THE DEVELOPMENT OF A GIS-BASED INVENTORY OF STANDING WATERS IN GREAT BRITAIN TOGETHER WITH A RISK-BASED PRIORITISATION PROTOCOL

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Abstract. An inventory of standing waters (freshwater lakes and lochs) was derived from Ordnance Survey digital map data at a scale of 1:50 000 and represents the most comprehensive survey of its kind for Great Britain. The inventory includes 43 738 water bodies in England, Scotland, Wales and the Isle of Man and contains basic physical data such as location, surface area, perimeter and altitude. Catchment areas were computed for water bodies with a surface area larger than 1 ha from a digital terrain model (DTM) using customised routines in a geographical information system (GIS). The resulting polygons were then used to derive catchment-related information from a variety of national datasets including population density, livestock density, land cover, solid and drift geology, meteorological data, freshwater sensitivity status, acid deposition and conservation status. Using data derived from the inventory a risk-based prioritisation protocol was developed to identify standing waters at risk of harm from acidification and eutrophication. This information is required by the Environment Agency, Scottish Environmental Protection Agency and the U.K. statutory conservation bodies to co-ordinate actions and monitor change under international, European and national legislation.

Keywords: acidification, catchment delineation, eutrophication, GIS, Great Britain, risk-assessment, standing waters

1. Introduction

The water bodies of Great Britain are an important resource with local, national and international significance. They support a wide range of activities including water supply, nature conservation, fisheries, tourism, leisure and scientific research and are important habitats for many plant and animal species. In 1979, Smith and Lyle published a paper describing the distribution of Great Britain's water resource based on 1:250 000 scale maps. Since then there has been no comparable survey published for Great Britain based on more detailed map data that has become available.

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Recent EU legislation together with the growing demands of Great Britain's statutory environmental protection and conservation agencies has led to the need for a comprehensive computer-based inventory of standing waters. The Water Framework Directive (EU, 2000), which came into force in December 2000, requires the setting of water quality objectives for all water bodies (not just those designated by the member state) and provides for a classification of water bodies according to ecological quality status (DEFRA, 2001). The implementation of U.K. Biodiversity Action Plans for both habitats (specifically eutrophic and mesotrophic standing waters) and species also require data on the extent, distribution and physical, chemical and biological status of standing waters across the U.K. (U.K. Biodiversity Group, 1998).

A consortium of stakeholders was brought together to build and populate the inventory and to develop a risk-based prioritisation protocol to help assess environmental harm from nutrients and acid deposition. The protocol requires catchment-based data for several environmental parameters and so it was necessary to compute catchment polygons. These were used in a GIS with appropriate national datasets to derive the environmental data required to apply the protocol.

This paper describes how the inventory was built, gives an account of the distribution of standing waters in Great Britain and outlines the development of the prioritisation protocol.

2. Methods

2.1. Assembling the Inventory

During the last 100 years there have been various attempts to describe the extent and distribution of standing waters in Great Britain (e.g. Smith and Lyle, 1979; Barr *et al.*, 1994; Fuller *et al.*, 1994; Haines-Young *et al.*, 2000), Scotland (e.g., Murray and Pullar, 1910; Lyle and Smith, 1994) and Northern Europe (e.g. Henriksen *et al.*, 1998). For Great Britain as a whole, the most comprehensive of these was the Smith and Lyle survey, which was based on a visual inspection of 1:250 000 paper maps from Ordnance Survey (OS). At this scale the lower level for inclusion is about 4 ha. The survey also undertook sample counts from 1:63 360 OS maps and it was estimated that the number of lochs was more than seven times the number found in the original survey, the additional lochs being small water bodies not shown at the 1:250 000 scale. Clearly, at larger scales there will be a greater number of water bodies defined and the lower level for inclusion will get smaller.

