions derived for each type. This is, essentially, the approach employed by USEPA (Section 4.10) in distinguishing between so-called “classification variables”, which describe attributes that are intrinsic to the system and relatively immune to human influence (e.g. geology, soils, lake and catchment morphology) to place each lake into a category for which reference conditions have been determined.

Table 19 Outline of “System A” and “System B” typology systems for lakes (WFD Annex II).

System A	System B	
DESCRIPTORS	OBLIGATORY FACTORS	OPTIONAL FACTORS
Ecoregion	Latitude and longitude	Hydrological regime: Water level fluctuation Residence time
Altitude category: High >800m Mid-altitude (200 – 800m) Lowland (<200m)	Altitude	Mixing characteristics (e.g. monomictic, dimictic, polymictic)
Depth category: < 3m 3m – 15m >15m	Depth	Morphology: Mean water depth Mean substratum composition Lake shape
Surface area category: 0.5 – 1 km^2 1 – 10 km^2 10 – 100 km^2 >100 km^2	Size (surface area)	Temperature: Mean air temperature Air temperature range
Geology: Calcareous Siliceous Organic	Geology	Chemical status: Acid neutralising capacity Background nutrient status

Wallin *et al*. (2002) state that, ideally, only physico-chemical, hydromorphological and pressure criteria (i.e. community driving forces) should be used in the first step of establishing reference conditions, principally because the use of biological quality elements at this stage may introduce circularity by employing the same variable to define the reference condition as will later be used to validate it. Also, human bias may be introduced; and rare water body types (e.g. naturally nutrient poor, low diversity water bodies) overlooked. However, the use of biological data at this stage is not precluded, largely for practical reasons. If it proves necessary to use all of the (limited) data that are to hand, including biological data, to identify potential reference sites, they recommend that additional biological data (e.g. for other quality elements) are collected to verify the final identification of a site as a reference. Reynoldson and Wright (2000) also emphasise that the population of reference sites must represent the full range of conditions that are expected to occur naturally, and propose a three-stage process for their selection. They suggest that a stratification method, usually based on physical attributes such as ecoregion and depth for standing waters, should first be applied to ensure that the full range of conditions is represented. Local knowledge and iterative examination of biological data might then be used in the final selection of reference sites. Perhaps these practical suggestions arise in part from the fact that our knowledge of functional relationships between physical factors and biological quality as defined by the Directive is incomplete. Nonetheless, there is some evidence in the literature that such relationships do exist; for example the close dependence demonstrated by Salmaso *et al*. (2002) between trophic status and the extent of spring vertical mixing and residence time in two large, deep subalpine lakes in Italy.

5.2.2 Existing approaches

Employing the "System A" approach of Table 19 would place the whole of the British Isles within two ecoregions (17 Ireland and Northern Ireland; 18 Great Britain), and define a maximum of 108 lake types for each (Table 20).

Table 20 Schematic Type A classification of lakes in Great Britain.

The maximum number of types that could be defined for one ecoregion on the basis of definition of three classes (L: lowland; M: mid-altitude; H: high) for altitude, three (S: Siliceous; C: Calcareous; O: Organic) for geology and three (1: < 3m. 2: 3m – 15m; 3: >15m) for depth in combination with four categories (A: 0.5 –1 km^2; B: 1–10 km^2; C: 10–100 km^2; D: >100 km^2) for lake area (Table 19), is indicated.

Ecoregion		18 Great Britain								
	Altitude	Lowland <200 m			Mid-altitude 200-800 m			High >800 m		
	Geology	S	C	O	S	C	O	S	C	O
Area	Depth									
A	1	LSA1	LCA1	LOA1	MSA1	MCA1	MOA1	HSA1	HCA1	HOA1
B	1	LSB1	LCB1	LOB1	MSB1	MCB1	MOB1	HSB1	HCB1	HOB1
C	1	LSC1	LCC1	LOC1	MSC1	MCC1	MOC1	HSC1	HCC1	HOC1
D	1	LSD1	LCD1	LOD1	MSD1	MCD1	MOD1	HSD1	HCD1	HOD1
A	2	LSA2	LCA2	LOA2	MSA2	MCA2	MOA2	HSA2	HCA2	HOA2
B	2	LSB2	LCB2	LOB2	MSB2	MCB2	MOB2	HSB2	HCB2	HOB2
C	2	LSC2	LCC2	LOC2	MSC2	MCC2	MOC2	HSC2	HCC2	HOC2
D	2	LSD2	LCD2	LOD2	MSD2	MCD2	MOD2	HSD2	HCD2	HOD2
A	3	LSA3	LCA3	LOA3	MSA3	MCA3	MOA3	HSA3	HCA3	HOA3
B	3	LSB3	LCB3	LOB3	MSB3	MCB3	MOB3	HSB3	HCB3	HOB3
C	3	LSC3	LCC3	LOC3	MSC3	MCC3	MOC3	HSC3	HCC3	HOC3
D	3	LSD3	LCD3	LOD3	MSD3	MCD3	MOD3	HSD3	HCD3	HOD3

Whilst the System A typology is straightforward and simple to implement, there seems to be no guarantee that the results will be ecologically meaningful. Wallin *et al*. (2002) state that the objective of establishing typologies is to partition among-group variance in order to facilitate the detection of ecological change, and point out that the classes established using System A may not adequately fulfil this function. Given the inflexibility of System A, they consider that most Member States are likely to use System B as a basis for characterising water body types, delimiting them using grouping procedures based on commonly used clustering techniques or more intuitive (expert opinion) methods. Statistical methods might also be employed to determine whether or not groups differ from one another (e.g. using randomisation techniques) and whether among-group variance can be adequately explained (e.g. using discriminant analysis). For Ireland and Austria, “System B” typologies based on the obligatory factors, and incorporating some additional attributes that are considered appropriate for each country, have been proposed by Irvine *et al*. (2002) and ÖNORM (2001) respectively (Table 21); although neither appears to be based upon rigorous statistical analysis at this stage.

Table 21 Proposed typological schemes and categories for Ireland and Austria

Sources: Irvine *et al*. (2002) and ÖNORM (2001).

Descriptors	Ireland		Austria
Location	Latitude, longitude (relevance to be investigated through field trials and consideration of the recommendations of the EU and EPA reference conditions projects).		Latitude, longitude
Ecoregion	Ireland is covered by a single WFD ecoregion.		According to Illies (1978)
Altitude	High: > 800 m Mid-altitude: 200 – 800 m Lowland: < 200 m		Alpine: > 1000 m High: > 800 - 1000 m Mid-altitude 2: 500 – 800 m Mid-altitude 1: 200 – 500 m Lowland: < 200 m
Depth	Mean depth (data will need collation and/or models)		Mean depth < 3 m 3 – <15 m 15 - < 30 m > 30 m
Surface area	< 2 ha 2 - 50 ha 51 - 100 ha 101 - 1000 ha 1001 - 10000 ha >10000 ha	< 0.02 km^2 0.02 - 0.5 km^2 >0.5 – 1 km^2 >1 – 10 km^2 >10 – 100 km^2 >100 km^2	< 0.5 km^2 > 0.5 - 1 km^2 > 1 – 10 km^2 > 10 – 100 km^2 > 100 km^2
Others	Residence time is likely to be critical for lakes and the absence of reliable residence time for many Irish lakes requires collaborative research to address this as a matter of priority.		Mean temperature
	Geology: conductivity defines mixed geology lakes and saline incursion.		Air temperature range
	Colour in Irish lakes is clearly important in defining typology, but may be covered by inclusion of drainage from peatlands.		Mixing characteristics (monomictic, dimictic, polymictic, meromictic)
	Specific lake types such as turloughs, spring-fed lakes, saline lakes, large lakes will need to be addressed separately in terms of hydromorphological typologies.		The above are examples of optional factors that might be included.
	There is a need to collate relevant hydromorphological data for lakes covering a wide geographical range with a view to statistical interrogation.		

A second approach to the identification of reference conditions and sites employs palaeoecological techniques, and is described by Bennion *et al*. (undated). Simple hierarchical clustering techniques were used to classify the diatom assemblages in existing cores from 166 UK lakes for the year 1850 (i.e. prior to human disturbance) into six groups. Discriminant analysis was then used to assess how well eight physical descriptors (altitude, surface area, maximum depth, fetch, stratification class, dominant freshwater sensitivity to acidification class (FWS), % calcareous geology, % peat) explained this grouping. Three of the descriptors were significant, explaining 17% of the diatom data distribution, as indicated in Table 22.

Table 22 Description of the six diatom groups identified by Bennion *et al*. (undated) according to physical descriptors.

Diatom group	No. of lakes	Altitude	Size	Depth	Mixing	Nutrients/ acidification	Other
1	19	Lowland	relatively large	range	stratified	Mostly low FWS (alkaline)	includes many loughs in Northern Ireland
2	22	Lowland	relatively small	Mostly shallow	Stratified	high % calcareous geology, low FWS, highly alkaline	
3	43	Mostly upland	relatively small	range	Mostly stratified	High FWS, acid	
4	23	Mostly lowland	large	deep	Stratified	Range of FWS, acid	
5	24	range	range	Relatively deep	Stratified	High FWS, acid	
6	35	range	range	range	-	Mostly med-high FWS, circumneutral	
Total	166						

The results were equivocal. The strongest signal appeared to be related to water chemistry (FWS being a reflection of alkalinity), but some relationships were apparent between diatom assemblages and hydromorphological attributes especially altitude, size and depth, identifying these as potentially useful typological criteria. A search for potential reference lakes was based on assessment of the similarity of present diatom assemblages to those recorded in 1850. This analysis indicated that there are very few, if any, potential (i.e. undisturbed) reference sites for Diatom Groups 1 and 2. The study will continue with analysis of new cores from 35 sites selected to represent lake types that are poorly represented in the existing database; to explore the use of the multi-proxy palaeoecological record (range of biological indicators) in defining site-specific ecological reference conditions for lakes for which reference sites cannot be found in the current UK lake population; and to develop an analogue matching approach for identification of the most suitable reference sites for impacted lakes.

Biological data are currently being collected at 30 apparently undisturbed Scottish lochs (Table 23) representing all six of the Diatom Groups listed in Table 22.

Table 23 List of Scottish lochs where biological data are being collected. Source: J. Tuck (SEPA).

Site Name	Grid Ref.	Max. Depth (m)	Macroinverts - Profundal	Macroinverts - Littoral	Macrophytes	Phytoplankton	Water Chemistry
Loch Borralie	NC 381670	17	Y	Y	N	Y	Y
Loch Croispol	NC 390 683		N	Y	N	Y	Y
Loch Swannay	HY 3112811	4.5	N	Y	N	Y	Y
Black Loch	NT 075 961	6.2	N	Y	Y	Y	Y
Loch Hempriggs	ND 343 471	2.3	N	Y	N	Y	Y
Muckle Water	HY 395300	5.1	N	Y	N	Y	Y
Loch Achnacloich	NH 664736	7.3	N	Y	N	Y	Y
Loch Lonachan	NG627191	9.7	N	Y	N	Y	Y
Loch Grogary (Croghearraidh)	NF716711	2	N	Y	N	Y	Y
Loch Skeltair	NF 897 688	11	N	Y	Y	Y	Y
Loch na Beiste	NC 004125	11.9	N	Y	Y	Y	Y
Lochan Dubh	NM 895710	6.3	N	Y	N	Y	Y
Loch Bharranch	NG 977575	12.2	N	Y	Y	Y	Y
Loch Maree	NG 985675	111.9	Y	Y	N	Y	Y
Loch Lomond North Basin	NS 365945	189.9	Y	Y	N	Y	Y
Loch Rannoch	NN 610580	134.1	Y	Y	N	Y	Y
Loch of Craiglush	NO 042444	13.4	N	Y	N	Y	Y
Loch Tarff	NH 425100	27.1	Y	Y	N	Y	Y
Loch Lubnaig	NN 585130	44.5	Y	Y	N	Y	Y
Loch Kinord	NO 442995	3.7	N	Y	N	Y	Y
Loch na Gaineimh	NC 768305	13.2	N	Y	N	Y	Y
Loch Doilet	NM 808678	16.8	Y	Y	Y	Y	Y
Loch Ussie	NH 505574	10.7	N	Y	N	Y	Y
Loch Osgaig	NC O38 129	55	Y	Y	N	Y	Y
Loch Ruthven	NH 603 276	13	Y	Y	N	Y	Y

Another biological approach that gives some indication of the physical attributes that may have significance for ecology is offered by the work of Palmer *et al*. (1992), who classified standing waters in Britain on the basis of an indicator species analysis of vegetation. The analysis yielded 10 site types and two variants, which were subjectively associated with different types of lakes with different distributions within the UK (Table 24). On this basis, the physical criteria of lakes associated with variation in composition of macrophyte assemblages appeared to be: nutrient status (oligotrophic, mesotrophic, eutrophic and saline influence); drift geology (peat); solid geology (base poor, slightly base-rich, calcareous); substrate texture (fine, coarse or rock), and size (small, large).

One further insight into the range of lake types in the UK is offered by the compilation of habitats and species of Annexes I and II of the Habitats Directive, under WFD surface water categories, prepared by Lewis (2002). The six standing water lake habitat types represented in the UK are included under lakes, namely:

3110 Oligotrophic waters containing very few minerals of sandy plains (*Littorelletalia uniflorae*)

3130 Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*

3140 Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.

3150 Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation

3160 Natural dystrophic lakes and ponds

3180 Turloughs

However, no hydromorphological attributes are given.

In all cases, there appears to be a strong link between biological variation and water chemistry. The latter is influenced in turn by bedrock (solid) geology and soil characteristics because different minerals and rock types vary in their resistance to chemical weathering, and by the presence of wetlands due to the capacity of humic material to exchange ions and bind metals (Håkanson and Peters 1995).

The failure of biological classifications to yield consistent hydromorphological typologies for lakes is reminiscent of the outcome of the New Zealand “100 Rivers Project”, reported by Biggs *et al*. (1990). This project involved a comprehensive programme of data collection on catchment characteristics, flow regime, water chemistry, optical properties, periphyton, benthic invertebrates and trout. Separate classifications based on flow variability, water quality, periphyton, invertebrates and trout were conducted, using correlative models, with the intention that the classifications would later be combined. However, there were no clear similarities amongst classifications performed on the different biological groups, so that it was impossible to develop a unified classification scheme based solely on the biological character of the country’s river systems. Discriminant analysis indicated that different environmental variables were important in each of the classifications (Table 25).

Table 24 Classification of standing waters in Britain (after Palmer *et al.* 1992).

