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Morphometric analysis of UK lake systems as a compliance tool for the European Water Framework Directive

JOHN S. ROWAN[1], IAIN SOUTAR[1] & GEOFF E. PHILLIPS[2]

1 *Environmental Systems Research Group, Department of Geography, University of Dundee, Dundee DD1 4HN, UK*
j.s.rowan@dundee.ac.uk

2 *Environment Agency, National Ecology Technical Team, Reading, Berkshire RG1 8DQ, UK*

Abstract The European Water Framework Directive 2000 (WFD) stipulates that surface water bodies, such as lakes, should achieve good ecological and chemical status (pollutant levels) by 2015. However, the extant environmental monitoring programmes of most member states have major deficiencies in terms of the baseline data required, thus potentially jeopardising the compliance schedules of the WFD. Great Britain has over 40 000 lakes >1 ha, but bathymetric data are available for less than 2%. This paper presents a collation of available bathymetric data (622 sites) and demonstrates the utility of morphometric analysis to bridge the gap between surveyed and un-surveyed systems. Type-specific relations between mean (D_{mv}) and maximum (D_{max}) water depths were developed for natural lakes (r^2 values ranging from 0.87 to 0.99), as well as modified systems and impoundments (r^2 values ranging from 0.74 to 0.99). Stepwise regression was also undertaken to predict D_{mv} and D_{max} using only map-derived information (such as lake area, catchment area and shoreline length). The results varied markedly between "geological types", with "medium alkalinity" (MA) lakes giving the highest coefficients of determination (R^2 of 0.79 and 0.82, respectively). Predicting D_{mv} is important because it permits calculation of parameters such as the volume (V) (and hence residence time) and dynamic ratio (D_R) which provides a measure of the likely extent of sediment re-suspension. This preliminary analysis has demonstrated the potential of the morphometric approach to generate valuable parameters from limited field investment and will provide a valuable stop-gap until the results of the WFD's comprehensive monitoring programmes are realized.

Key words hydromorphology; lake(s); morphometric analysis; Water Framework Directive

INTRODUCTION

The EU Water Framework Directive (WFD) was introduced in 2000 to establish a new legal framework for the protection, improvement and sustainable use of all water bodies across the European Union. Broader in scope than previous European water legislation, the WFD introduces more comprehensive environmental objectives, designed to protect and improve the water environment, halting any further deterioration of aquatic ecosystems and, where possible, restoring surface waters and groundwater damaged by pollution, water transfers or engineering activities to "good status" by 2015. As with all EC Directives, the WFD is a binding framework agreement which requires member states to have in place existing, or create new "enabling" domestic legislation in line with the principle of "subsidiarity", to implement its objectives.

With lakes, as with all other surface water bodies, the WFD requires member states to monitor their status and to assess any long-term changes brought about by natural or anthropogenic activities, as well as setting quality objectives for both natural lakes and reservoirs (Premazzi *et al.*, 2003). Future success in managing Europe's water environment will be judged principally by the achievement of these ecological goals. However, it is widely recognized that the political ambition of the WFD, and its strict timetable for implementation, has exposed numerous deficiencies in the scientific knowledge-base, e.g. the paucity of available base-line monitoring data (biological, physico-chemical and hydromorphological); the non-standard sampling protocols extant across Europe (Rowan *et al.*, 2006); and the need to classify status with respect to type-specific reference conditions. The fact that no member state has in place all the necessary systems to enable compliance with the WFD (cf. Søndergaard e*t al.*, 2005) has stimulated concerted research efforts across the European community to develop new tools for classification and intercalibration purposes (Moss *et al.*, 2003).

A key early requirement of the Directive was that each member state should establish a reporting typology—describing a limited number of physical lake types, such that the "ecological status" of any given lake can be determined against "type-specific" reference conditions. In reference condition, water quality, biology and hydromorphology should be "totally, or near totally pristine", such that the chemical, biological and hydromorphological "quality elements" of any particular lake can be assessed against this benchmark. Obvious objections exist in relation to any scheme classifying lakes into "types", when the variability of natural systems occurs over a continuum. Nevertheless, establishment of a "Reporting Typology" is a compliance requirement, and in the case of the UK, where Great Britain represents Ecoregion 19, a tiered System B typology was reported based around a core of six "geologically-defined" types, expressed through alkalinity, conductivity and colour, viz. Peat (P), Low Alkalinity (LA), Medium Alkalinity (MA), High Alkalinity (HA), Marl (Marl) and Brackish (B), and two (later revised to three) mean depth (D_{mv}) classes: very shallow, shallow and deep. Further divisions, taking into account basin altitude and surface area, generate a maximum of 162 lake types.