In choosing the data source for the inventory the main consideration was the degree of detail needed. The basic requirements were for an outline of the water body from which the co-ordinates of its centroid, surface area and perimeter could be derived. It was decided at an early stage to concentrate on water bodies with a surface area of at least 1 ha. OS Land-Form PANORAMA™ contour data at

1:50 000 contain features representing contours, spot heights, ridge lines, coastline and lake outlines as seen on the 1:50 000 Landranger paper map series. Lakes in PANORAMA are defined as 'bodies of inland water, including ponds, lakes, lochs and the lower parts of some rivers' (Ordnance Survey, 2001). Each lake outline has an associated elevation attribute (to the nearest meter) and all line objects have a quoted spatial accuracy of 3 m root mean square error (Ordnance Survey, 2001). A visual inspection of the data indicates that water bodies with surface areas as small as 0.5 ha are accurately represented and although smaller water bodies do exist in the dataset (the smallest being 0.02 ha), their representation is somewhat generalised. The dataset remains relatively manageable in terms of computer processing whereas data at a larger scale (such as OS Land-Line™) would have introduced problems of data manageability and unnecessary complexity (see Hughes and Fisher, 2000).

Each of the 812 400 km^2 PANORAMA tiles was processed individually to extract the lake features (OS feature code 0202) using 3 SPARC Ultra-5 workstations and ESRI software. Tiles were converted to ArcInfo coverages using ESRI's MapManager software and subsequently lake features were extracted automatically, converted to polygons using custom scripts in ArcInfo and assembled as a single coverage. Each lake polygon was then assigned a pair of geometric centroid co-ordinates (to the nearest metre) and basic physical parameters (surface area in hectares, altitude and perimeter both to nearest metre, number of islands).

The data were error-checked using a variety of methods, both automatic and manual. Lake features that did not form whole polygons were closed automatically using an iterative process where snapping distance was gradually increased from 2 to 10 m. Open polygons with gaps larger than 10 m were edited manually with reference to the paper map, resulting in more than 700 additional water bodies. The conversion to polygon process occasionally produced slivers (very small polygons adjacent to 'real' polygons) and these were searched for automatically (by size) but checked visually against the map. Some 300 polygons were rejected as being slivers. The original dataset contained large rivers coded as lakes and split into sections appearing as long chains of adjacent rectangular polygons. These were removed manually, resulting in the loss of a further 2200 polygons. The final number of polygons in the database was 46 570; of which 43 738 were lakes and the remaining 2832 were islands.

Additional parameters were derived for each lake polygon. OS-style grid-references, geographic coordinates, distance to sea, shoreline development index (a measure of shoreline complexity), and length and bearing of line of maximum fetch were all computed using Microsoft Excel, ArcView and ArcInfo. Attribute data were managed in a Microsoft Access database and linked to the GIS using unique identification codes. The lake centroids were used in a series of overlays to identify co-occurrence with a range of national datasets (Table I). Measured depth data for approximately 5% of the water bodies >1 ha were collected from a wide range of sources (including Murray and Pullar, 1910) and used in a simple multiple

TABLE I

Data available for lake centroids	Data available for catchments
Agency (EA/SEPA) Region co-occurrence	LCM90 Landcover class (Fuller *et al*., 1994)
1995–1997 Acid Deposition (CEH)	Drift Geology (1:625 000)
Freshwater Sensitivity (Hornung *et al*., 1995)	Solid Geology (1:625 000)
Protected areas co-occurrence (includes National Park, Forest Park, National Nature Reserve (NNR), RAMSAR, Special Area of Conservation (SAC), Special Protection Area (SPA), Site of Special Scientific Interest (SSSI))	1995–1997 Acid Deposition (CEH)
	Freshwater Sensitivity (Hornung *et al*., 1995)
	Animal stocking density (MAFF)
	Modelled hindcast P load (Johnes *et al*., 2000)
	Modelled current P load (Hilton *et al*., 1999)
	1991 Population (Bracken and Martin, 1995)
EN Character/Natural Area co-occurrence	Mean annual runoff (CEH)
OS Landranger Map sheet	

regression model to predict mean and maximum lake depths (for the calculation of volume and retention time) based on surface area, altitude and perimeter. Separate models were developed for England, Wales and Scotland – giving better results than a global model. The model used was a least squares regression which, despite large residuals, did at least give a good prediction of depth if broad depth classes (such as those used in the Water Framework Directive) were used.