Type	Nutrient status	Dominant species	Lake characteristics
1	Dystrophic	Submerged *Sphagnum*, *Juncus bulbosus*	Pools and small lochs on blanket bog in northern Scotland; a few pools on acid substrates in southern Britain
2	Oligotrophic/ base poor	*Juncus bulbosus*, *Potamogeton polygonifolius*	Upland tarns in the English Lake District; peaty lochs in northern Scotland; pools on Lizard peninsula in Cornwall
3	Oligotrophic/ base poor	*Myriophyllum alterniflorum*, *Isoetes lacustris*, *Fontinalis antipyretica*	Larger and rockier than Type 2, on base-poor rocks in Scotland (Loch Lomond), the English lake District (Wastwater, Buttermere, Coniston), north Wales (Llyn Ogwen, Llyn Idwal, occasionally elsewhere (Oak Mere, Cheshire).
4	Mixture of influences	As Type 3 with *Potamogeton filiformis*, *P. praelongus*, *Myriophyllum spicatum*, *Chara* spp.	Coastal freshwater lochs of the Scottish islands
5	Mesotrophic	Var A: (species-rich): *Littorella uniflora*, *Myriophyllum alterniflorum*, *Nitella* spp., *Potamogeton* spp., *Elodea canadensis* Var B: (species-poor): *Potamogeton natans*, *Nymphaea alba*.	Lakes in Scotland and northern England, often on slightly base-rich rock (e.g. Bassenthwaite, Windermere, Esthwaite Water, Lake of Menteith)
6	Brackish	*Potamogeton pectinatus*, *Ruppia* and *Fucus* spp.	Brackish sea lochs on islands off the north and west coasts of Scotland
7	Eutrophic/ base rich	As Type 4 but lacking *Myriophyllum alterniflorum*, *Juncus bulbosus*	Lochs with a strong marine influence on shell sand, limestone and Old Red Sandstone in northern Scotland
8	Eutrophic/ base rich	Poor in open water species but rich in emergents; *Lemna minor*, *Callitriche stagnalis*, *Polygonum amphibium*.	Meres of glacial origin in the West Midlands, scattered sites elsewhere. All have fine substrates. Calthorpe Broad, Norfolk.
9	Eutrophic/ base rich	*Nuphar lutea*, *Nymphaea alba*	Scattered throughout England and Wales, very few in Scotland
10	Eutrophic/ base rich	*Myriophyllum spicatum*, *Potamogeton pectinatus*. Var A: *Elodea canadensis*, *Lemna minor*; Var B: *Chara* species	Lowland lakes on sedimentary rocks, often calcareous, with predominantly fine substrates. Artificial sites such as gravel pits and little-used canals, also Malham Tarn in Yorkshire

Table 25 Summary of variables identified as significant at primary and secondary level in each of the classifications of New Zealand rivers.

Classification based on :				
Flow variability	**Water quality**	**Periphyton**	**Invertebrates**	**Trout**
Primary variables				
% flat land Northern steep soils Site elevation Water storage high Water storage med.	Catchment elevation % developed pasture % exotic forests % lime % schist % soft sediments % steep land % town % tussock grass % volcanic ash	Catchment elevation % developed pasture % hard sediments % southern alpine soils % yellow-grey soils	Catchment elevation % developed pasture	% alluvium % rolling % scrub % tussock % volcanic ash
Secondary variables				
Area % lakes	Inverse specific yield*	Conductivity Dissolved reactive-P Low-flow power Silica Specific yield* Temperature	Absorbance Conductivity Mean annual temp. Mean / median flow Median flow Slope of river Visibility	% lakes Mean annual low / median flow Minimum annual temperature

* Specific yield calculated as (median flow ÷ catchment area)

Ecologically sensible groupings of rivers were achieved using an alternative approach, involving distinction of five “ecoregions” with boundaries positioned on the basis of rock type, flow and water quality characteristics, chosen because the biological communities had been shown to be primarily related to these physical factors:

1. Northern Ecoregion: low-moderate mean catchment elevations, moderate enrichment, and moderate-high mean annual water temperature.
2. Central Ecoregion: high mean elevations, high amounts of volcanic ash, low variability of flow and low-conductivity waters.
3. Eastern Ecoregion: moderate to high amounts of soft sedimentary rock, associated high conductivities and enrichment, and high flow variability.
4. South-western Ecoregion: small catchment sizes, low amounts of pasture, and low-conductivity waters.
5. Southern Ecoregion: high catchment elevations, low water temperatures, high amounts of hard sedimentary rock, low conductivity and enrichment.

ANOVA analysis indicated that the primary variables distinguishing ecoregions were climate, catchment elevation, geology (% volcanic ash, hard and soft sediments) and land use (% pasture, grassland, forest); and that the secondary variables were hydrology (area, median flow, specific yield, flow variability) and water quality (conductivity, dissolved reactive-P {DRP}, mean annual temperature, total inorganic-N {TIN}, TIN:DRP ratio). Once the ecoregions had been defined, it proved possible to define the dominant biological communities for each.

5.2.3 Towards a UK typology for lakes

On the basis of the typologies proposed for Ireland and Austria, and the advice of Wallin *et al.* (2002), it appears that the System A typology is unlikely to prove adequate for UK purposes. An *ad hoc* System B typology would generate a large number of classes, many of which may not be represented in the UK. Therefore, development of a System B typology through statistical clustering of UK data is preferable (Section 6.2). Such a typology could be developed only after collection and collation of data, so that it will not be clear at the outset exactly which variables are to be included in the eventual typology. However, the short time available makes it likely that only one data collection exercise can be undertaken during the first phase of implementation of the Directive. The results must, therefore, serve not only to derive an effective typology but also retrospectively to place each lake into the appropriate class. Therefore, the choice of variables is critical and constrained by such considerations as:

1. Ideally, non-biological attributes only should be considered. They should be relatively insensitive to human activities, i.e. "classification variables" as described by USEPA (1998) (Section 4.10) and linked, as far as is known, to ecological quality.

2. The data compiled should be capable of generating at least all the variables required to fit each lake into the minimum System A or System B typology required by the Directive. However, it is desirable to include additional information so that some of the optional descriptors can be introduced if appropriate.

3. In view of the wide geographical range and limited time available for establishment of the typology, variables should, as far as possible, be derivable by desk study (using maps and other existing sources of information, e.g. aerial photographs) rather than by field survey. They should, on the one hand, reflect the WFD hydromorphological quality elements; but on the other hand be selected economically in terms of the effort required to locate, collate and analyse them.

The typologies proposed for Ireland and Austria (Table 21) both include mean depth as one of the typological variables. This has little physical significance for a lake with more than one basin (e.g. Figure 16; it has been suggested that such lakes should be sub-divided for WFD purposes). An alternative that seems worthy of consideration is to base the typology on maximum depth (which reflects stratification behaviour, Figure 13) and lake form class (Table 5) which, when combined with lake area, provide a useful representation of the physical size and shape of the lake's basin.

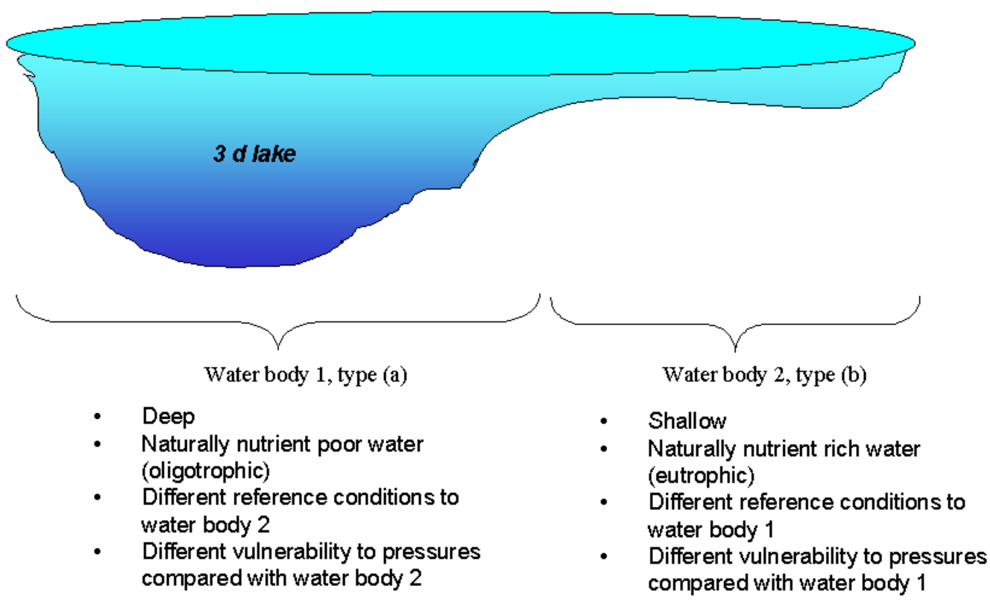

Figure 16 Representation of a lake comprising two basins with significantly different morphological (and ecological) characteristics. From Wallin *et al.* (2002).

Candidate data and reasons for their selection are listed in Table 26. Whilst the morphological variables do not correspond exactly to those listed by the Directive, both the minimum typological requirements and a wide range of additional variables (Sections 4.2 and 4.3) could be derived from this information.

Table 26 Non-biological data required to form the basis of lake classification.

Variable	Source	Reason
Location		
Latitude/longitude	Published maps	Obligatory WFD location reference
National Grid Reference	Published maps	UK location system. Climate and net surface water balance vary with geographical location; these in turn influence quantity and dynamics of flow, water level regime (and hence connection to groundwaters) and residence time of lake.
Catchment characteristics		
Altitudinal range of catchment	Published maps	Influences climate and climate-dependent factors; also enables estimation of lake volume and depth (Table 7)
Solid geology	Published geological maps	Influences water chemistry, connection to groundwaters and sediment structure.
Drift geology	Published geological maps	Influences water chemistry, connection to groundwaters and sediment structure. Peat is of special importance.
Catchment area	Published maps	Enables calculation/modelling of lake volume and theoretical discharge (Table 7); influences flow dynamics, water level, residence time and sediment processes.
Attributes of lake		
Altitude of lake surface	Published maps	Obligatory WFD factor. Also affects temperature, climate and climate-dependent factors.
Surface area	Published maps	Obligatory WFD factor; required for calculation of mean and maximum depths and shore development (Table 7); influences flow dynamics and water level.
Perimeter	Published maps	Enables calculation of shore development (Tables 6, 7); influences sediment dynamics and connection to groundwaters.
Depth data	Published bathymetry Calculation Modelling	Ideally, full bathymetric data from published sources or new survey, which gives access to maximum depth (influences stratification), mean depth and a range of other morphometric variables plus the hypsographic curve (Table 6). Where such data cannot be obtained, maximum depth and lake form class (Table 5) might be substituted. As a last resort, depth data could be obtained by calculation/modelling (Table 7).

5.3 Pressures and impacts

5.3.1 Rationale

Once a typology has been established, the next phase of WFD implementation involves identification of undisturbed reference sites; reporting of actual and potential anthropogenic pressures on non-reference water bodies; and assessment of their susceptibility to these pressures in terms of impacts on surface water status. The material which follows suggests how the pressures operating on lakes in the UK might be identified, the ways in which these pressures may influence the hydromorphological quality elements, and how the assessment of risks associated with current activities and proposed developments (e.g. river engineering works) might be approached.

5.3.2 Identification of pressures

The pressures operating in the catchment of an individual lake can be assessed by direct observation; one scheme is outlined in Table 27. However, the scale of the exercise required for WFD implementation is such that it will be expedient to use desk-based information sources as far as possible. Indicators of pressures (Table 3), and possible reference sources, are shown in Table 28.

Table 27 Evidence of human pressures on lakes (Herlihy, 1997)

ACTIVITY	EVIDENCE
Residences	Presence of houses around the lake
Construction	Presence of recent construction in the immediate area around the lake
Pipes/Drains	Presence of pipes and drains feeding into or out of the lake (add type of activity e.g. storm sewer, plant intake etc. if known)
Waste Water Treatment Plant	Presence of sewage treatment facility
Landfill	Any evidence of landfill or dumping around the lake, including rubbish pits and informal dumping of large amounts of trash or cars and appliances along roads or lakeshore.
Parks etc.	Presence of organised public or private parks, campgrounds, beaches or other recreational areas around the lake.
Resorts	Level or resort activity e.g. hotels, resorts, golf courses and stores
Marinas	Presence of any marinas
Litter	Relative abundance of trash or litter around the lake
Scum/Slicks	Relative abundance of scum or slicks around the lake
Agriculture	Present of cropland, pasture, orchards and livestock
Industry	Any industrial activity (e.g. chemical, pulp) around the lake or catchment.
Mining/Quarrying	Evidence of mining and quarrying within or around the lake
Power Lines	Present of any power generating facilities or heavy duty transmission lines around or across the lake (not ordinary telephone or electric wires)
Power Plants	Presence of power station
Logging/Fires	Any evidence of logging or fire removal of trees in the lake area
Macrophyte Control	Any evidence of dredging or the application of chemicals
Liming	Any evidence of liming activities
Angling Pressure	Estimate of the intensity of fishing activity in the lake
Fish Farms	Evidence of fish cages within or around the lake

Table 28 Information that is relevant to assessment of pressures on the WFD hydromorphological quality elements for lakes, with potential sources.

Pressure	Field observations	Desk-based	Source
Agriculture in catchment	Present of cropland, pasture, orchards and livestock	Land cover maps for Scotland; any similar sources for rest of UK	*Land Cover of Scotland* dataset (Macaulay Institute, Aberdeen)
Forestry in catchment	Presence of plantations	Plantations shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Irrigation in catchment	Observations during dry weather	Abstraction licences for England	Environment Agency (EA) records
Recreational use of catchment	Presence of organised public or private parks, campgrounds, beaches or other recreational areas around the lake; presence of sign-posted footpaths	Campgrounds, car parks, footpaths etc. shown on published maps	Ordnance Survey 1:50,000 and 1:25,000 (e.g. *Explorer* and *Outdoor Leisure* series) maps
Military use of catchment	Signs and observation	Military training areas marked on published maps	Ordnance Survey 1:50,000 and larger scale maps
Use for water supply (abstraction)	Evidence of pipelines, catchwaters etc.	Abstraction licences in England	Environment Agency (EA)
Upstream water use	Presence of power stations, dams and reservoirs upstream	Power stations, impoundments and reservoirs shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Urbanization	Presence of buildings	Buildings shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Mineral exploitation	Presence of mine workings and quarries	Mines and quarries shown on published maps; mining records	Ordnance Survey 1:50,000 and larger scale maps
Water supply	Presence of dam, flow diversions, water treatment works	Dam, diversions and works shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Hydro-power	Presence of dam, flow diversions, power station	Dam, diversions and power station shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Watersports	Presence of equipment and facilities for access to water (e.g. slipway)	Buildings, piers, slipways shown on published maps	Ordnance Survey 1:50,000 and larger scale maps
Navigation	Presence of boats, quays, ferry terminals etc.	Ferry routes marked on published maps	Ordnance Survey 1:50,000 and larger scale maps
Mineral exploitation	Rig, sight of operations, stockpiles	Possibly known to environment and conservation Agencies	SEPA, EA, EN, SNH, CCW
Fish farming	Presence of cages	Monitored by Agencies	SEPA, EA

It is apparent that not all of the pressures can be identified reliably in this way throughout the UK; for example because water abstraction in Scotland is not yet subject to licensing. Thus, a brief field visit or input of local knowledge may be necessary to supplement desk-based data collection. It is noteworthy that land cover data, based on information produced by the Macaulay Institute, have already been compiled for the catchments of the 29 Scottish freshwater lochs[9] sampled by Bennion *et*

[9] The sites for this study were selected for either high environmental value or the fact that they showed some signs of degradation; they were Lochs Awe, Butterstone, Carlingwark, Castle, Castle Semple, Chon, Davan,

al. (2001). Air photography might also be considered as a source of information, although most of the existing prints are several years old and at scales that will reveal little more information than can be obtained from Ordnance Survey maps. The coverage of the whole UK flown by "Get Mapping" in 2000/2001 and available in high resolution TIF format may be worth investigation in this context.

