'SYNOPTIC SURVEY OF NORTHERN IRELAND SMALL LAKES' PROJECT: WATER QUALITY ASSESSMENT BY AERIAL SAMPLING AND GIS BASED LAKE CATCHMENT DELINEATION FOR IDENTIFYING CATCHMENT CHARACTERISTICS

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ABSTRACT

The 'Synoptic Survey of Northern Ireland (NI) Small Lakes' is a collaborative research initiative to aid compliance with the EC Water Framework Directive 2000. It aims to sample small lakes in NI in quasi-synoptic mode and to classify them hydromorphologically by taking account of land-use in the lake catchments and the expected nutrient status of the water. Lake sampling by helicopter was shown to be the most cost-effective method of synoptic survey. By this means, 112 lakes were representatively sampled within 4 working days. The quality of water in these lakes was assessed by analysing the water samples for key parameters. Comparison of lake chemistries resampled 1 year later showed that the samples collected were truly representative of the lakes in question and could safely be used to classify the lakes. The catchment of each lake was delineated within ArcView GIS 3.2 using the Hydrological Modelling extension and grids of flow-direction and flow-accumulation derived from a 50 m DEM with sinks filled. This procedure was automated using an 'Avenue' script. All but 12 lake catchments were delineated without problem. For the 12 problem lakes, new flow grids were created from the DEM, this time without filling sinks. Catchment delineation using these new grids, together with a pixel-by-pixel investigation of the DEM and flow-accumulation around each lake, allowed delineation of catchment boundaries to each problem lake identified.

KEYWORDS: Catchment, DEM, flow-accumulation, flow-direction, GIS, lake, synoptic survey.

INTRODUCTION

Many land-use activities including modern agricultural practices have a significant impact on river and lake water quality. Northern Ireland has approximately 1,670 lakes covering 4.4% of the land surface area of the Province. The majority of lakes have an area less than 100 ha. It is important that the lakes should be protected from pollution and managed as a sustainable resource. Lake water quality assessment forms an essential component of lake management. The Environment and Heritage Service (EHS) of Northern Ireland (NI), an agency within the Department of Environment (DoE(NI)), identified eutrophication as the most widespread single threat to good water quality in NI, and recommended monitoring of surface waterbodies to determine their trophic status. The European Community (EC) Water Framework Directive (EC 2000) insists that Member States monitor and classify the ecological quality of all surface waters including lakes. Under this EC Directive, surface waterbodies including lakes must be divided into types and classified according to their biological, hydromorphological, chemical and physical status. Currently, there are no classification methods in use throughout Europe that would meet the requirements of this legislation.

The Northern Ireland Lake Survey (NILS), which was carried out in the years 1988-1990, sampled over 600 lakes for aquatic plants and the water was analysed for 20 variables (Smith et al., 1991 & 1992). The purpose of this survey was to assess lake conservation status based on the aquatic macrophyte flora and to create a database for future lake conservation for DoE(NI). As the sampling was carried out over the summer periods with two teams each averaging two lakes per day, the nutrient data were a reflection of annual minimum rather than maximum values (Gibson et al., 1996). The survey occupied a protracted period and, at least for the nutrients, comparisons between lakes were not strictly valid since they could have been sampled months apart in the seasonal cycle and in different years throughout the 3-year survey. Finally, the data are now at least 13 years old and many changes are likely to have occurred in the intervening period.

The new 'Synoptic Survey of Northern Ireland Small Lakes' project is a collaborative research initiative between EHS and the Department of Agriculture and Rural Development (DARD), framed according to the recommendations of the European Community Water Framework Directive. This project aims to sample small lakes in NI (selected by conservation importance) in a quasi-synoptic mode (i.e. almost simultaneously) and to classify them hydromorphologically by taking account of land-use in the lake catchments and the expected nutrient status in the water. The delineation of accurate lake catchment boundaries is the first step in many aspects of lake management. Using Geographic Information System (GIS) technology, it is now possible to automatically delineate lake catchments and to predict which way water flows at any point within the lake catchment. GIS makes catchment delineation much faster using spatial data sets derived from a digital elevation model (DEM). With the requirements of the EC Water Framework Directive in mind, it was felt that a new survey should be conducted in late winter when nutrient concentrations are likely to be a truer reflection of the trophic status of the lake. It was also felt that the lakes should be sampled over the shortest possible time interval, and various options were considered. It was concluded that, for a quasi-synoptic mode sampling (i.e., almost simultaneous sampling procedure), the most cost-effective method was to use a helicopter (Gibson & Jordan, 2002). The sampling method was successfully tested in August 2001 using a trial sampling of 8 lakes to ensure that the helicopter did not produce any sampling artefacts such as disturbing the bottom sediments with the downdraft.