2.2. Catchment delineation and overlay

Catchment areas were derived for all water bodies with a surface area >1 ha. The lake polygons (n = 14 353) were extracted and processed with a flow grid derived from the Institute of Hydrology digital terrain model (DTM) (Morris and Flavin, 1990) to generate catchment polygons. This 50 m resolution DTM is based on digitised contours from the Ordnance Survey 1:50 000 map (the same source as the lake polygons used in the inventory), but has been adjusted to conform to a digitised stream network for greater accuracy. An assessment of DTM quality for hydrological applications (Wise, 2000) found that this particular model gave the lowest RMSE error statistics and was well suited for hydrological applications due to its low number of sinks (groups of cells that do not flow into any surrounding cells).

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

The catchment overlay process for each dataset took one of two forms depending on the data type. A catchment-weighted procedure was used for overlay with gridded maps of distributed data at varying resolutions (such as acid deposition (1 km) and P load (5 km)) whereby a mean value was found by calculating the proportion of each gridded data cell overlaid by the catchment polygon. For datasets containing categorical data in discrete units (such as geology and land cover), the proportion of each category was calculated as an actual area (in ha) and percentage of catchment. (Note: many of the national datasets did not cover the Isle of Man therefore these water bodies were excluded from the risk prioritisation exercise.)

2.3. Risk Prioritisation

The purpose of the risk prioritisation exercise was to assess the risk of harm from nutrients (eutrophication) and acid deposition (acidification) to ecological condition, which in turn would allow a prioritisation of water bodies for action. The approach follows DETR guidelines for environmental risk assessment (DETR, 2000) whereby risk is placed in an objective framework with multiple tiers, ensuring that actions are focused where they are most beneficial to society (Pollard *et al.*, 2000). A detailed account of the protocol can be found in Bennion *et al.* (2002) but in short, the prioritisation system for lakes is based on three essentially independent properties: importance – or value to society; hazard – posed to a lake from sources of nutrients and acidity; and sensitivity – of a lake to change in water quality.

The first tier of the protocol takes as its input the entire population of lakes larger than 1 ha in surface area and applies a simple set of risk screening criteria under the three headings: importance, hazard and sensitivity. Lakes that meet these criteria then fall through to tier 2 where a more detailed risk assessment is performed. Lakes that are output from this tier are then carried forward into the third and final tier where a detailed quantitative risk assessment can be carried out on a site-specific level. The protocol results in a list of water bodies ranked by importance, exposure to hazard and sensitivity, which can be used by managers to coordinate and prioritise actions. It is also hoped that this process may help identify previously overlooked water bodies with conservation value.

Importance criteria were selected in consultation with stakeholders to satisfy the key requirements of EU legislation (Water Framework Directive), U.K. Biodiversity Action Plans (specifically the Lakes Habitat Action Plans) and the agency's (EA/SEPA) eutrophication strategies. The criteria were size (>50 ha), conservation status (RAMSAR, SAC or SPA) and designation under EU Bathing Waters Directive.

At tier 1, an assessment of the risk of harm from eutrophication is made from estimated nutrient loads for water bodies using the GIS-derived catchment polygons

TABLE II
Numbers of water bodies by country and surface area

	<1 ha[a]	1–5 ha	5–10 ha	10–50 ha	50–100 ha	>100 ha	Total
England	10738	4260	710	625	64	51	16448
Scotland	17727	5294	1195	1205	168	171	25760
Wales	894	394	88	90	10	17	1493
Isle of Man	26	9	0	2	0	0	37

[a] The dataset contains no water bodies <0.02 ha and the number between 0.02 and 0.2 are almost certainly under-represented.