One outcome of this exercise will be the identification of those lakes that are subject to little or no human influence, and are thus potential reference sites.

5.3.3 The association between pressures and hydromorphological impacts

Tables 29 and 30 list the range of activities that might be carried out in association with each type of pressure identified for British lakes (Table 3), and their effects on hydromorphology. Thus, a set of potential hydromorphological impacts is associated with each of the human pressures. This provides a basis for screening each lake for quality elements at risk of distortion, by ascertaining which of the activities are actually present.

Table 29 Human pressures in lake catchments, the associated activities, and their potential impacts on hydromorphological conditions.

PRESSURE IN CATCHMENT	
Activities	Potential effects on hydromorphological conditions
AGRICULTURE	
Clearance of natural vegetation alters surface water balance	Change in flow dynamics, water level regime, connection to groundwaters, and residence time
Soil erosion associated with vegetation changes and tillage alters composition of sediment load and sedimentation rate	Influence on lake depth; quantity and structure of substrate
Cultivation cycles alter seasonal water balances	Change in flow dynamics, water level regime, connection to groundwaters, and daily/monthly residence times
Trampling of shore zone by animals; artificial modification of shore zone	Change in structure and condition of shore zone
Land drainage	Change in flow dynamics, water level regime, connection to groundwaters, and daily/monthly residence times
Changes in agricultural practice	May influence all hydromorphological quality elements, depending on nature of changes
FORESTRY	
Drainage and ploughing prior to planting leads to soil erosion, altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Drainage	Change in flow dynamics, water level regime, connection to groundwaters, and daily/monthly residence times
Water balance changes due to changes in structure of vegetation; occurring abruptly at planting/harvest, gradually as trees grow/mature.	Abrupt and progressive changes in flow dynamics, water level regime, connection to groundwaters, and residence time

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Dee, Doon, Earn, Eck, Einich, Eye, Grannoch, Harray, Kilbirnie, Kinord, Leven, Lomond, Lowes, Lubnaig, Maree, Menteith, Mill, Muick, Rannoch, Shiel, Skene and Ussie.

Irrigation (often associated with agriculture and forestry)	
Water abstraction directly from lake (water drains back into lake but potential for evaporative losses enhanced); direct modification of shore at abstraction point	Change in flow dynamics and daily/monthly residence times; also in water level regime and thus in connection to groundwaters and structure of shore zone
Dams and weirs to raise water level; direct modification of shore at dam	Change in water level regime and thus in connection to groundwaters, structure of shore zone, flow dynamics and residence time. Disruption of sediment transport.
Water abstraction from borehole(s)	Change in groundwater storage and connection of lake to groundwaters; possible influences on water level regime, structure of shore zone, flow dynamics and residence time
Recreation	
Erosion of paths and shoreline due to over-use by hill walkers and other visitors, altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Trampling or direct intervention causing changes in vegetation and thus in surface water balance	Change in flow dynamics, water level regime, connection to groundwaters, and residence time
Military activities	
Trampling or direct intervention causing changes in vegetation and thus in surface water balance	Change in flow dynamics, water level regime, connection to groundwaters, and residence time
Erosion, altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Mechanical disruption of vegetation and soil cover, especially at the water's edge	Alters structure and condition of shore zone
Water supply	
Groundwater abstraction	Change in groundwater storage and connection of lake to groundwaters; possible influences on water level regime, structure of shore zone, flow dynamics and residence time
Upstream water use	
Modification of flow regime of feeding watercourses	Change in flow dynamics, and thus in residence time, water level regime and connection to groundwaters.
Road building	
Excavation during building increases sediment supply altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Shoreline reinforcement/fixation using bricks, stone or concrete	Alters structure and condition of shore zone
Change in catchment infiltration capacity and artificial drainage alter surface water balance	Change in flow dynamics, water level regime, connection to groundwaters, and residence time
Culverting of lake outflow alters rate of discharge and sediment dynamics	Change in flow dynamics, and thus in residence time, water level regime and connection to groundwaters. Sediment effects may influence lake depth and quantity/ structure of substrate
Erosion of road-sides altering sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Urban development	
Disturbance of ground increases sediment supply altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Shoreline reinforcement/fixation using bricks, stone or concrete	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
Changes in catchment vegetation infiltration capacity and land drainage alter surface water balance	Change in flow dynamics, water level regime, connection to groundwaters, and residence time
Discharge of sewage leads to algal growth and increase in sedimentation	Influence on lake depth, quantity and structure of substrate
Mineral exploitation (mining and quarrying)	
Changes in sediment type and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Drainage and pumping of workings alters quantity and temporal pattern of water supply to lake	Change in flow dynamics, water level regime, connection to groundwaters, and residence time

Table 30 Human pressures within lake basins, and the associated risks and potential impacts on hydromorphological conditions.

PRESSURE WITHIN LAKE BASIN	
Activities	Potential effects on hydromorphological conditions
WATER SUPPLY (RESERVOIR)	
Construction works increase sediment supply altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Damming to raise water level	Change in water level regime and thus in structure of shore zone, connection to groundwaters, flow dynamics and residence time
Direct modification of shore at and in vicinity of dam	Localised change in structure of shore zone
Increase in maximum water level	Increase in area and maximum depth, changes in mean depth and depth variation
Sediment trapped by dam, disrupting sediment dynamics	Influence on lake depth, quantity and structure of substrate
Flow diversions to increase effective catchment area of reservoir	Change in flow dynamics, and thus in residence time, water level regime and connection to groundwaters.
Water abstraction	Change in flow dynamics and thus in water level regime, connection to groundwaters and residence time
Shoreline reinforcement/fixation using bricks, stone or concrete	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
HYDRO-POWER GENERATION	
Construction works increase sediment supply altering composition of sediment load and sedimentation rate	Influence on lake depth, quantity and structure of substrate
Damming to raise water level	Change in water level regime and thus in structure of shore zone, connection to groundwaters, flow dynamics and residence time.
Direct modification of shore at and in vicinity of dam	Localised change in structure of shore zone
Increase in maximum water level	Increase in area and maximum depth, changes in mean depth and depth variation
Sediment trapped by dam, disrupting sediment dynamics	Influence on lake depth, quantity and structure of substrate
Flow diversions to increase effective catchment area of reservoir	Change in flow dynamics, and thus in residence time, structure of shore zone, water level regime and connection to groundwaters.
Power generation	Change in flow dynamics and thus in water level regime, connection to groundwaters and residence time
Shoreline reinforcement/fixation using bricks, stone or concrete	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
RECREATION	
Construction of quays, jetties, slipways, marinas etc.	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
Mechanical damage to aquatic flora and increased wave energy, due to passage of craft	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
Damming to raise water level, e.g. for fishing and watersports; direct modification of shore at dam	Change in depth and water level regime; and thus in connection to groundwaters, structure of shore zone, flow dynamics and residence time. Disruption of sediment transport influences lake depth, quantity and structure of substrate.
Dredging to maintain suitable depth of water	Alters lake depth, quantity and structure of substrate

NAVIGATION	
Mechanical damage to aquatic flora and increased wave energy, due to passage of craft	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
Dredging to maintain navigation channel	Alters lake depth, quantity and structure of substrate
Construction of quays, jetties, slipways, etc.; shore reinforcement	Alters structure and condition of shore zone, both directly and through influence on shoreline sediment dynamics
Construction of locks and weirs	Localised change in structure of shore zone; change in flow dynamics and thus in water level regime, shoreline, connection to groundwaters and residence time
MINERAL EXPLOITATION	
Extraction of material from the lake bed, such as gravel	Alters lake depth, quantity and structure of substrate
Use of barges in mineral exploitation	See Navigation
FISH FARMING	
Use of boats to visit cages	See Navigation

5.3.4 Assessment of impacts

Having identified pressures and the aspects of hydromorpholgical quality that are susceptible to alteration through their operation, it remains to assess the degree of alteration in terms that indicate the degree of risk of impact on biota. Methods that could be employed in this context are described below.

5.3.4.1 Hydrological regime (quantity and dynamics of flow and water level)

The Dundee Hydrological Regime Assessment Method (DHRAM) is a method for calculating the degree of anthropogenic impact on surface waters in Scotland (Black *et al.* 2000b; 2002b). The scheme was designed to quantify the degree to which the hydrological regime of a river or lake departs from the natural condition (i.e. in the absence of anthropogenic influences). For rivers, the DHRAM scheme utilises an extensive array of regime measures, i.e. magnitude of monthly discharge characteristics, magnitude and duration of annual extreme discharge conditions, frequency and duration of high/low flow pulses, which are used to describe the ecologically significant aspects of the flow regime. For standing waters the water level regime is assessed through characterising the magnitude, frequency, timing and duration of water level fluctuations. The DHRAM process translates into one of five classes, ranging from ‘unimpacted condition’ to ‘severely impacted condition’. Central to the procedure is the concept of a natural neighbour (analogue site) which is used as a baseline against which to measure alteration.

Thus, DHRAM might be employed to assess the alteration of water level fluctuations in the lake; or to estimate impacts on the flow regimes of the watercourses that feed and drain the lake; there are links also to estimation of impact on residence time.

5.3.4.2 System sensitivity to water level changes

Smith *et al*. (1987) carried out a comparative study of water level regimes and littoral benthic communities in 27 lochs and reservoirs of the north and west of Scotland. On the basis of long term data they divided the water bodies into three categories according to water level changes:

- Natural water level fluctuations (N.B. limited data available): range zero – 2.1 m
- Minor water level fluctuations (i.e. within regulated reservoirs): range 1.0 – 3.7 m
- Major water level fluctuations (i.e. within regulated reservoirs): range 5-30 m

It is important to note that water level fluctuations in natural lochs (category 1) can be as great as those observed in reservoirs (category 2). However, this observation is based on a very limited dataset; and indeed there are very few long term datasets of water level variations on natural lochs in Scotland (Section 4.5). It was found (Smith *et al*., 1987) that littoral (defined as the zone 0-0.5 m in depth) macrophytes and zoobenthos communities were generally depleted where regular water level changes took place. This was the case not only under conditions of major fluctuations (5-30 m) in level but also when the variations were minor (1.0-3.7 m). Rich littoral communities, comparable with those associated with natural water level regimes, were found in regulated reservoirs that had an annual water level range of less than 5 m and where weekly fluctuations in water level were not greater than 0.5 m for 85-100% of the time. Impoverished communities were present at sites that failed to meet *either or both* of these criteria.

Clearly it is necessary to acquire some long time series data on natural lake level fluctuations so that the observed ranges in water level can be evaluated and compared with the Smith *et al*. (1987) data. Ideally, data acquired before and after a specific anthropogenic activity took place (see below) are needed, together with observations on the littoral communities (macrophytes, invertebrates etc.). The most important anthropogenic activities are likely to be:

<u>Causing a fall in water level</u>
Direct abstraction of water from a loch
Improved drainage (e.g. ditching)
Decrease in loch catchment area
Changes in hydrogeological drainage (e.g. due to groundwater abstraction)
Increase of woodland in the catchment

<u>Causing a rise in water level</u>
Damming of outflow from a loch
Increase in loch catchment area
Loss or decrease of woodland in the catchment
Removal of peat from the catchment

Whilst most consideration is intuitively (and quite correctly) given to the impacts of low water levels on littoral communities, anthropogenically-induced rises in water level must also be included. In this situation communities which are normally emergent can become periodically or permanently submerged. Fluctuations in loch water level (i.e. vertical amplitude) as a consequence of anthropogenic activities, though relatively easily recorded, are, however, not the sole control on biological communities inhabiting the littoral zone.

A significant complication in the consideration of the influence of lake level fluctuations on littoral communities is introduced by the angle of slope of the littoral zone. This may range from essentially vertical in lakes bounded by rocky cliffs (i.e. littoral zone is almost non-existent) to almost horizontal in very shallow lakes. Moreover, it is unlikely to remain constant along any given onshore-to-offshore transect. A vertical fall in level of, say, 5 m would have a much greater impact on very low angle slopes, in which the exposed width of littoral zone would be large, as compared with near vertical slopes, where the littoral exposure would be small in horizontal extent. Indeed, within an individual lake, variations in upper slope angle could range from c. 90º to close to 0º. For example, in the northern, deep, narrow basin of Loch Lomond, the steep rocky cliffs and an absence of beaches in may areas, give rise locally to very steep slope angles. By contrast, the broader, shallower, southern basin is generally characterised by much shallower slope angles and the exposure of extensive beaches during periods of low water level. Thus a fall in level of 5 m would have different impacts on littoral communities in different parts of the loch. Therefore, it is necessary to have good bathymetric data for a lake before an accurate prediction of the horizontal extent of littoral zone exposure (assuming that this will have the most significant impact on littoral communities) for a given fall in water level can be made for different shore zone reaches.

The hypsographic curve represents certain elements of the form of the lake basin and, importantly, it provides a means whereby the area of any depth level may be determined. With the availability of such a curve, a more meaningful assessment of the impact of a specific fluctuation in water level can be made in terms of the area either exposed or inundated, as compared with that related to a simple expression of change in vertical amplitude.

Reference to Figures 7 and 8 (Section 4.2) clearly demonstrates that lakes of the very convex type, f(-3.0) – f(-1.5), having laterally-extensive marginal shallows, are the most likely to show impact to littoral benthic communities when subjected to a fall (or a rise) in water level. However, such lake forms have a probability of occurrence of only 6.5% (Table 5). By contrast, littoral communities of lakes of the concave type, f(3.0) – f(1.5), having steeply inclined upper margins, are the least likely to be affected by water level fluctuations. Again, however, the probability of occurrence of such lake forms is only 6.5%. Most lakes are of the convex, slightly convex or the linear type. Thus, according to Håkanson (1981), the mean lake form, $f(\bar{x})$, is slightly convex.