METHODS

Lake Water Sampling by Helicopter Survey

Selection of Lakes for Sampling

The number of lakes sampled needs to be large enough that each catchment type can be sampled to give proper confidence limits and a statistically robust model. This was provisionally estimated at 100+ lakes. Accordingly, EHS identified 112 lakes based on conservation importance to be sampled during the first phase of the project. All lakes to be sampled were marked on a set of 1:50,000 scale Ordnance Survey of Northern Ireland (OSNI) Discovery Series maps for the use of scientific staff. Unlike the earlier Northern Ireland Lake survey, the lakes were not chosen by a stratified random method so the results cannot be used to generalise on the state of lakes in Northern Ireland. However, they do provide a data set consistent with the objectives of EHS in developing a lake classification and determining the trophic state of some lakes of high conservation value.

Sampling by Helicopter

A lake-water sampler was specially developed for this survey. It consisted of a weighted container into which could be fitted a 1 litre plastic sample bottle held in place by an elastic cord. It had a float (approximately 40 cm in diameter) one metre above the cord holding the sampler, which prevented the sampler sinking more than 1 m below the lake water. The lake water samples were taken from a JetRanger helicopter (chartered from Helicopter Training and Hire Ltd., Newtownards) carrying two scientists and the pilot. The list of lakes with Irish Grid references and matching lat/long co-ordinates was supplied to the helicopter company. The helicopter pilot was responsible for locating the lake from his maps and for deciding on the order in which they were sampled. The passenger door on the pilot's side of the aircraft was removed to allow the sampler to be deployed. Once on-site, the pilot read out the position from the onboard GPS (latitude and longitude values in the format degrees, minutes and decimal minutes) and this was noted by the inside scientist. The scientist on the outside seat behind the pilot deployed the sampler through the open side while the other took care of the samples and kept records of helicopter readouts. In action, the helicopter hovered at approximately 6 to 7 m above the lake surface; the sampler was carefully lowered until it reached its maximum depth. On retrieval, the sample bottle was removed, capped and replaced with the next empty bottle. The helicopter then flew to the next lake. Lakes were flown in groups in 2-hour sectors, in which at least 30 lakes could be sampled. At the end of a sector, the helicopter landed, refuelled and the scientific crew changed if planned. After the survey, all GPS readings were converted into Irish Grid co-ordinates using the Geographic Calculator software from Blue Marble Geographics and compared with the Irish Grid references given for the lakes in Smith et al. (1991) to ensure the correct lakes had been sampled.

Lake Catchment Delineation using ArcView GIS Methodology

Watersheds were delineated in ArcView GIS (version 3.x) using the Hydrologic Modelling extension together with flow-accumulation and flow-direction grids created using the OSNI 50m DEM with the option to fill sinks selected. This extension allows delineation of watersheds in two ways. In the first method, one needs to predefine the minimum size of the watershed and the size of the watershed returned is controlled by the number of cells that need to flow into a cell to classify it as a stream. As one has to predefine the minimum size of a watershed, this method is generally unsuitable for lake catchment delineation. The second method requires the identification of a pour point for which a watershed should be created. A pour point is the lowest point of a drainage boundary and represents the end of a drainage basin. All the runoff within a watershed accumulates to, and then exits through, the pour point outlet. As one can specify lake outlets as pour points, this method is suitable for lake catchment delineation.