and national datasets of land cover (Fuller *et al.*, 1994) and population (Bracken and Martin, 1995) and published phosphorus export coefficients (Hilton *et al.*, 1999). At tier 2, the eutrophication risk assessment is improved by the addition of measured chemical and biological data on current trophic status and an estimate of enrichment based on hindcast models (e.g. Bennion *et al.*, 1996; Johnes *et al.*, 1996; Ferrier *et al.*, 1997). The sensitivity of a lake to eutrophication was assessed using an estimate of retention time (or flushing rate) derived from measured or modelled lake depths.

For acidification, the main hazard is regarded as atmospheric deposition and this was estimated at tier 1 using the GIS-derived catchment polygons and national maps of acid deposition (provided by the Centre for Ecology and Hydrology). At tier 2 the acidification scheme is enhanced with calculations of critical loads and exceedances (e.g. Curtis *et al.*, 2000) and pH hindcast models (e.g. Jenkins *et al.*, 1990; Jones *et al.*, 1993). Sensitivity was assessed using a national map of sensitivity of freshwaters to acidification (Hornung *et al.*, 1995).

3. Results and Discussion

3.1. Lakes inventory – Summary data

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

In their survey of Scottish lochs, Lyle and Smith (1994) grouped water bodies larger than 25 ha into logarithmic area classes to investigate the relationships between numbers of lochs, accumulated area and volume. They found that there was a natural order in the frequency of occurrence based on surface area, which is confirmed by the present study for Great Britain as a whole. The relationship