To determine whether or not this approach has any viability to the impact assessment of water level changes on littoral benthic communities, it would be necessary to construct the hypsographic curves from a number of sites from which data are available. Data for twelve lakes in the Cumbrian Lake District (England) are presented in Figure 17, as percentage hypsographic (percentage cumulative area versus actual depth) curves. These indicate that the lakes included have a range of forms, and in particular that water level drawdown of 5 m would expose only c. 15% of the floor of Wastwater, whilst a similar drawdown at Bassenthwaite would expose around 65% of the total area of the lake. Table 31 shows the depth of drawdown that would expose 25% of the floor of each lake (25% exposure depth). A first approach to assessment of sensitivity is made in terms of whether this exposure would occur under the regimes of “minor” or “major” artificial water level fluctuations of Smith *et al*. (1987) (see above). For Bassenthwaite, Esthwaite, Grasmere, Haweswater (before impoundment) and Blelham Tarn, 25% of the lake floor would be exposed if the water level was drawn down by 3.2 m or less; so that if 25% exposure is ecologically significant, this threshold would be exceeded even under a regime of “minor” water level fluctuations. The remaining lakes are less sensitive; here the threshold exposure would be attained only under a regime of “major” fluctuations.

Table 31 Ranking of Cumbrian lakes according to their sensitivity to water level drawdown, assessed on the basis of 25% exposure depth.

Lake	25% exposure depth (m)	Sensitivity to water level fluctuations
Bassenthwaite	1.9	H
Esthwaite	2.0	H
Grasmere	2.6	H
Haweswater (natural)	3.1	H
Blelham Tarn	3.2	H
Loweswater	3.8	M
Windermere south basin	4.1	M
Ennerdale	4.8	M
Windermere north basin	5.0	M
Thirlmere	8.1	M
Haweswater (impounded)	11.2	M
Wastwater	13.0	M

Obviously, full utility from this approach can be realised only if sensitivity can be calibrated in ecologically meaningful terms. One possible route is offered by the pelagic : littoral habitats ratio of Hofmann (1998) (Section 3.2.4.2). The approach also has potential for extension to include the assessment of changes in the character of water level fluctuations by combining hypsographic data with level duration curves for unimpacted and impacted situations (Figures 11, 12).

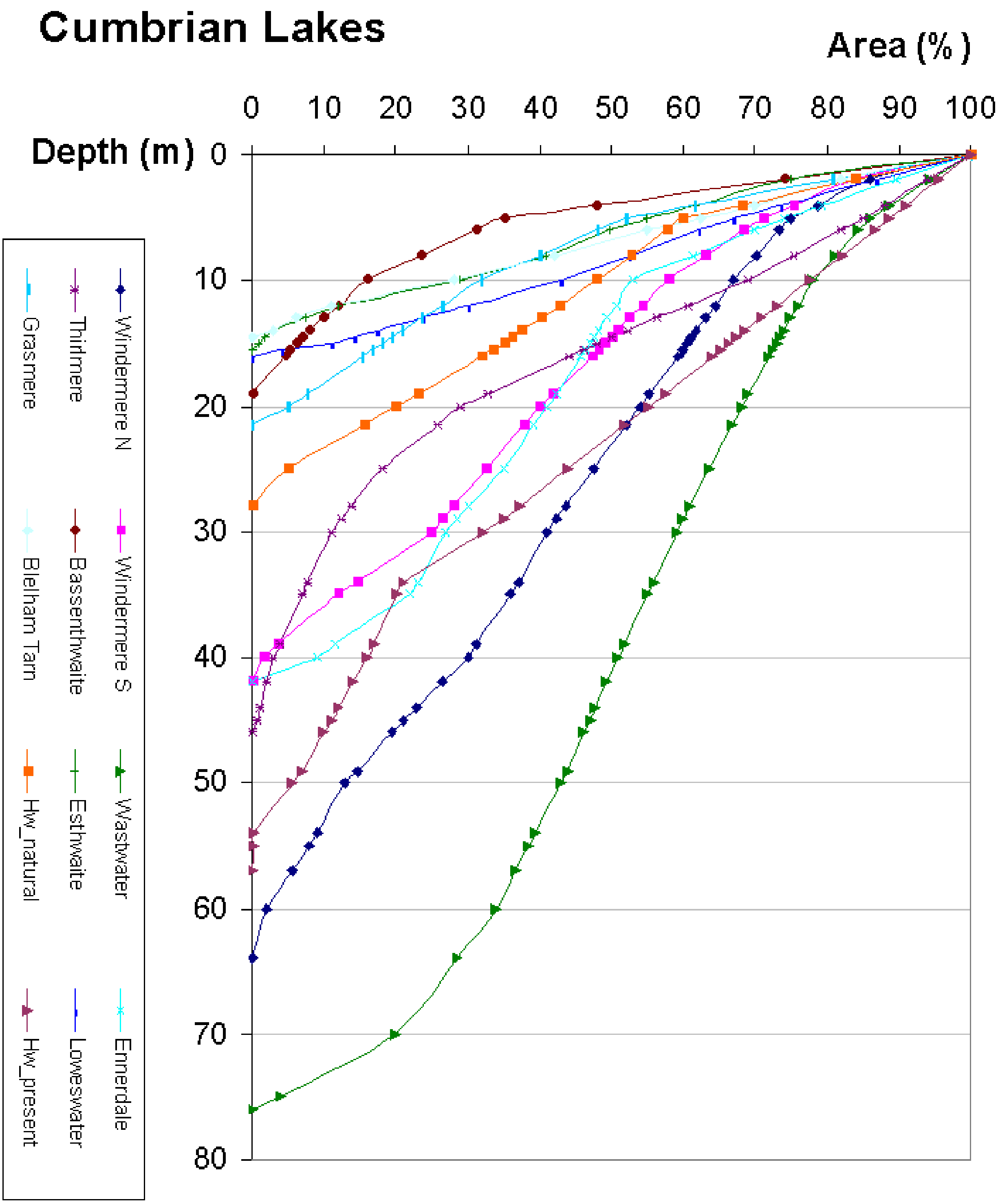


Figure 17 Percentage hypsographic curves for 12 lakes in Cumbria, England, derived from data given by Ramsbottom (1976).

"Hw" refers to the lake known as Haweswater; "natural" and "present" curves represent the situations before and after impoundment respectively (see also Section 3.2.4.1 and Figure 4).

5.3.4.3 Sensitivity to changes in groundwater status

Methods for direct assessment of connectivity to groundwater are described by Vanek (1985) but are generally too labour intensive to be suitable for general WFD purposes, and their use is likely to be appropriate only when specific requirements arise in operational monitoring. However, geological information (Section 4.9) offers a practical analogue. Strong groundwater-lake linkages, and hence high sensitivity to changes in groundwater status, might be assumed for lakes in limestone terrain, and particularly in karst landscapes of Ireland for which the intermittent lakes known as turloughs are characteristic. Strongly fissured bedrock also offers opportunities for such connections. Some types of drift deposits also offer opportunities for ready exchange of water between lakes and groundwater (C. Soulsby pers comm.), whilst special consideration must be given to peat in this context. The permeability classes of Zhang (undated) (Section 4.9) offer a starting-point for development of a more rigorous index of groundwater connectivity.

5.3.4.4 Assessment of changes in depth variation

The Directive seems to allow some latitude in interpretation of the terms “depth” and “depth variation”, which could be a function of both basin morphology and water level movements. Littlejohn *et al*. (2002) consider variation in depth and water level together but point out that it is important to measure depth over both space and time. Håkanson (1981) defines five types of depth (maximum, mean, median, quartile and relative), and these will change not only if water level is altered, but also if there is build-up, loss or removal by dredging of sediment on the lake floor. If the bottom topography is altered, the morphological parameters “lake bottom roughness” and “form roughness” (Table 6 and Figure 9, Section 4.2), which express the topographical irregularity of the lake floor, could be relevant. Lake floor topography is also summarised by hypsographic curves. Impoundment or lowering of the water level may passively alter basin form, as expressed by the relative hypsographic curve (Table 6 and Figure 8, Section 4.2; Figure 18). Thus, both types of impacts could be quantified by repeat bathymetric survey and hypsographic analysis, if baseline survey data are available (Section 4.2). Post-impoundment hypsographic curves have also been produced by combining dam construction data with pre-impoundment hydrographic survey (e.g. Figure 4); whilst historical changes in sedimentation rates might also be detected by analysis of core samples or acoustic survey (Section 4.4).

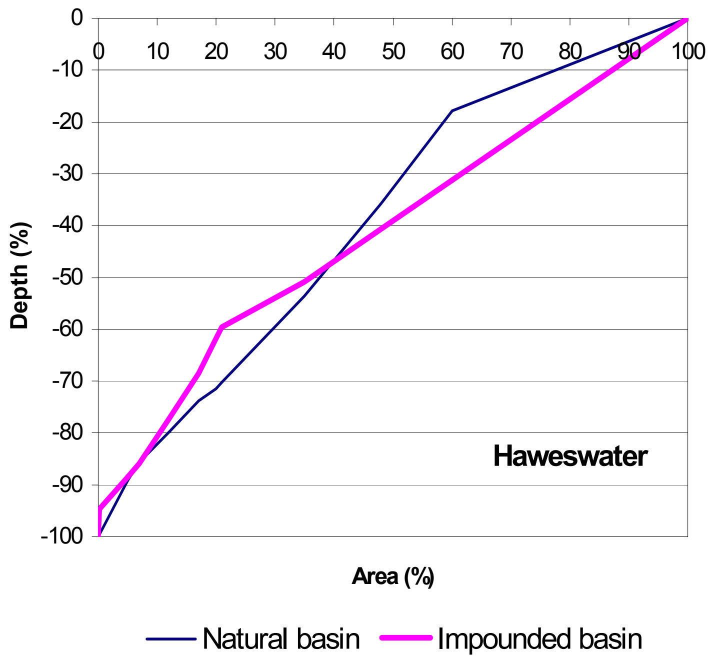


Figure 18 Comparison of relative hypsographic curves (lake form) for Haweswater before and after impoundment. The same data are plotted in depth-area form in Figure 4.

5.3.4.5 Assessment of changes in quantity and structure of the substrate

This history of sediment accumulation, in terms of both quantity (rate of deposition) and structure is readily obtainable by coring, dating and particle size analysis; techniques are described in Section 4.4. Location of the core(s) should take into account the distribution of high and low energy environments within the lake, and the dating method (e.g. ^{14}C *versus* ^{137}Cs) should be chosen according to the time resolution required.

5.3.4.6 Residence time

Since residence time is a function of lake volume and rate of throughflow, it may be altered by a change in either of these variables. Thus, impacts may be associated with sedimentation, with impoundment of the lake, with water abstraction directly from the lake, or from pressures that alter the flow regimes of the rivers and streams that feed it. Thus, impacts on residence time would appear to be covered by quantification of impacts on the variables used to calculate it.

5.3.4.7 Structure and condition of the shore zone

The protocol for RHS (River Habitat Survey) incorporates detailed methodology for recording the nature and extent of artificial modification of river banks, expressed as the Habitat Modification Score (HMS) (Section 4.6). The Habitat Modification Score (HMS) describes the extent of channel modification through the development of an impact score resulting from channel and valley-floor modifications, such as resectioning, revetting, the creation of weirs etc, identified from spot-checks and from the sweep-up survey. The score is truly independent of river type and thus provides a general measure of hydromorphological alteration on a six point scale, ranging from 'pristine' to 'severely modified' (Raven *et al.* 1998b). Its extension to lakes and transitional water bodies has been proposed but not yet implemented (D. Corbelli pers. comm.).

A very useful framework for the translation of an RHS approach to lake systems was found in the EMAP (Environmental Monitoring Assessment Program) 'Field Operations Manual for Lakes' (Baker *et al*., 1997). This US EPA commissioned field manual was the result of a four-year development and testing programme spanning the period 1991-1994 and brought various EPA agencies under the aegis of the Environmental Monitoring and Assessment Program (EMAP). EMAP is concerned with evaluating ecological conditions at both regional and national scales. The Field Operations Manual for Lakes (FOML) presents protocols for site selection, sampling strategies for ecological, water quality and hydromorphological data. Methodological, field logistical and data management procedures are described for a number of key variables such as chlorophyll *a*, water chemistry, diatoms, zooplankton, macro benthos, fish assemblage, riparian birds and physical habitat structure. The manual contains example field data forms and checklists of equipment and for personnel to follow (e.g. survey maps and data templates shown in Figures 19-22).

Of particular relevance to this project is Section 5 Habitat Characterization (Kaufmann and Whittier, 1997), the basis of which has three elements:

- measures of temperature and dissolved oxygen at index sites
- measures or observation of littoral and riparian physical habitat structure at 10 predetermined stations (Figure 19)
- macro scale classification and mapping of riparian and littoral habitat for the whole lake.