Watershed delineation using the second method described above is performed through an extra ArcView tool identified as 'W'. This tool allows the user to specify a point as pour point on a flow-accumulation grid using the cursor in the GIS 'View'. The default 'Avenue' code behind this tool generates a watershed by snapping the pour point to a new location having maximum accumulated flow within a default snap distance of 240 map units. This effectively moves the outlet downstream from the specified outlet point. The net effect is that the delineated watershed will be larger than expected. Such a catchment will be useless for relating lake water chemistry to runoff water chemistry or to other catchment characteristics. To delineate a lake watershed using a pour point which exactly coincides with the lake outlet, the code behind this tool was modified by setting the snap pour point distance to 0 or 1 map units (in our case, 0 or 1 metre).

Automated Lake Catchment Delineation Script/Program

Lake catchment delineation for a large number of lakes becomes a tedious task using the Hydrologic Modelling extension as each lake outlet has to be identified in turn using the cursor. Later each generated catchment grid theme has to be saved and/or converted to a shapefile for further analysis. A program was written specifically to automate lake watershed boundary delineation. Using ArcView's Spatial Analyst and Hydrologic Modelling extensions, this program allows delineation of any number of watersheds using a lake location database (in csv, txt or dbf format) detailing the 'Easting'(E) and 'Northing'(N) co-ordinates values of the lake outlets. The program automatically loads the Hydrologic Modelling extension and, using the E and N co-ordinates values of the lake outlets in the input table, automatically creates an event theme showing the locations of the lake outlets. Lake watersheds (grids) are then generated using the E and N co-ordinates values of the lake outlets and a user-specified snap distance for moving pour point or lake outlet to the cell of highest accumulated flow. Each generated watershed and shapefile is named using the lake name in the database and added into a View. In addition, the program calculates the catchment perimeter (in meters) and the catchment areas (in m^2, hectare and acres). Due to limitations in ArcView's merge command, a merged grid file of all the lake watersheds is generated and added into the View provided the number of records in the database is less than or equal to 20.

Extraction of Pour Points / Lake Outlets from OSNI Data

As explained previously, the first step in lake catchment delineation work is to obtain accurate Irish Grid co-ordinates (E and N) for the lake outlets in six-digit format. These were read from OSNI raster maps at 1:50,000 and 1:10,000 scales within the GIS. In a few cases, the lake outlets were simply estimated from the OSNI 50m DEM and contours generated from the DEM, by clicking along the periphery of the lake and identifying points of low or minimum elevation. A database of lake outlet points was created. This database of 112 lake outlet locations were first split into records of 20 lakes per work sheet and the new worksheets exported as comma delimited text format files. These files were used in turn as the input data table for the automated watershed delineation program. Each run of the program selected a database table of 20 records at a time so that, in each run, 20 watersheds were delineated. The final run was with records of 12 lakes only. A snap distance of zero was chosen during these runs. Using the ArcView Geo-Processing extension all the catchment shapefiles were merged into a single shapefile and saved.

RESULTS AND DISCUSSION

Lake Sampling Survey

The lake sampling survey began on 4 March 2002. Weather that week was stormy, and flying was impossible on Wednesday 6 March 2002. There was approximately 40 minutes travel time to the furthest lakes. Apart from the weather and problems in finding some lakes, the following schedule was achieved (see also Fig. 1):

Table 1 Lake Sampling programme

Date	Number of lakes samples	County
4 March 2002	30	Fermanagh & Tyrone
5 March 2002	34	Fermanagh
7 March 2002	40	Armagh & Down
12 March 2002	8	Antrim Plateau

Chemical Analysis of Lake Samples

Lake water samples were returned to the laboratory at the end of each sampling day and stored in the dark at 4°C. Analyses were carried out the following day for electrical conductivity, pH, nitrate-nitrogen, soluble phosphorus, total phosphorus and colour. Electrical conductivity was determined by a Phillips PW5909 digital conductivity meter calibrated by reference to a certified reference standard of 100 $\mu S\ cm^{-1}$ and results were corrected to 25°C using the in-built temperature coefficient for the meter. pH was determined on an Orion EA90 ion-meter, using separate glass and KCl reference electrode calibrated by two certified buffer solutions. Nitrate-nitrogen was determined after reduction to nitrite by copper sulphate and hydrazine (Chapman *et al.* 1967). Soluble phosphorus fractions were determined after filtration through a pre-washed 0.45 µm pore-size membrane filter by the ascorbic acid-molybdate method of Murphy & Riley (1962) on a filtered undigested sample (soluble reactive phosphorus, SRP) and a digested sample (total soluble phosphorus, TSP). Total phosphorus (TP) was determined after digestion of an unfiltered sample. Digestion was by the persulphate digestion method of Eisenreich *et al.* (1975). Colour was determined by measuring the optical density of an unfiltered sample at 340 nm and a turbidity reading at 700 nm was subtracted to give a corrected value. Summary results are given in Table 2.