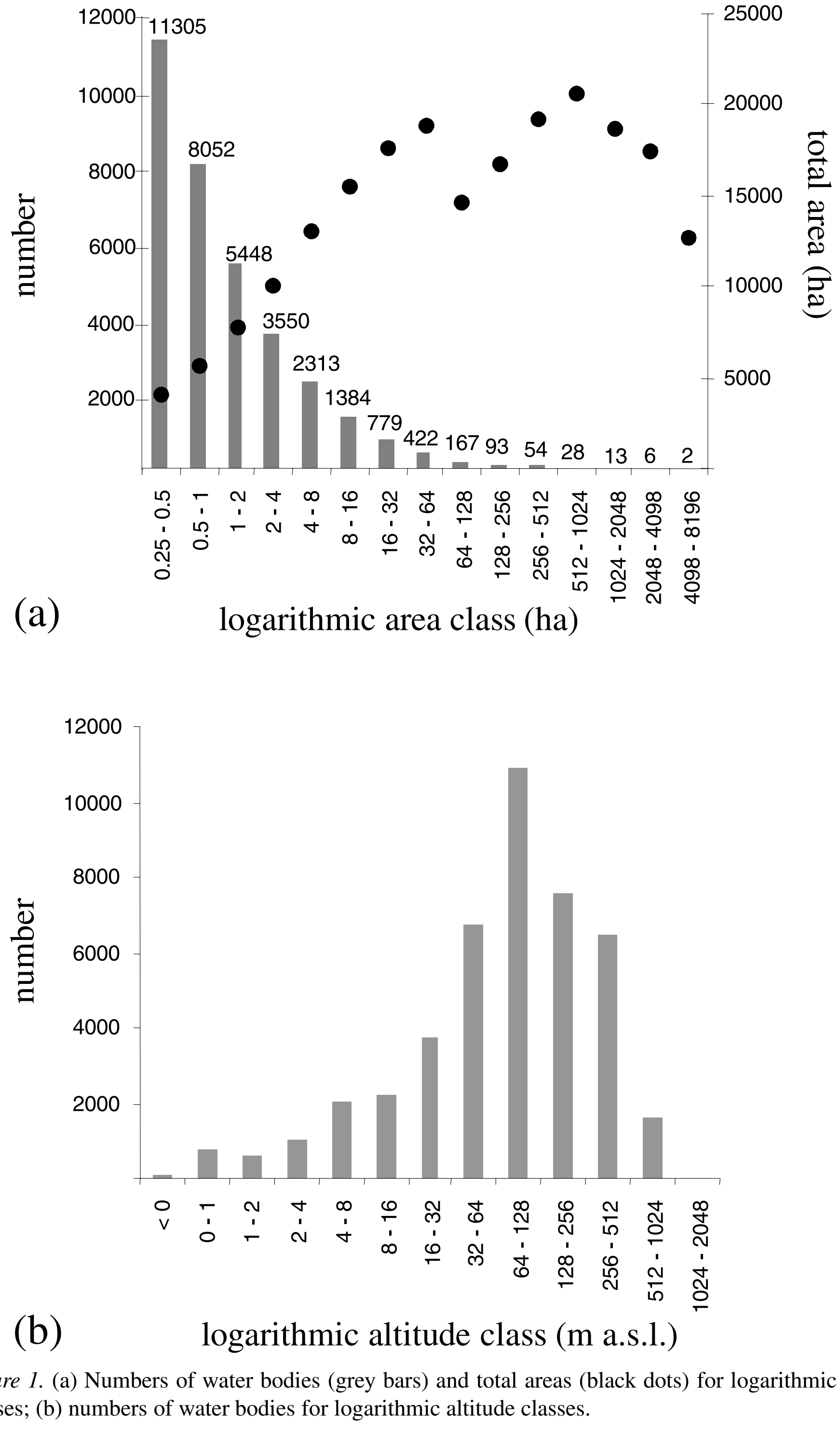

Figure 1. (a) Numbers of water bodies (grey bars) and total areas (black dots) for logarithmic area classes; (b) numbers of water bodies for logarithmic altitude classes.

TABLE III

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

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

between numbers of water bodies and total area for each logarithmic area classes is shown in Figure 1 and shows that although the number of water bodies increases as the logarithmic area class decreases, the total area starts to decrease – something which Lyle and Smith predicted but were unable to demonstrate with their dataset. It is useful to look at this relationship because it gives an idea of the level at which water bodies, in a strategic sense at least, become unimportant in terms of surface area and volume. By extrapolating the relationship between logarithmic area class and total surface area of water bodies (e.g. polynomial curve-fitting) it can be estimated that although the number of very small (<0.25 ha) water bodies in Great Britain almost certainly exceeds one hundred thousand their accumulated area is probably no more than 5% of the total for GB and their accumulated volume less than 1%. The estimated total surface area of standing water for Great Britain based on these results is ∼220 000 ha. This includes the water bodies in the inventory and estimates for the smaller water bodies not shown at 1:50 000 and is somewhat larger than the recent Countryside 2000 survey estimate of 190 000 ha, but smaller than Smith and Lyles 1979 estimate of 240 400 ha. The Countryside 2000 survey (Haines-Young *et al.*, 2000) was based on a stratified random sampling of 1 km^2 squares and despite the lower total area claims to include lowland ponds, giving a total number of standing water bodies at 400 000 (although they do not give a lower limit of inclusion).

Table III and Figure 1 show the distribution of water bodies by altitude and country and by logarithmic altitude class, respectively. There are two different distributions influenced by topography – England with the majority of its water bodies at lower altitudes and Scotland and Wales with the majority at slightly higher altitudes. In terms of the Water Framework Directive ‘System A’ ecoregions, 75.8% of water bodies (by number) occur in the lowland ecoregion (<200 m), 23.8% in the mid-altitude ecoregion (200–800 m) and the remaining 0.4% in high ecoregion (>800 m). The figures for distribution by surface area are similar except for the high ecoregion, which only has 0.06% of the total surface area for Great Britain.

3.2. RISK PRIORITISATION PROTOCOL

Two schemes were developed for assessing the risk to standing waters from eutrophication and acidification. Both relied on data generated by overlay of catchment polygons and national datasets. The protocol was tested on a subset of 30 lakes for which measured data were available with the primary objective of assessing the reliability of the importance, hazard and sensitivity measures as indicators of risk. Detailed results can be found in Bennion *et al.* (2002).