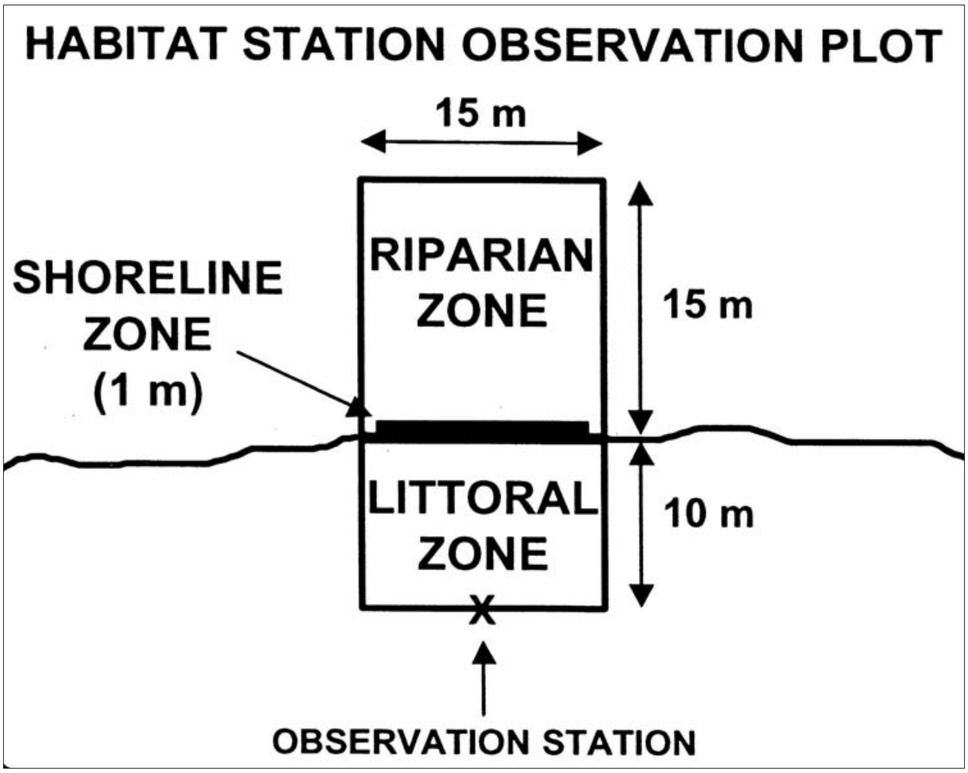
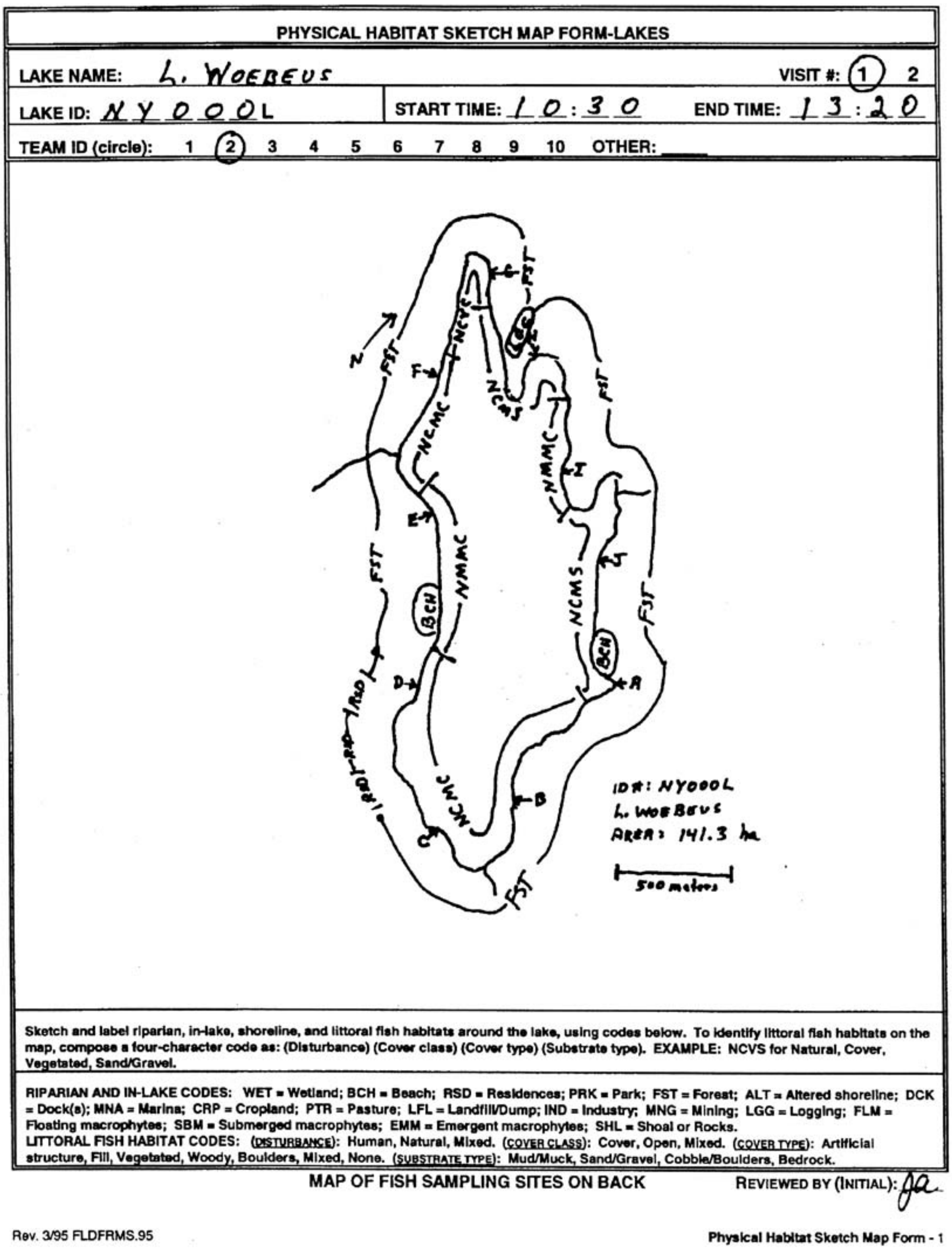


Figure 19 Sketch map showing the dimensions of observation plot at each station of the EMAP scheme.

Considering the success of the RHS approach and the comprehensive data collection associated with the FOML there is real potential to fuse best practice from both schemes, i.e. to adapt the comprehensive suite of measurements and observations (metrics) obtained from the FOML and translate into numerical equivalents of the Habitat Quality Assessment (HQA) and HMS indices produced from RHS. Development of the new approach, which could be termed Lake Habitat Survey (LHS), into a working scheme is beyond the remit of this project. The particular indices of water body quality to be developed remain to be finalised, indeed considerable development of the RHS approach is presently under way. New measures include the 'Benchmark Distance Score (BCD), which indicates the extent of difference between a site and a pristine analogue, and a River Habitat Quality (RHQ) score derived from combining the other indices which provides an overall evaluation (Buffagni and Erba 2002). Future developments should enable HQA, HMS, BCD and RHQ scores to be developed for lake systems and it is envisaged that this may form the basis for future CEN Standardisation. All the necessary data could be derived from FOML metrics along with key morphological variables obtained from field survey and map data (see Table 32).



PHYSICAL HABITAT SKETCH MAP FORM-LAKES

LAKE NAME: L. WOEBEUS VISIT #: (1) 2

LAKE ID: NY000L START TIME: 10:30 END TIME: 13:20

TEAM ID (circle): 1 (2) 3 4 5 6 7 8 9 10 OTHER: ____

Sketch and label riparian, in-lake, shoreline, and littoral fish habitats around the lake, using codes below. To identify littoral fish habitats on the map, compose a four-character code as: (Disturbance) (Cover class) (Cover type) (Substrate type). EXAMPLE: NCVS for Natural, Cover, Vegetated, Sand/Gravel.

RIPARIAN AND IN-LAKE CODES: WET = Wetland; BCH = Beach; RSD = Residences; PRK = Park; FST = Forest; ALT = Altered shoreline; DCK = Dock(s); MNA = Marina; CRP = Cropland; PTR = Pasture; LFL = Landfill/Dump; IND = Industry; MNG = Mining; LGG = Logging; FLM = Floating macrophytes; SBM = Submerged macrophytes; EMM = Emergent macrophytes; SHL = Shoal or Rocks.
LITTORAL FISH HABITAT CODES: (DISTURBANCE): Human, Natural, Mixed. (COVER CLASS): Cover, Open, Mixed. (COVER TYPE): Artificial structure, Fill, Vegetated, Woody, Boulders, Mixed, None. (SUBSTRATE TYPE): Mud/Muck, Sand/Gravel, Cobble/Boulders, Bedrock.

MAP OF FISH SAMPLING SITES ON BACK REVIEWED BY (INITIAL): JA

Rev. 3/95 FLDFRMS.95 Physical Habitat Sketch Map Form - 1

Figure 20 Physical habitat sketch map produced during EMAP field survey.

PHYSICAL HABITAT CHARACTERIZATION FORM-LAKES

LAKE NAME: L. WOEBEUS DATE OF VISIT: 7/4/94 VISIT #: (1) 2

LAKE ID: NY000L TEAM ID (circle): 1 (2) 3 4 5 6 7 8 9 10 OTHER: ___

RIPARIAN ZONE		A	B	C	D	E	F	G	H	I	J
	NEW STATION ID (If needed):										
VEGETATION TYPE (N=NONE, D=DECID., C=CONIF., M=MIXED)	CANOPY LAYER (> 5 M)	M	M	M	M	N	M	M	C	M	M
	UNDERSTORY (0.5 TO 5 M)	M	M	M	M	D	M	M	M	M	M
AREAL COVERAGE CATEGORIES 0 = ABSENT 1 = SPARSE (<10%) 2 = MODERATE (10 TO 40%) 3 = HEAVY (40 TO 75%) 4 = VERY HEAVY (> 75%)											
CANOPY LAYER (> 5 M HEIGHT)	TREES ≥ 0.3 M DBH	1	2	2	2	0	1	3	2	1	2
	TREES < 0.3 M DBH	2	3	3	2	0	2	2	2	2	3
UNDERSTORY (HEIGHT=0.5 TO 5 M)	WOODY SHRUBS & SAPLINGS	2	3	2	2	2	2	4	4	3	3
	TALL HERBS, FORBS, & GRASSES	2	1	1	1	2	1	0	1	2	1
GROUND COVER (< 0.5 M HEIGHT)	WOODY SHRUBS & SEEDLINGS	2	3	2	3	2	1	4	4	3	3
	HERBS, FORBS, & GRASSES	3	1	2	2	3	3	1	1	2	1
	STANDING WATER OR INUNDATED VEGETATION	0	0	0	0	2	0	0	0	0	0
	BARREN OR BUILDINGS	0	1	2	2	0	2	0	0	0	1
SHORELINE SUBSTRATE ZONE	BEDROCK (> 4000 MM; BIGGER THAN A CAR)	0	0	0	0	0	0	0	0	0	0
	BOULDERS (250 - 4000 MM; BASKETBALL - CAR SIZE)	1	0	4	3	2	0	1	0	0	3
	COBBLE/GRAVEL (2 - 250 MM; LADYBUG - BASKETBALL SIZE)	3	4	0	1	1	3	3	3	3	0
	LOOSE SAND (0.06 TO 2 MM; GRITTY BETWEEN FINGERS)	0	0	0	0	0	0	0	0	0	0
	OTHER FINE SOIL/SEDIMENT (< 0.06 MM; NOT GRITTY)	0	0	0	0	0	0	0	0	0	0
	VEGETATED	2	0	2	3	3	3	3	3	3	3
	OTHER (EXPLAIN IN COMMENTS)	0	0	0	0	0	0	0	0	0	0
BANK FEATURES (WITHIN PLOT)	ANGLE: V = NEAR VERTICAL/UNDERCUT, S = 30-75°, G = <30°	G	G	S	G	G	G	G	S	G	V
	VERTICAL DISTANCE (M) FROM WATERLINE TO HIGH-WATER MARK	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.2
	HORIZONTAL DISTANCE (M) FROM WATERLINE TO HIGH-WATER MARK	1.0	1.0	0.6	1.0	F3	1.0	1.0	0.6	1.0	0.3
HUMAN INFLUENCE 0 = ABSENT CHECK (✓) = PRESENT WITHIN PLOT B = OBSERVED ADJACENT TO OR BEHIND PLOT											
	BUILDINGS	0	✓	0	B	0	B	0	0	0	0
	COMMERCIAL	0	0	0	0	0	0	0	0	0	0
	PARK FACILITIES	0	0	0	0	0	0	0	0	0	0
	DOCKS/BOATS	0	0	0	B	0	0	0	0	0	0
	WALLS, DIKES, OR REVETMENTS	0	0	0	0	B	0	0	0	0	0
	LITTER, TRASH DUMP, OR LANDFILL	0	0	0	0	0	0	0	0	0	0
	ROADS OR RAILROAD	0	0	0	✓	0	0	0	0	0	0
	ROW CROPS	0	0	0	0	0	0	0	0	0	0
	PASTURE OR HAYFIELD	0	0	0	0	0	0	0	0	0	0
	ORCHARD	0	0	0	0	0	0	0	0	0	0
	LAWN	0	✓	0	B	0	✓	0	0	0	0
	OTHER (EXPLAIN IN COMMENTS)	0	0	0	0	0	0	0	0	0	0

FLAG CODES: K = MEASUREMENT OR OBSERVATION NOT OBTAINED; U = SUSPECT MEASUREMENT OR OBSERVATION; F1, F2, ETC. = MISC. FLAGS ASSIGNED BY EACH FIELD CREW. EXPLAIN ALL FLAGS ON SEPARATE COMMENTS FORM.

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Physical Habitat Characterization Form - 1

Figure 21 Sample of field recording form used in the EMAP habitat assessment, page one.

LAKE ID: NY000 L **PHYSICAL HABITAT CHARACTERIZATION FORM (continued)** VISIT #: (1) 2

NEW STATION ID (If needed):										
LITTORAL ZONE — STATION ID:	A	B	C	D	E	F	G	H	I	J
STATION DEPTH (M) AT 10 M OFFSHORE	0.8	1.1	0.8	0.7	0.8	0.6	1.0	1.8	0.7	0.8
SURFACE FILM TYPE (S=SCUM, A=ALGAL MAT, P=OILY, N=NONE/OTHER)	N	N	N	N	N	N	N	N	N	N
BOTTOM SUBSTRATE: AREAL COVERAGE: 0=ABSENT 1=SPARSE (<10%) 2=MODERATE (10 TO 40%) 3=HEAVY (40 TO 75%) 4=VERY HEAVY (>75%)										
BEDROCK (>4000 MM; LARGER THAN A CAR)	0	0	0	0	2	0	0	0	0	0
BOULDERS (250 - 4000 MM; BASKETBALL - CAR SIZE)	1	0	1	1	0	0	1	0	0	0
COBBLE (64 - 250 MM; TENNIS BALL - BASKETBALL SIZE)	2	0	1	3	0	2	2	3	2	3
GRAVEL (2 TO 64 MM; LADYBUG TO TENNIS BALL SIZE)	2	4	0	2	0	2	2	3	2	3
SAND (0.06 TO 2 MM; GRITTY BETWEEN FINGERS)	1	1	3	1	0	2	1	1	1	1
SILT, CLAY, OR MUCK (< 0.06 MM; NOT GRITTY)	0	0	0	0	2	0	0	0	0	0
WOODY DEBRIS	1	1	1	0	2	2	1	0	2	2
COLOR (BL=BLACK, GY=GRAY, BR=BROWN, RD=RED, N=NONE OR OTHER)	K	K	K	K	GY	GY	K	K	GY	K
ODOR (S=H$_2$S, A=ANOXIC, P=OIL, C=CHEMICAL, N=NONE)	K	K	K	K	N	N	K	K	N	K
MACROPHYTES AREAL COVERAGE: 0=ABSENT 1=SPARSE (<10%) 2=MODERATE (10 TO 40%) 3=HEAVY (40 TO 75%) 4=VERY HEAVY (>75%)										
SUBMERGENT	1	0	1	1	1	1	1	1	1	1
EMERGENT	1	0	0	2	1	1	0	0	1	0
FLOATING	0	0	0	1	2	0	0	0	0	0
TOTAL WEED COVER	1	0	1	2	3	2	1	1	2	1
DO MACROPHYTES EXTEND LAKEWARD? (Y OR N)?	N	N	Y	Y	Y	Y	Y	N	Y	Y
FISH COVER 0=ABSENT 1=PRESENT BUT SPARSE 2=PRESENT IN MODERATE TO VERY HEAVY DENSITY										
AQUATIC WEEDS	1	0	1	2	2	1	1	1	1	1
SNAGS > 0.3 M DIAMETER	0	0	0	0	2	0	1	0	0	0
BRUSH OR WOODY DEBRIS < 0.3 M DIAMETER	1	1	1	0	2	1	1	0	1	2
INUNDATED LIVE TREES > 0.3 M DIAMETER	0	0	0	0	0	0	0	0	0	0
OVERHANGING VEGETATION < 1 M ABOVE SURFACE	0	0	0	0	2	1	1	0	0	1
ROCK LEDGES OR SHARP DROPOFFS	0	0	0	0	0	0	0	2	0	0
BOULDERS	1	0	1	1	0	0	1	0	0	0
HUMAN STRUCTURES (E.G., DOCKS, LANDINGS, PILINGS, RIPRAP, ETC.)	0	0	0	0	0	0	0	0	0	0
LITTORAL FISH HABITAT CLASSIFICATION										
DISTURBANCE (H=HUMAN N=NATURAL M=MIXED)	N	N	N	N	N	N	N	N	N	N
COVER CLASS (C=COVER, O=OPEN, M=MIXED)	M	O	M	C	C	M	M	C	M	M
COVER TYPE (A=ARTIFICIAL F=FILL V=VEG. W=WOODY B=BOULDERS M=MIXED N=NONE)	M	N	M	M	M	M	M	M	M	M
SUBSTRATE (M=MUD/MUCK, S=SAND/GRAVEL, C=COBBLE/BOULDER, B=BEDROCK)	S	S	S	C	M	S	S	S	S	S
GEAR (G=GILL NET, T=TRAP NET, S=SEINE, 0=NONE)	T	S	S	T	T	T	G,T	G	T	T
GEAR LOCATION (DIST. & DIR. TO NEAREST REPRES. MACROHABITAT)	0	0	30m	0	0	0	0	0	0	0

FLAG CODES: K = MEASUREMENT OR OBSERVATION NOT OBTAINED; U = SUSPECT MEASUREMENT OR OBSERVATION;
F1, F2, ETC. = MISC. FLAGS ASSIGNED BY EACH FIELD CREW. EXPLAIN ALL FLAGS ON SEPARATE PHYSICAL CHARACTERIZATION HABITAT COMMENTS FORM.