Table 2. Summary statistics of all lakes sampled in March 2002.

	pH	Conduct. $\mu S\ cm^{-1}$	SRP $\mu g\ l^{-1}$	TSP $\mu g\ l^{-1}$	TP $\mu g\ l^{-1}$	NO_3-N $mg\ l^{-1}$	OD_{340}
Maximum	8.4	543	222	223	264	4.5	0.80
Minimum	4.0	46	1	1	5	0.0	0.01
Average	7.5 (median)	200	13	21	41	0.6	0.14

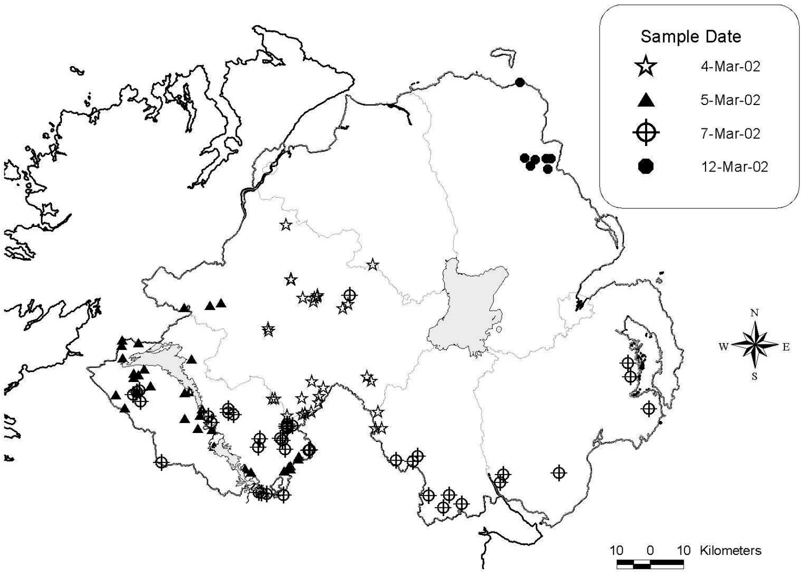

Fig. 1. Locations of small lakes in Northern Ireland sampled by helicopter.

Phosphorus

Phosphorus results are shown in Fig. 2. It was surprising that there were so many low SRP values, suggesting perhaps the spring bloom had already started but the TP data are more as expected with many values over 50 µg l^{-1}.

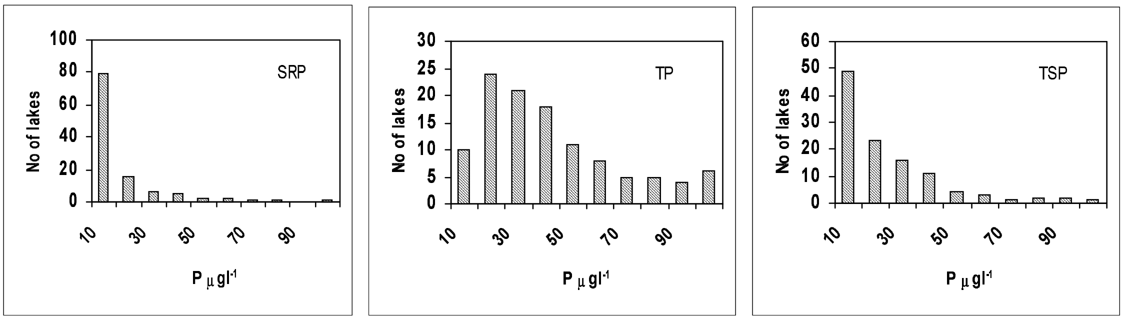

Fig. 2. Distribution of concentrations for phosphorus fractions in all the lakes sampled.