For eutrophication, the protocol reliably models the risk of enrichment and the likelihood of response to restoration in most cases. Modelled current nutrient loads are well estimated when inputs from humans, land cover and livestock are considered and there are no point sources of nutrient input, which the inventory does not include. Results suggest that the lake depth model is not performing well and consistently overestimates depth. For shallow lowland lakes this is significant because depth is used to predict stratification class suggesting a better response to restoration than would be expected in reality. A more rigorous model of lake depth is planned for the future based on morphometric analysis using surrounding slope angles derived from contours.

The acidification scheme was tested using palaeolimnological data (diatom assemblages) to confirm high risk of acidification and lakes predicted as being at low risk due to agricultural improvements in the catchment are confirmed. The use of critical load and exceedance data to improve risk assessments was found to be beneficial, especially the diatom critical load since the diatom community is regarded as the most sensitive aspect of aquatic biota.

This work considers just two possible risk-assessments based on eutrophication and acidification, but the protocol could easily be adapted to account for any other type of environmental pressure provided that sufficient datasets were available.

3.3. ERRORS AND UNCERTAINTY

The main drawback of using PANORAMA data as the basis for the inventory is that it is a static dataset. OS has not updated it since data capture took place in 1983. This means that water bodies created or modified since 1983 will not appear in the dataset in their present form. On the whole, this is not a problem since water bodies do not change much over time. A visual comparison of all lakes >1 ha and current 1:50 000 maps indicates that around 4% of water bodies in the inventory have been significantly modified or no longer exist, however the majority of these occurrences appear to be related to cartographic errors in both the original data (e.g. features incorrectly coded as water features) and the current map. Real cases of lake loss are concentrated in areas around extractive industries, quarries, urban areas, docks and dunes. Conversely, it can be expected that many new lakes have been created since the PANORAMA data capture in 1983 and this is confirmed by other surveys, especially in lowland regions (e.g. Haines-Young *et al.*, 2000).

In several cases, catchment-derived data for certain lakes were suspect, leading to an incorrect risk assessment. Closer inspection revealed that the catchment delineation process had failed to produce an accurate watershed for the lake concerned. The majority of these 'errors' occur when a small water body is close to a large river. The cell that gets selected as the pour point for the catchment is the one with the highest accumulated flow and if a lake cell coincides with a river cell then the river catchment will actually be computed. In the risk assessment protocol this leads to a small water body being erroneously attributed large nutrient and acid deposition loads. Another type of error that may occur is poor catchment delineation in areas of low relief – such as in the Fens or the Norfolk Broads. The vertical resolution of the DTM is insufficient in these cases to allow the accurate mapping of a lake's catchment. A confounding factor in these areas is that lake catchments often are influenced by man-made drainage features, which are not represented in the DTM. Clearly, these lowland water bodies represent a challenge. Higher resolution LiDAR data could be used as a means to more accurately delineate their catchments (Lloyd and Atkinson, 2002).

4. Conclusions

Despite being based on 25 year old data, the inventory presented in this paper provides the most comprehensive survey of Great Britain's standing water resource published to date. Together with the catchment-derived data and risk-prioritisation protocol, it represents a valuable resource for GB's statutory environmental protection and conservation agencies. Potential applications include use in stock-at-risk assessments (e.g. Kernan *et al.*, 2004), the development of a lake classification scheme or 'typology' as required by the Water Framework Directive, and investigations into the relationships between catchment-related parameters such as rainfall, erosion, sediment loads, ecological conditions and catchment morphology. Already the inventory (together with additional datasets) is being used as part of a project to predict in-lake phosphorus from diffuse and point sources. The catchment delineation routine needs refining for water bodies in areas of low relief and to take account of man-made drainage before catchment-based data for these lakes can be used with confidence in the risk-assessment protocol.

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