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Rev. 3/95 FLDFRMS.95 — Physical Habitat Characterization Form - 2

Figure 22 Sample of field recording form used in the EMAP habitat assessment, page two.

Table 32 Physical features of likely significance for determining hydromorphological condition in terms of degree of habitat modification and overall status 'Habitat Quality' and 'Habitat Modification' in a proposed Lake Habitat Survey scheme

Category	Functional significance	Candidate variables	Data sources
Lake Morphology	Identification of sub-set of key morphological parameters linked to the ecological sensitivity of the system.	Catchment/lake ratio; hypsographic curve type (lake form); lake shoreline development, $A_a^{0.25}/H_{max}$	Map analysis and field survey; GIS database
Riparian zone	Vegetation type, canopy type and structure Shoreline substrate Human influence	% cover canopy, under-storey and ground cover Grain size distribution Land use types e.g. buildings, walls, crops	P-Hab observations from FOML
Littoral zone	Depth Surface films Bottom substrate Macrophytes Human structures	10 m offshore Abundance and type Grain size distribution Submergent/emergent Docks, landings, pilings, dams and extent of each category	P-Hab observations from FOML
Riparian/littoral macrohabitat	A hierarchical scheme to assess the extent of major riparian and littoral macrohabitats: In-lake disturbance in-lake cover cover type main substrate	Record of human activities in the riparian zone and in-lake features e.g. wetland, beach, residences, dock, industrial, landfill etc	Physical Habitat Sketch Map form from FOML

Once the LHS method has been refined there is then scope to integrate it with hydrological regime alteration (measured using the DHRAM scheme) into a single Abiotic Index (Table 33) representing the interplay of the key hydrological and morphological quality elements of a water body.

Table 33 Proposed scheme to develop an Abiotic Index employing both hydrological regime change and morphological alteration.

The letters indicate the WFD's five levels of ecological status: **H**igh, **G**ood, **M**oderate, **P**oor and **B**ad.

HMS Class from LHS	DHRAM Class 1	2	3	4	5
1	H	G	M	P	B
2	G	G	M	P	B
3	M	M	M	P	B
4	P	P	P	P	B
5	B	B	B	B	B

Dundee Hydrological Regime Alteration Method (DHRAM) for standing waters (Black *et al*. 2000b)

DHRAM CLASS	Description
1	Un-impacted condition
2	Low risk of impact
3	Moderate risk of impact
4	High risk of impact
5	Severely impacted condition

Habitat Modification Score (HMS)

Describes the extent of habitat alteration using proposed Lake Habitat Survey schemes

HMS Score	**Class**	Descriptive category of channel
0 – 2	1	Pristine to Semi-natural
3 – 8	2	Predominantly unmodified
9 – 20	3	Obviously modified
21 – 44	4	Significantly modified
45 +	5	Severely modified

5.3.4.8 Heavily Modified Water Bodies

The Directive provides for the designation of so-called Heavily Modified Water Bodies (HMWBs), where the requirement to achieve good ecological status is relaxed to allow specifically justified uses of water. In such cases, the target status is good ecological potential (GEP). Detailed guidance on identification and designation of HMWBs is given by CIS (2002). Steps 1 to 6 of the designation process are part of the WFD's requirements for characterisation of River Basin Districts (Figure 23).

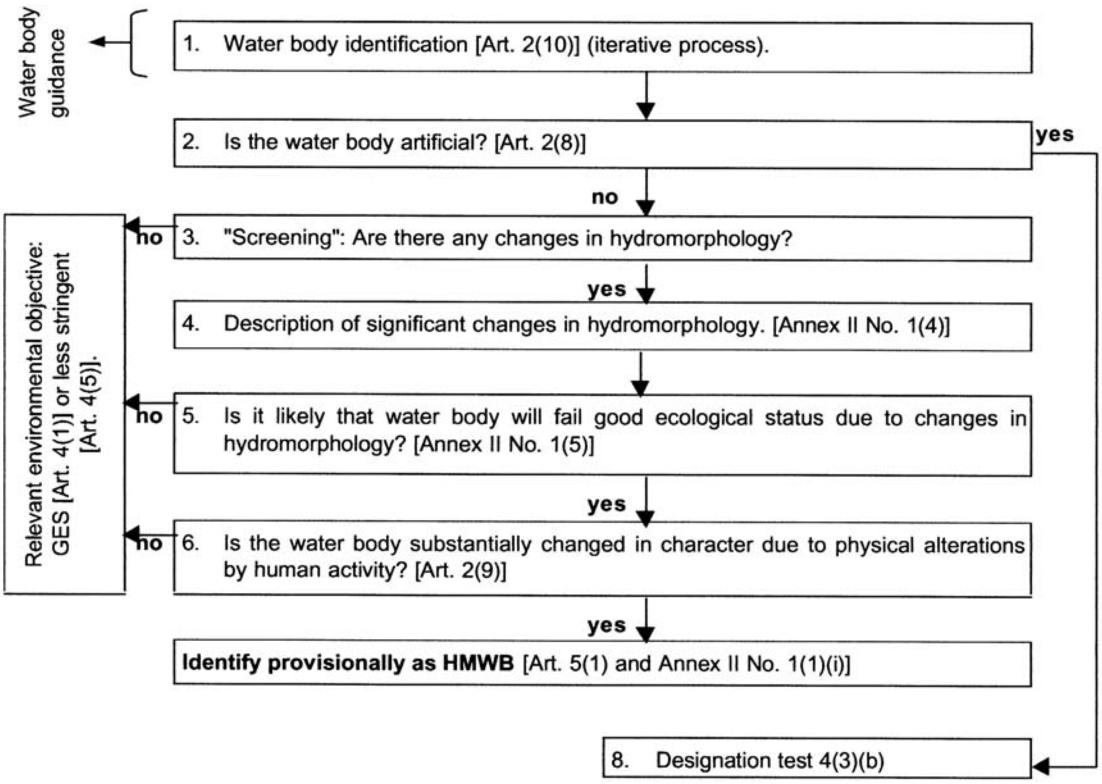

Figure 23 Steps leading to the provisional identification of HMWB. From CIS (2002).

Candidature for HMWB designation is available only for water bodies whose character is "substantially" changed due to physical alterations, or where there are "significant" changes in hydromorphology, associated with human activity. Thus, assessment of the severity of hydromorphological impacts is pivotal. Where a river has been impounded (substantially changing its character – Step 6), identification of the resulting reservoir as a provisional HMWB is relatively straightforward, and the award of heavily modified status enables the reference condition of a similar lake to be applied in assessing ecological potential. In many cases, however, dams are built to enlarge and/or raise the levels of existing lakes, and Steps 4 and 5 of the designation process become critical. Where the decision on designation has financial implications for water users, the degree of confidence that can be placed in calibration of the scale of hydromorphological alteration against the risk of failure to achieve GEP is especially important.

A case study by Black *et al*. (2002c) explored the process of HMWB designation with reference to the Tummel-Garry hydro-electric scheme in Scotland, which includes eight reservoirs. This was a desk-based study focusing on the designation process itself, and no new field data were collected. The morphological changes due to impoundment of the various reservoirs were investigated systematically by comparing their outlines on maps published in the early 1900s with outlines derived from current UK Ordnance Survey maps (Figure 24). The changes indicated by this exercise are summarised in Table 34. The areas of Lochs Rannoch and Garry had changed by less than 5%, and that of Loch Ericht by less than 20%, and none of their perimeters have increased by more than 6%, due to impoundment. Damming of Lochs Faskally and Errochty caused relatively uniform widening of the respective sections of river to create more (Faskally) or less (Errochty) narrow lochs, whilst there was a marked difference in the degree of widening of Dunalastair Water between its upstream and downstream sections. Again, changes in perimeter were small (all below 10%) although it is interesting that the perimeter of Loch Errochty actually decreased. At Loch Tummel, closure of the dam caused flooding of an additional length of river almost equal to the original length of the loch, whilst the original form of Loch Eigheach appears to have been intermediate between river and loch, resembling a series of large pools which were amalgamated at impoundment, more than doubling the area of water surface. It was noteworthy that the perimeters of the last two water bodies declined by more than 20%.

In the terms of the HMWB designation decision tree given by CIS (2002), Dunalastair Water and Loch Errochty have clearly undergone substantial changes in character, from river to lake. The situation is less clear-cut for the other lochs, and a decision on the level of significant alteration is required. For the purposes of the case study, substantial alteration was judged to have occurred if surface area has doubled and/or perimeter has changed by 20%. Thus, substantial morphological alteration was inferred for all the reservoirs except Lochs Garry, Rannoch and Ericht.

In this exercise, the “pre-Hydro” outline was taken as the total perimeter of the pre-impoundment lake and river enclosed by the outline of the impounded loch. A very different set of results would be obtained using the more conventional approach of comparing the outlines of the lochs only in their pre- and post-impounded forms. For Loch Tummel, the natural shoreline length was 12.3 km and this increased to 24.0 km after impoundment (Duck 1982), giving an increase in perimeter of 62.6% rather than a decrease of 22.7%. For Loch Errochty, the increase calculated by this method would be 100%. However, it is not clear how the alternative approach would be applied to Loch Eigheach, which consisted of a series of pools before impoundment. Both approaches would yield the same conclusions in conjunction with application of a 20% alteration threshold.

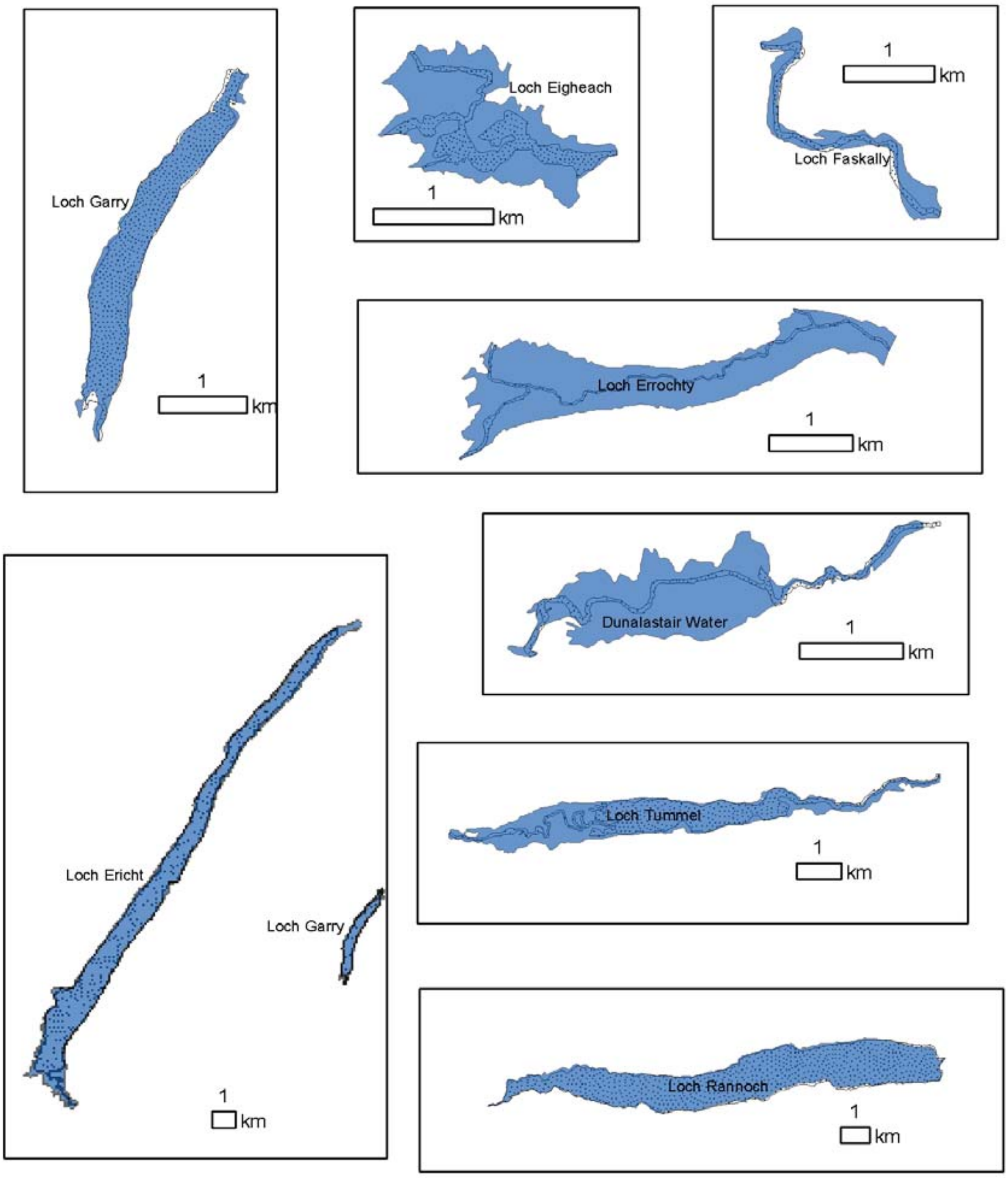

Figure 24 Comparisons of the present shapes of the Tummel hydro-power reservoirs (blue) with their shapes before closure of the dams (stippled).

Modern outlines derived from Institute of Hydrology Digital Loch Boundaries dataset with modifications based on current Ordnance Survey 1:50,000 coverage. "Pre-Hydro" outlines derived from UK Ordnance Survey Popular Edition sheets 48, 56 (revised 1925-28) and Geological Survey of Great Britain (Scotland) sheets 54, 55 (surveyed 1869-1906), all at scale 1" to 1 mile.

Table 34 Changes in area and perimeter of the eight reservoir water bodies of the Tummel catchment due to impoundment. Derived by GIS (ArcGIS 8.1) analysis of the digital data used to construct Figure 18.