Nitrate-Nitrogen

Fig. 3 shows the nitrate-N values, which resemble the SRP results in that many values were in the lowest category. Approximately half the lakes had concentrations below 0.25 mg N l^{-1} while others had over 4 mg N l^{-1}.

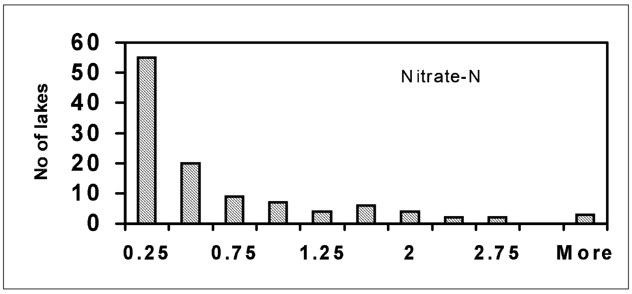

Fig. 3. Nitrate-nitrogen concentrations (mg N l^{-1}).

pH & conductivity

The pH of the majority of lakes was in the range 6.5 to 7.0, but there were some strikingly acid lakes which had a pH less than 4.5. The acid lakes were also dilute, with low conductivities but not all dilute lakes were the most acid. By contrast, the hardest water lakes were those on the Lower Calp limestones (South Fermanagh) with conductivities > 500 µS cm^{-1}.

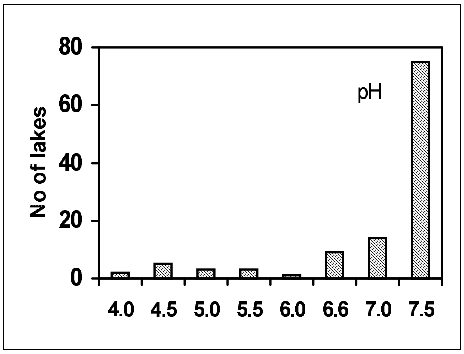

Fig.4. pH values obtained.

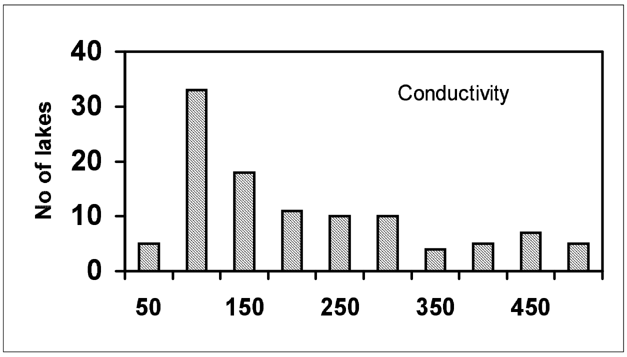

Fig. 5. Electrical conductivity ($\mu S\ cm^{-1}$).

Colour

Colour is caused by dissolved humic substances from the catchment soils. Rainfall, spring-fed or carbonate lakes typically have low colour whereas upland lakes with peaty catchments can be highly coloured. The extreme example in this survey was Lough Shannagh in the Mournes with OD_{340} of 0.74. The clearest lakes were lakes Tullybrick, Atona and Fardrum, which had colour values of less than 0.04.

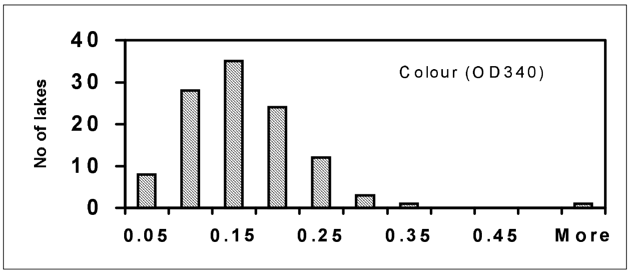

Fig. 6. Colour (OD_{340})

Resampling of a subset of the lakes exactly one year later (February 2003), showed that the one-off samples were truly representative of the lake in that, for most variables, there was a 1:1 relationship between chemical concentrations between years. The exception was nitrate-nitrogen where, although the two data sets were closely correlated, the 2002 values were on average twice those found in 2003.