Directly physical attributes (area, altitude, depth, location characteristics) are essential for typology purposes, but morphometric data such as volume (V) and basin form are also key to calculate parameters such as residence time (T) and the sensitivity of particular basins to pressures such as nutrient loading or abstraction (e.g. water level variability). Implementing the WFD thus presents a range of challenges to individual member states depending on the number and diversity of the standing water resource base, inclusive of fully natural, modified and completely artificial systems, and the extent and quality of existing data on lake bathymetry and hydrology.

This paper provides an insight into the challenges of implementing the WFD by reviewing a lake bathymetry database assembled for Great Britain and exploring the utility of morphometric analysis to produce generalized relations between mean (D_{mv}) and maximum (D_{max}) depths for different lake types. These data provide the basis to calibrate models of D_{mv} and V using observations of D_{max} collected using hydromorphological assessment tools such as the Lake Habitat Survey (LHS) (Rowan *et al.*, 2006). A further aim was to evaluate the performance of models of D_{max} and D_{mv} using only map-derived parameters, i.e. to bridge the gap between surveyed and un-surveyed systems, and, in so doing, provide data essential to the development of decision-making tools suitable for managing lake systems.

Distribution of UK standing waters and available bathymetric data

Despite the obvious resource and conservation value of UK lakes, knowledge of the distribution and physical characteristics of natural lakes and reservoirs remains incomplete. Of the four countries of the UK (Scotland, England, Wales and Northern Ireland), Scotland possesses the bulk of the standing waters, with 79% of the total surface area and 91% of the included volume (Smith & Lyle, 1979). Establishing numerical totals has been problematic, because the lower size limit used to define lakes has varied between authors and because some of the smallest systems are ephemeral (Bailey-Watts *et al.*, 2000). Smith & Lyle (1979) counted 5505 lakes ≥4 ha in Great Britain, and by extrapolation estimated there are approx. 81 000 lakes with an area >0.25 ha. For Scotland, analysis of 1:50 000 OS Landform Panorama digital data generates 28 302 "lochs" with the following breakdown: 547 lakes of >50 ha; 3281 of >4 ha; 5302 of >2 ha and 8233 of >1 ha (R. Gosling, SEPA, personal communication). In Northern Ireland, Smith *et al.* (1991) found a similar bias towards smaller water bodies, with approx. 75% of the 1668 catalogued sites smaller than 2 ha, whilst the largest five lakes (including Lough Neagh at approx. 380 km^2) occupy over 90% of the total lake surface area.

Systematic bathymetric survey campaigns have been carried out for specific regions such as the Lake District of northwest England (Ramsbottom, 1976) and Northern Ireland (Smith *et al.*, 1991), but otherwise bathymetric data are very scarce. For Scotland, the situation is different because of the pioneering surveys of 562 lochs undertaken by Murray & Pullar (1910). Hughes *et al.* (2004) reported the development of the GBLakes database (excluding Northern Ireland), which provides the first comprehensive national archive of lake-related data in the UK. It contains over 40 000 water bodies with areas greater than 1 ha, but bathymetric data (D_{max} and D_{mv}) available for only 622 sites, representing approx. 1.5% of the national inventory. This collation does not fulfil the requirements of a probability-based sample designed to estimate the population characteristics of all UK lakes (cf. Whittier *et al.,* 2002), instead its value lies in the large number of constituent sites. Sub-dividing the 622 sites into two classes: "natural" and "regulated" (including reservoirs), reveals that the distribution of "natural" sites is highly biased to the western uplands of Britain (Fig. 1(a)), whereas "regulated" lakes and reservoirs have a more southern and eastern distribution, reflecting their connection to major centres of population (Fig. 1(b)).

"Natural" lakes are those which appear from map and air photo analysis to be free from observable hydromorphological alteration, in the form of impoundments or other significant hydraulic structures, and whose bathymetry and basin form is therefore likely to conform a natural condition. Conversely, "regulated" lakes span a spectrum of types from completely artificial systems, e.g. flooded gravel pits, natural lakes which have been raised or lowered for a variety of water resource management reasons, and reservoirs formed by damming pre-existing river valleys.

Fig. 1 The distribution of (a) natural and (b) regulated lakes in Great Britain for which bathymetric data are available.

Application of lake morphometric analysis to the WFD

Three groups of morphometric parameters (size, form and special) can be recognized in lake morphometry studies (Håkanson, 2005). Size factors equate to the basic dimensions of a lake and include: maximum length, width, water depth, shoreline length, area and volume. Form factors are second-order metrics derived from size factors, key examples being mean water depth and shoreline development—relating shoreline length against the circumference length of a circle with area the same size as the lake. Finally, special factors are those from which behavioural characteristics of the system can be inferred—examples include volume development (V_d) expressing the relationship between mean and maximum water depth and thus whether the basin is convex or concave in form (Hutchinson, 1957), and the dynamic ratio (D_r), which is derived from surface area and mean depth and provides an index of fine sediment re-suspension potential (Bachmann *et al.*, 2000). Morphometric analysis can also provide the basis to modelling key aspects of lake ecosystem functions and predicting whole-system response, e.g. by developing load models and modelling the behaviour of key functional groups (Håkanson & Peters, 1995). A selected range of the most important morphological parameters is provided in Table 1.