LOCH	AREA (km^2)			PERIMETER (km)		
	pre-Hydro	now	% increase	pre-Hydro	now	% increase
Loch Rannoch	18.71	18.83	0.6	36.3	37.5	3.1
Loch Garry	1.58	1.64	4.0	10.6	11.2	6.0
Loch Ericht	19.22	22.39	16.5	56.5	59.7	5.8
Loch Tummel	3.16	5.81	84.2	34.0	26.2	-22.7
Loch Faskally	0.25	0.60	142.3	8.1	8.4	4.2
Loch Eigheach	0.40	1.33	231.1	9.8	7.6	-22.1
Dunalastair Water	0.26	1.65	530.0	11.9	12.5	4.8
Loch Errochty	0.21	3.04	1325.0	15.6	14.5	-7.4

Further hydromorphological information on the eight reservoirs appears in Table 35. DHRAM scores were included, with the proviso that they were based on comparison with natural water level regimes for Scottish lochs and so offered no insight into hydromorphological alteration due to impoundment of reservoirs which were essentially sections of rivers that had been thus transformed into standing waters; ideally, DHRAM scores for both standing and running waters should be calculated in such cases. For depth and turnover (residence) time, impacts could not be assessed due to lack of (calibrated) standards.

Table 35 Some hydromorphological characteristics of the Tummel reservoirs.

Reservoir	Present depth (m)	Depth increase due to impound-ment (m)	Annual range of water level fluctuation (m)	DHRAM score (assessed as standing water)	Turnover time
Rannoch	51.04 (mean)		1.35m	2	11 months
Garry	32 (max.)		6m	5	
Ericht	57.67 (mean)		3m	2	
Tummel	44.8 (max.)	5.8	1m	5	12-18 days
Faskally			1.7m	(3)-4	
Eigheach	26 (approx.)	~26	3m	3	
Dunalastair	1.5 (mean)	1.5	1m	5	16.5 hr
Errochty	25 (approx.)	~25	9m	4	

Some information was also found on shore/littoral widths and slopes for four of the reservoirs (Smith *et al*. 1987). In general, the shore zones of all the Tummel reservoirs were steep in comparison to those of natural lochs (Table 36). Again, lack of standards and calibration precluded reliable assessment of the associated risk of impact on biota.

Table 36 Physical characteristics of the shore zones of four Tummel reservoirs (bold type) and five natural Scottish lochs observed during the week 14-18 July 1980. From Smith *et al*. (1987).

Loch	Shore width (m)	Littoral width (0-0.5m water depth) (m)	Slope (m m^{-1})
Dunalastair Water	**1**	**3.4**	**0.147**
L. Tay	3	6.2	0.081
L. Arkaig	4	3.1	0.161
L. Faskally	**10**	**2.2**	**0.227**
L. Voil	10	7.1	0.070
L. Lubnaig	12	8.1	0.062
L. Shiel	13	12.2	0.041
L. Ericht	**27**	**4.4**	**0.114**
L. Errochty	**21**	**1.5**	**0.333**

Potential distortion of the hydrological regime is assessed mostly on the basis of the example DHRAM scores listed in Tables 3, 4 and 6. However, significant distortion of the hydrological regime is assumed automatically for the four reservoirs whose area was more than doubled by impoundment and whose character has thus essentially changed from moving to standing water (Dunalastair Water and Lochs Faskally, Eigheach and Errochty).

5.3.4.9 Summary of methods for impact assessmemt

The literature review has revealed that methods are available for measurement of all aspects of hydromorphological quality listed by the Directive. However, few methods are immediately applicable to impact assessment for the WFD; firstly because baseline (pre-impact or undisturbed analogue) data are not available, and secondly because the relationships between the degree of hydromorphological disturbance and risk of impact on biological quality elements are poorly understood. The exceptions are DHRAM, which was developed specifically for WFD purposes; and use of the sediment record which contains its own historical archive. Suggestions of ways in which established methods could be applied for WFD purposes are listed in Table 37; several of these have been expanded on in the preceding sections.

Table 37 Summary of methods for hydromorphological impact assessment that are appropriate to WFD implementation.

Element / Metric	Method	Comments
	QUANTITY AND DYNAMICS OF FLOW	
DHRAM scores	DHRAM (running waters) assessment for rivers upstream and downstream of lake)	Designed specifically for WFD purposes, but uncalibrated. Most reliable when based on actual flow records, which are sparse. However, it does not rely on these since a modelling option is included.
	WATER LEVEL REGIME	
DHRAM score	DHRAM (standing waters)	Designed specifically for WFD purposes, but uncalibrated
Shoreline sensitivity	Calculation of area exposed at critical drawdown depths, derived from hypsographic curves	Data available from bathymetric survey archives where these exist; otherwise new survey required. Method requires development and calibration
	DEPTH VARIATION	
Change in maximum depth	Sediment coring and dating, combined with pre- and post-impact water level data Acoustic survey combined with pre- and post-impact water level data Repeat bathymetric survey	
Change in lake floor roughness	Repeat bathymetric survey	
Change in form of hypsographic curve	Repeat bathymetric survey	
	QUANTITY OF SUBSTRATE	
Change in lake floor topography	Repeat bathymetric survey	
Change in sedimentation rate	Dating of sediment cores (^{14}C, ^{137}Cs or ^{210}Pb methods depending on time resolution required); distribution of cores relative to sediment sources and local energy environment is important	
Present sedimentation rate	Sediment traps	
	STRUCTURE OF SUBSTRATE	
Change in particle size distribution between different depositional layers	Particle size analysis on dated sediment cores	
Particle size distribution for sediment currently being deposited	Sediment traps	
	RESIDENCE TIME	
Change in lake volume	Repeat bathymetric survey	
Change in inflow/outflow rate	Water budget relationship	
DHRAM score (rivers u/s and d/s of lake)	DHRAM	

Structure and condition of shore zone		
Change in shoreline length	Measurement from pre- and post-pressure maps; GIS techniques highly appropriate	Data readily accessible; produces quantitative score; uncalibrated
Shoreline exposure	Calculation of area and exposure time for a series of shoreline contour zones	Requires bathymetric curve and water level data; method requires development and calibration.
Habitat Modification Score	Fusion of River Habitat Survey and EMAP approaches (Lake Habitat Survey)	Method requires development and calibration

5.4 Monitoring and management

5.4.1 Rationale

The requirements of WFD Articles 1 and 4 to prevent deterioration in ecological status and to protect, enhance and restore lakes to good status are to be met through application of programmes of measures (Article 11). These will be designed to address risks - identified under Article 5 - that individual lakes will fail to meet the necessary environmental objectives. Monitoring programmes to provide a coherent and comprehensive overview of water status, and therefore of water bodies at risk of failing to meet the environmental objectives, are to be in place by December 2006 (Article 8). In this section, the place of hydromorphological methods in these monitoring programmes will be explored.

5.4.2 Objectives of monitoring

Two types of monitoring programmes are specified in Annex V of the Directive.

1. ***Surveillance monitoring*** is to be carried out for a period of one year during the currency of each river basin management plan[10], at sufficient water bodies to provide an assessment of the overall surface water status within each catchment or subcatchment, and in particular at points where the rate of water flow and/or the volume of water is significant. It should provide

[10] The deadline for the first River Basin Management Plan (RBMP) is 22 December 2009 and the monitoring programmes must start by 22 December 2006. There will, therefore, be no information arising from surveillance monitoring for the first impact/risk assessment, which is to be completed by December 2004. Later in WFD implementation, the frequency of monitoring might be reduced to once every three RBMPs (each Plan is of 6 years' duration) if a previous surveillance monitoring exercise has demonstrated that the water body has attained good status and there is no evidence of change in human impacts.

information for supplementing and validating the impact assessment procedure, streamlining the design of future monitoring programmes, and assessing long-term changes (both natural and anthropogenic). Parameters indicative of all biological, hydromorphological and general physico-chemical quality elements and all pollutants are to be monitored.

2. ***Operational monitoring*** is intended to be used for establishing the status of those water bodies identified as being at risk of failing to meet their environmental objectives, and to assess any changes in the status of such bodies resulting from the programmes of measures. For water bodies at risk from significant hydromorphological pressure, operational monitoring will focus on assessing the magnitude and impact of these pressures, by investigating parameters indicative of the hydromorphological quality element most sensitive to the pressure identified.

In addition, investigative monitoring is available as a response to pollution incidents and to ascertain the reasons for individual failures to achieve environmental objectives.

5.4.3 Existing approaches to monitoring of lakes

The European Environment Agency (EEA) has a statutory duty to provide the European Union and Member States with objective, reliable and comparable information to assess the state of the European environment. It was found that information on surface waters provided by individual countries were not comparable. EUROWATERNET (Nixon *et al*. 1998, Lack and Nixon 2000) incorporates a basic network of river stations and lakes based on the relative surface area of countries, aiming to give a representative assessment of water types and variations in human pressures within each member country and also across the EEA area. The network is flexible, and additional water bodies might be required to meet some of the EEA's information needs, especially on impacts. However, the hydromorphological factors under consideration here are not given prominence in the scheme of data acquisition proposed, so that EUROWATERNET sites will not necessarily be suitable as hydromorphological reference sites, since monitoring focuses on water quality.

The EC research project SALMON (SAtellite remote sensing for Lake MONitoring) involves co-operation between limnologists and remote sensing specialists with the goal of evaluating the capabilities and potential of current and forthcoming space-borne remote sensing for the monitoring of European lake water quality, with the aim of producing guidelines and protocols for the definition of a suitable tool in water quality monitoring and management. However, the focus appears to have been on monitoring chlorophyll concentrations, and resolution problems are reported in the context of its use for inland waters (Premazzi and Cardoso 2000).

Guidance on monitoring of WFD hydromorphological and other quality elements has been developed very recently (Littlejohn *et al.* 2002a, 2002b). The current state of development of the WFD monitoring protocol for Ireland is outlined in Table 38; the lack of baseline reference conditions for all quality elements is seen as a significant impediment (Irvine *et al*. 2001, 2002).

5.4.4 Principles of monitoring for the WFD

The Directive specifies quality elements for the classification of ecological status that include hydromorphological elements supporting the biological elements and chemical and physicochemical elements supporting the biological elements. "Supporting" means that the values of the physicochemical and hydromorphological quality elements are such as to support a biological community of a certain ecological status, as this recognises the fact that biological communities are products of their physical and chemical environment. The latter two aspects fundamentally determine the type of water body and habitat, and hence the type specific biological community. It is not intended that these supporting elements can be used as surrogates for the biological elements in surveillance and operational monitoring. Rather, the monitoring or assessment of the physical and physicochemical quality elements is to support the interpretation, assessment and classification of the results arising from the monitoring of the biological quality elements (Littlejohn *et al*. 2002b).

Table 38 Monitoring hydromorphological quality elements in Irish lakes: summary table. After Irvine *et al*. (2002).

			Research needs / outstanding issues	
Element	Methods available	Current activities	Reference values	Methodologies
Hydrological regime	Bathymetric survey for basin typology and estimation of annual residence time using meteorological data. Downstream gauging stations for estimates of outflow. Map of impediments (e.g. dams)	Lake level readings and outflow rates of reservoirs and Shannon lakes	Estimation of residence time available for some lakes and reservoirs	Develop morphological indices that can be measured on numerical scales and increase extent of bathymetric survey. Consider the development of aerial survey techniques
Morphological conditions	Bathymetry. Mapping shoreline (including index of shoreline development). Ranking substrata through proportions of sediment size fractions.	No routine activities. Sporadic recording of some parameters.	No known records of good baseline data. Some video footage of shoreline recorded in individual projects.	Develop indices that can be measured on numerical scales. Consider use of aerial survey techniques.

Premazzi and Chiaudani (1992) set out criteria for selection of variables with which to measure the ecological status of lakes, as follows:

a) redundancy/simplicity: do not select closely related or correlated variables
b) integration: do select variables whose values are a function of the interacting effects of several (physical, chemical, biological) factors if possible
c) relevance: do select variables that are sensitive to subtle perturbations of the system
d) stability: variables that lack stability, e.g. are subject to severe hourly/daily fluctuations, should be avoided or interpreted with care
e) cost: the variables chosen should be inexpensive and easy to measure

5.4.5 Surveillance monitoring of lake hydromorphology

The practice of surveillance monitoring will involve collection of similar data at reference and non-reference lakes, to enable comparison of their biological quality. Eventually, it is intended that biological data from the lake under scrutiny will also be compared with the results of previous surveillance monitoring campaigns at the same lake. The primary focus will be on biological data, although Littlejohn *et al*. (2002b) identify a need to incorporate physical data in some situations; for example to provide estimates of the effects of reduction in habitat area on the overall abundances of biota. However, the principal function of the supporting hydromorphological data will be to indicate possible reasons for failure to achieve good ecological status, where this is indicated by the biological data. Therefore, efficient surveillance monitoring programmes will include assessment of only the minimum set of attributes that will provide an indication of the severity of impacts on the hydromorphological quality elements and their associated conditions. The requirement could be met by monitoring water level, sediment deposition and shoreline habitat condition (Table 39).

5.4.5 Operational and investigative monitoring

According to Littlejohn *et al*. (2002), operational monitoring (or in some cases investigative monitoring) will be used to establish or confirm the status of bodies thought to be at risk. It is highly focused on parameters indicative of the quality elements most sensitive to the pressures to which the water body or bodies are subject. Operational monitoring has to be undertaken <u>for</u> (but not necessarily <u>at</u>) all water bodies that have been identified, by the review of the environmental impact of human activities (Annex II) and/or from the results of the surveillance monitoring, as being at risk of failing the relevant environmental objectives under Article 4.

Table 39 Suggested scheme for surveillance monitoring of lakes.