Lake Catchment Delineation using GIS

The watersheds delineated in each run of the program were closely examined. Some of the delineated watersheds appeared too small, comprising of only a single grid cell. Examination of the flow-accumulation values associated with these lake outlet locations showed that the chosen lake outlet locations did not fall on a grid cell of high accumulated flow or on a cell which formed part of a stream network ('stream segment'). For those problem-lakes having very small catchments, new lake outlet points falling on nearby 'stream segments' of the flow-accumulation grid were identified and fed into the database table. For the few lakes situated on hilltops (e.g., Lake Craigfad A), the previously selected lake outlet points were seen to be very distant from a 'stream segment'. In such situations, a distant lake outlet point falling on a nearby stream segment of the flow-accumulation grid cannot be chosen as the lake outlet. The catchments of such lakes were manually delineated using the contour lines.

Some watershed boundaries appeared to be correct, but, on examining them superimposed on the OSNI raster maps, it was found that their catchment boundaries did not completely enclose the lake. In such cases, another lake outlet point that fell on a different flow-accumulation point was identified on a 'stream segment' of the flow-accumulation grid. The 'Avenue' script for automated watershed delineation was rerun for each set of modified lake outlet data and the final sets of watersheds re-examined. From these runs, it was observed that 12 lakes were still found to be problematic due to flaws in the flow-direction and flow-accumulation grids and hence the DEM.

Catchment Delineation of the 12 Problematic Lakes

Instead of using the flow-accumulation and flow-direction grids with sinks filled, new flow-direction and flow-accumulation grids created from the OSNI 50m DEM *without* filling the sinks were used. This reduced the number of problem lakes from 12 to only 3; the latter were delineated manually. Further details on the catchment delineation of the problematic lakes are documented in Jordan et al. (2003).

Examination of Delineated Lake Catchment Boundaries and their Areas

The final set of shapefiles of delineated lake catchments were merged into a single shapefile containing all 112 lake catchments. For a few lakes, the catchment of one lake enclosed the catchments of one or more other lakes. Of the lakes sampled, Carrick Lough had the maximum catchment area (3145.41 ha) while Doo Lough had the minimum catchment area (2.7 ha). Thirty-eight lakes had catchment areas greater than 100 ha. The catchments of 16 lakes extended into the Republic of Ireland.

CONCLUSIONS

Aerial sampling by helicopter is suited to the quasi-synoptic sampling of lakes. The lakes provided a wide range of values for all the variables measured, was repeatable from year to year and could be safely used to classify lake trophic status. Aside from the scientific advantage of sampling lakes at the same stage of the annual cycle, it is very efficient. Samples were analysed very close to the time of sampling, which helped in reducing the problems of handling, and storage that would arise if the lakes were sampled over several weeks by traditional methods. In addition, the economics of helicopter sampling are favourable. One hundred and twelve lakes sampled in this way over four days with two scientific staff costing less than £100 per lake. Under conditions that are more favourable and with less travel time, considerable savings could have been made in helicopter usage time thereby reducing the price per lake sampled still further. On the other hand, sampling the lakes by boat would take approximately 110 man-days plus subsistence, which equates to £250 per lake. Sampling from the lake margin without a boat would allow more lakes to be sampled in a day, but even so, the cost of helicopter sampling still compares favourably. This is especially true for remote, inaccessible lakes and if we include the substantial extra effort required in a land-based survey to collect samples, transport them back to the laboratory and include the added analytical costs of storage for later analysis.

Using ArcView GIS software and existing flow grids generated from OSNI's DEM with and without filling sinks, the automated delineation procedure successfully delineated 109 of the 112 small lakes sampled in this study. The accuracy of the lake catchment delineated depends primarily on the accuracy and resolution of the DEM and the locations of pour points selected. For lakes situated on hill tops and hill sides, manual delineation of the catchment boundaries using elevation data and topographic contours was found to be more appropriate. The lake catchment boundaries delineated by this project will be used by DARD, EHS, watershed managers, consultants etc., in the future management of these lakes. By overlaying these boundaries on a range of spatial data sets, it will be possible to identify catchment characteristics which, together with lake water chemistry, will help create a classification of the lakes sampled.

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