METRIC			
WATER LEVEL	Rationale	1	One of the WFD hydrological quality conditions (Section 1.3).
		2	Provides an index of the storage term of the water balance, which is the net result of all water exchanges between the lake and its surroundings. It thus reflects quantity and dynamics of flow, and is related to residence time and connection to groundwaters.
		3	Contributes directly to lake depth variation.
		4	Influences structure and condition of the lake shore and sediment dynamics.
		5	Relevant to streamlining monitoring procedures, in that data could be used to refine and calibrate the DHRAM and lakeshore sensitivity procedures.
	Method		Electronic pressure transducer, securely anchored below minimum water level, at a single station within the lake (for large lakes and data security reasons, use of replicate transducers might be considered). For reservoirs, data may be available from operators (Section 4.5).
	Data		Hourly records throughout a water year, which might begin in early spring (rather than January) to coincide with timing of biological sampling programme.
	Data analysis	1	Annual hydrograph (Figures 5, 6).
		2	Level duration curve (Figures 11, 12).
		3	Maximum, minimum, mean and modal water levels.
		4	Comparison of 1, 2 and 3 with equivalent data for reference site.
		5	Derivation of DHRAM score.
	Cost implications	1	Pressure transducer (and anchoring system) for each station to be operational at any one time.
		2	Portable computer or telemetric system for downloading data.
		3	Staff time for installation, data download and analysis.
SUB-LITTORAL SEDIMENT DEPOSITION	Rationale	1	Quantity and structure of the substrate is one of the WFD quality conditions (Section 1.3)
		2	Contributes directly to lake depth variation and indirectly to residence time.
		3	Provides a direct index of the principal impact of changes in catchment land use on lake hydromorphology (Section 3.2.2).
		4	Could be combined with diatom/multi-proxy work (Bennion *et al.*)
	Method		Sediment traps placed at replicate sites in high energy and low energy zones for one year.
	Data	1	Location (GPS) and depth below water surface at times of placement and collection.
		2	Quantity of sediment collected.
		3	Grain size analysis of sediment collected.
		4	Mineralogical characterisation and provenance.
	Cost implications	1	4-5 sediment traps and marking/installation/recovery gear for each lake to be monitored during a single year; boat and GPS.
		2	Staff time for installation and recovery of equipment, processing of samples.
SHORELINE HABITAT CONDITION	Rationale		Structure and condition of the shore zone are WFD quality conditions (Section 1.3).
	Method		Lake Habitat Survey (LHS); to be developed – see Section 5.3.4.7; to be conducted in summer.
	Data	1	Sketch map of riparian, littoral and in-lake habitats (Figure 19).
		2	Ten spot-check survey forms.
		3	Habitat Quality Assessment (or variants).
		4	Habitat Modification Score (or variants).
	Cost implications	1	Boat and GPS may be required.
		2	Staff time for survey and data analysis.

Contrary to a literal interpretation of the Directive (see Section 5.4.2), Littlejohn *et al.* (2002) state that the use of non-biological indicators for estimating the condition of a biological quality element may complement the use of biological indicators but cannot replace it; since non-biological indicators cannot be relied on without checking their inference using biological indicators because we do not have perfect knowledge of cause-effect relationships, pressures, the effects of pressure combinations etc. (i.e. non-biological indicators are generally uncalibrated). Investigative monitoring also focuses on specific problems. For example, where surveillance monitoring indicates that good ecological status is not likely to be achieved and operational monitoring has not already been established, investigative monitoring can be used to ascertain the reasons. The results would be used to inform the establishment of a programme of measures for the achievement of the environmental objectives.

Thus, any needs for operational and investigative monitoring will be indicated by biological data; and since they are to be targeted according to the type of biological impact detected, it is not possible to make rigorous prescriptions for hydromorphological methodologies to support them. However, the information contained in Table 3 offers some pointers to the aspects of hydromorphology that have been associated with specific impacts on biological quality. Since these might assist in the design of targeted monitoring campaigns, the material is re-worked in this form in Table 40.

Table 40 Associations between impairment of biological quality and hydromorphological impacts reported in the literature*.

BIOLOOGICAL QUALITY ELEMENT	NATURE OF DEVIATION FROM REFERENCE CONDITION	CANDIDATE CAUSES	ASSOCIATED HYDROMORPHOLOGICAL FACTOR(S)	CANDIDATE HYDROMORPHOLOGICAL PARAMETERS TO BE INCLUDED IN MONITORING PROGRAMME**
	High algal growth rate	Catchment land use	High sedimentation rate and suspended sediments	Quantity and structure of substrate
	Phytoplankton populations differ from reference state; cyanobacterial blooms	Upstream water use Reservoir operation regime	Water level and hypolimnion volume affected by alteration of inflow/ outflow rates and/or residence time	Water level
				Quantity and dynamics of flow (inflow and outflow rates, DHRAM)
				Residence time
Macrophytes	Retreat of reed fringe	Catchment land use	Accelerated catchment erosion and lake sedimentation rates	Quantity and structure of substrate
		Culverting of outflow		Structure and condition of shore zone (presence of artificial structures)
	Emergent macrophytes (*Typha*, *Phragmites*) favoured	Sewage discharge	Sedimentation of persistent algal remains	Quantity and structure of substrate
	Succession in marginal plant communities	Reservoir operation regime	Altered water level, maximum and mean depths	Level (average, seasonal, period water level range); Depth variation
	Reduced growth of submerged macrophytes		High water level	
	Deviations in littoral macrophyte populations		Distortions to character and rate of water level fluctuations	Level (hourly water levels)
Invertebrate fauna	Deviations in benthic invertebrate communities	Reservoir operation regime	Distortions to character and rate of water level fluctuations	Level (hourly water levels)
	Siltation/degradation of fish spawning grounds	Dredging (navigation) Gravel extraction	Distortions to sediment deposition and distrubution patterns	Quantity and structure of substrate
Fish fauna	High productivity	Reservoir operation regime	Increased lake area and depth	Level (average, seasonal, period water level range) Depth variation
	Distortions to spawning success		Distortions to character and rate of water level fluctuations	Level (hourly water levels) Dynamics of flow

* Information re-worked from Table 3. ** See Table 17 for methods

6. RESEARCH NEEDS

6.1 Typology

In Section 5.3.2 it was concluded that a System A typology is likely to prove unsatisfactory for the UK. The development of an effective System B typology is a key research need for the efficient implementation of the WFD. Work in Ireland and Austria (Irvine *et al.* 2002; ÖNORM *et al.* 2002) has proposed System B typologies, but both comment on the desirability to undertake rigorous statistical analysis based on clustering. This form of analysis, beyond the scope of this project, could include the full range of variables listed in Table 41, from which the key classification variables will be isolated (cf. Palmer *et al.* 1992).

Table 41 Input data (variables) required to determine hydromorphological quality elements

Quality element	Variables
Quantity and dynamics of flow	Water balance (rainfall, evapotranspiration, inflow, outflow rates), wind, maximum depth, lake area and plan shape, basin form, catchment relief, temperature
Water level	Water balance (rainfall, evapotranspiration, inflow, outflow rates)
Residence time	Rainfall, catchment area, lake volume
Connection to groundwaters	Solid geology, drift geology, level, level variation
Lake depth variation	Basin form
Quantity and structure of substrate	Solid geology, drift geology, water level, water level variation, basin form
Structure and condition of shore zone	Solid geology, drift geology, water level, water level variation, wind, lake area and plan shape, basin form

A first list of nine primary variables is given in Table 26. From these, a number of other variables might be calculated. Table 42 illustrates the considerable overlap in the physical factors contributing to hydromorphological quality, e.g. that geographical location is likely to influence lake water balance, water level and residence time.

Table 42 Inter-relationships between System B candidate variables and hydromorphological quality elements

		Quantity and dynamics of flow	Level	Residence time	Connection to groundwaters	Lake depth variation	Quantity and structure of substrate	Structure and condition of shore zone
	From geological, topographical maps, remote sensing							
1	Location (National Grid Reference; latitude/longitude)	*	*	*				
2	Altitude	*						
3	Solid geology	*	*		*		*	*
4	Drift geology	*	*		*		*	*
5	Catchment area	*	*	*			*	
6	Altitudinal range of catchment	*	*	*				
7	Lake surface area	*	*					*
8	Shoreline length				*		*	*
	From bathymetric survey or maps							
9	Hypsographic curve	*		*	*	*	*	*
	By calculation							
	Lake volume			*		*		
	Maximum depth	*					*	
	Basin form class (relative hypsographic curve)				*	*	*	*
	Shoreline development ratio				*			*
	Lake geometry ratio	*		*		*		
	Relief of drainage area	*						
	Mean depth					*		
	Relative depth					*		
	Dynamic ratio					*	*	
	Volume development					*		

6.2 Data sources for assessment of pressures

Characterisation of catchments within River Basin Districts will be large undertaking requiring formalisation of the procedure. It will be necessary to develop a comprehensive list of desk-based data and sources for assessment of pressures. A first attempt is presented in Table 43 and in practice should take advantage of existing databases, exploiting where possible GIS query techniques.

Table 43 Information that is relevant to assessment of pressures on the WFD hydromorphological quality elements for lakes, with potential sources.

			Risk for						
Feature	Pressure(s) indicated	Source	Quantity and dynamics of flow	Level	Residence time	Connection to groundwaters	Lake depth variation	Quantity and structure of substrate	Structure and condition of shore zone
% forestry	Forestry	Maps (OS, land cover etc.)	*	*	*	*	*	*	*
% woodland	Degree of catchment modification	Maps	*	*	*	*			
% agricultural land	Food production	Maps	*	*	*	*	*	*	*
%natural vegetation	Degree of catchment modification	Maps	*	*	*	*			*
%urban and residential	Intensity of urbanization	Maps	*	*	*	*	*	*	*
Population density	Demand for services	Census						*	*
Sewerage works	Discharge	Local authorities							
Road density	Intensity of road network	Maps						*	*
Water treatment works	Water supply	OS maps	*					*	*
Abstractions	Water supply	EA/SEPA	*	*	*	*	*		
Water diversions	Water supply	EA/SEPA	*	*	*	*	*	*	
Dams	Water supply, hydro-power, flood control	OS maps	*	*	*	*	*		*
Power stations	Hydro-power generation	OS maps	*	*					
Quarries	Mining	OS maps					*	*	*
Industry	Loss habitat	OS maps	*	*	*	*	*	*	*
Marinas, water sports centres	Recreation	OS maps						*	*
Picnic areas	Recreation	OS maps							*
Footpaths	Recreation	OS maps							*
Fishing	Recreation	EA/DSFB/Angling Associations						*	*
Fish farms	Food production	Air photos						*	*

6.3 Use of remote sensing in site assessment

Further research is needed into the utility of a broad range of remote sensing techniques, especially aerial photography, for site assessment. Issues to be considered include flying height, vertical versus oblique, film type, video or still photography, conventional versus digital photography and time of year of the survey. With respect to the latter, beds of macrophytes will only be observed during the midsummer growing season and scale is important for mapping shoreline modifications, e.g. walls, jetties etc. Such imagery must also be up-to-date. Selective coverage of the UK flown by "Get Mapping" in 2000/2001 may be useable, otherwise dedicated missions might be considered.
Other earth observation platforms such as MODIS, SPOT offer scope to complement data gathering on hydromorphological quality elements (e.g. turbidity) especially of large standing water bodies.

6.4 Towards the development of an abiotic screening tool for lakes

The Directive stipulates that surface water bodies such as lakes should achieve good ecological and chemical status (pollutant levels) by 2015. Good ecological status is then defined on the basis that there is only slight deviation of biological quality from that of the appropriate natural reference condition. In relation to biological data, the Directive clearly identifies that the composition and abundance of aquatic flora, benthic invertebrate fauna and fish (including age structure) should be utilised. Such data were sought in relation to a calibration exercise for the DHRAM model produced for the recently completed SNIFFER projects 'Anthropogenic impacts on the hydrology of rivers and lochs' (Black *et al.* 2000) and in relation to designations of Heavily Modified Water Bodies (HMWB) in Europe (Black *et al*. 2002b,c). For both these projects extensive consultation exercises were undertaken with relevant agencies and stakeholders such as SEPA, SNH, Fisheries Trusts, RSPB, Scottish Power etc. However, the data obtained were rarely appropriate in terms of coverage, frequency or comprehensiveness leading to serious questions of temporal and spatial representativeness.

In the absence of the necessary biological data the alternative approach to characterising ecological status is to employ abiotic criteria (critically the interplay between hydrological regime and the physical structure of lakes). A quantitative assessment of hydromorphological alteration is proposed using a composite score for regime alteration and physical disruption, using the integration of DHRAM scheme to characterise hydrological regime and Lake Habitat Survey scheme, the latter derived through the adaptation of the RHS and FOML. This Abiotic Index (Table 33) represents the interplay of the key hydrological and morphological quality elements of a water body and thus offers potential as a screening tool in the determination of which water bodies are at risk of failing to achieve Good Ecological Status (Annex II). Such a tool also offers the basis for developing subsequent Programmes of Measures (Article11(i)) which will be required to improve hydromorphological quality elements to achieve good ecological status or good ecological potential in the case of HMWBs. Extensive field-testing is required to calibrate the Abiotic Index with ecological data. Such a calibration, and ultimately validation exercise, is deemed essential to both the scientific credibility of such screening tools and to provide all stakeholders within a river basin district with a transparent assessment process.

7. SUMMARY AND CONCLUSIONS

Lakes form an important national resource within the UK. With the implementation of the WFD all European standing water bodies of area greater 0.5 km^2 that are affected by human activity should achieve good ecological status, or the highest ecological status/potential that is possible given specifically justified human needs.

The purpose of this report was to review the implementation requirements of the WFD in the UK, particularly the requirements that the high status for lake hydromorphology can be defined. The main objectives were:

- To search the (worldwide) published literature on methods for assessing the physical (hydromorphological) features of lakes.
- To review and evaluate existing methods, especially in terms of their relevance and feasibility for use in implementing the WFD.
- To make recommendations for an appropriate methodology for use in the UK and to consider how it is linked with ecological assessment methods required by the WFD.
- To consider the relevance of River Habitat Survey techniques to standing waters and to propose a scoring system for lake shoreline assessment.

The literature review has provided an overview of human pressures on lakes, and the resulting impacts on hydromorphology and biota (Tables 3-4). A review is also presented of methods used to measure the hydromorphological attributes of lakes. Several potential metrics have been identified for each attribute. Methods vary in the ease with which they can be adapted for the purposes of the Directive (Tables 17-18).

Member states are required to produce a lake typology based on a modelling and/or a reference network of undisturbed water bodies that define high ecological status. A System A typology is unlikely to prove adequate for UK purposes. A priority need is therefore the development of a UK-specific System B typology, using statistical clustering to determine the most significant optional factors to be included (Tables 26, 41, 42).

The pressures operating in the catchment of an individual lake can be assessed by direct observation (e.g. Tables 27-28). However, the scale of the exercise required for WFD implementation is such that it will be expedient to use desk-based information sources as far as possible. An outline scheme is presented (Table 43). In practice this should take advantage of existing databases, exploiting where possible GIS query techniques. A screening tool is proposed in the form an Abiotic Index (Table 33) based on a combination of the Dundee Hydrological Regime Alteration Method (DHRAM) for standing waters and a newly proposed Lake Habitat Survey (LHS) approach derived from the integration of the Environment Agency's River Habitat Survey (RHS) and the USEPA's Field Operations Manual for Lakes (FOML). Extensive field testing is required to calibrate such screening tools with ecological data.

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ANNEX 1 LITERATURE SEARCH METHODS

The information sources that were identified as potentially useful for this work were:

1. Literature already held by members of the project team and Dundee University Library
2. *Web of Science* on-line literature archive
3. *Geobase* literature database (on compact disk)
4. On-line library catalogues, e.g. English Nature, European Environment Agency
5. UK libraries, e.g. SEPA, Environment Agency, SNH, CEH, FBA, British Library
6. Personal contacts

All of these sources have been explored, and all have yielded some useful information. However, the external sources that were used most intensively were *Web of Science* and the jointly-maintained library of the Centre for Ecology and Hydrology (CEH) and the Freshwater Biological Association (FBA) at Windermere, Cumbria.