The basic building block of lake morphological analysis is the bathymetric survey. Lake basin bathymetry can be represented graphically in the form of hypsographic curves, constructed by plotting water depth against cumulative area, which can be expressed in either absolute, or percentage (relative) terms (Håkanson, 1981). Another way to capture the form characteristics of a lake, where summary metrics such as mean

Table 1 Definitions and formulae for lake morphometric parameters.

Parameter (units)	Symbol	Derivation
Maximum length	l	From topographic map
Maximum width	w	From topographic map
Lake area (km^2)	A	From topographic map
Altitudinal range of drainage area (m)	dh	From topographic map
Drainage area (km^2)	ADA	From topographic map
Relief of drainage area (-)	RDA	$RDA = dh/(\sqrt{ADA})$
Lake volume (km^3)	V	$\log(1000V) = 0.134 + 1.224\log A + 0.332\log RDA$
Mean depth (m)	D_{mv}	$D_{mv} = 1000 \times V/A$
Maximum depth (m)	D_{max}	$\log D_{max} = -4.202 + 4.558 \times (1000V)^{0.1} - 1.008\log A$
Relative depth (-)	D_{rel}	$D_{rel} = (D_{max} \times \sqrt{\pi})/(20 \times \sqrt{A})$
Depth of wave base (m)	D_{wb}	$D_{wb} = (45.7 \times \sqrt{A})/(21.4 + \sqrt{A})$
Dynamic ratio (-)	D_R	$D_R = (\sqrt{A})/D_{mv}$
Volume development (-)	V_d	$V_d = 3 \times D_{mv}/D_{max}$
Shoreline length (km)	L_o	From topographic map
Shore development (-)	L_d	$L_d = L_o/(2\sqrt{(\pi A)})$
Specific runoff (m^3 m^{-2} year^{-1})	SR	From hydrological measurements/topographic maps
Theoretical water discharge (m^3 year^{-1})	Q	$Q = ADA \times SR$
Theoretical retention time (year)	T	$T = V/Q$
Areas of erosion and transportation (fraction %)	ET	$ET = 0.25 \times D_R \times 41^{0.061/DR}$ (if $A > 1$ km^2)
Areas of accumulation (fraction %)	BA	$BA = 100 - \mathrm{ET}$

If $A < 1$ km^2, then $ET = 1 - [A\{(D_{max} - D_{wb})/(D_{max} + D_{wb} \times \exp(3 - V_d^{1.5}))\}^{0.5/Vd}]/A$

The bottom dynamic parameters are: *ET* (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) (after Håkanson, 2005).

and maximum depths are available, is with the dimensionless volume development ratio ($V_d = 3 \times D_{mv}/D_{max}$), which relates lake volume ($V = A \times D_{mv}$) to the volume of a cone whose basal area is equal to lake surface area, and whose height is equal to maximum depth (D_{max}). Thus shallow lakes with low V_d values have large bottom areas subject to wind and wave induced sedimentation, because extensive areas are within the depth of the wave base. Such lakes have a high likelihood of frequent re-suspension events, with consequences for water clarity. Conversely, lakes with a high V_d value have relatively limited shallow zones, generally greater volumes, and steeper bed slopes where slope-induced sedimentation is likely to occur (Håkanson & Peters, 1995).

MORPHOMETRIC ANALYSIS OF BATHYMETRIC DATA IN THE GBLAKES DATABASE

Data transformations (principally logarithmic) were undertaken to ensure normality in the data sets before undertaking a range of statistical tests including bi-variate and multiple regression analysis. D_{mv} was regressed against D_{max} for each of the six geologically-defined lake types (P, LA, MA, HA, Marl and B) to ascertain the degree by which mean depth can be predicted from a single point measurement of maximum depth. These regressions were repeated for both “natural” and “regulated” lake sub-sets. Stepwise multiple regressions were also performed to predict the extent to which D_{mv} and D_{max} could be predicted from independent map-derived parameters, such as surface area (A), catchment area (ADA) and catchment relief (dh). The stepwise regression procedure was carried out in the statistical package SPSS® to determine the highest coefficient of determination (R^2). Models were not computed for those data sub-sets with inadequate numbers of observations.

Correlation between D_{mv} and D_{max} on a type-specific basis

The relationships between D_{mv} and D_{max} for the entire data set, as well as separately for natural and regulated lake systems, are illustrated in Fig. 2. The relationship between log-transformed D_{mv} and D_{max} is extremely good for the entire data set (n = 622), with $r^2 = 0.92$ ($p < 0.001$), and improves when natural and regulated lakes are considered separately, with coefficients of determination reaching 0.94 and 0.96, respectively

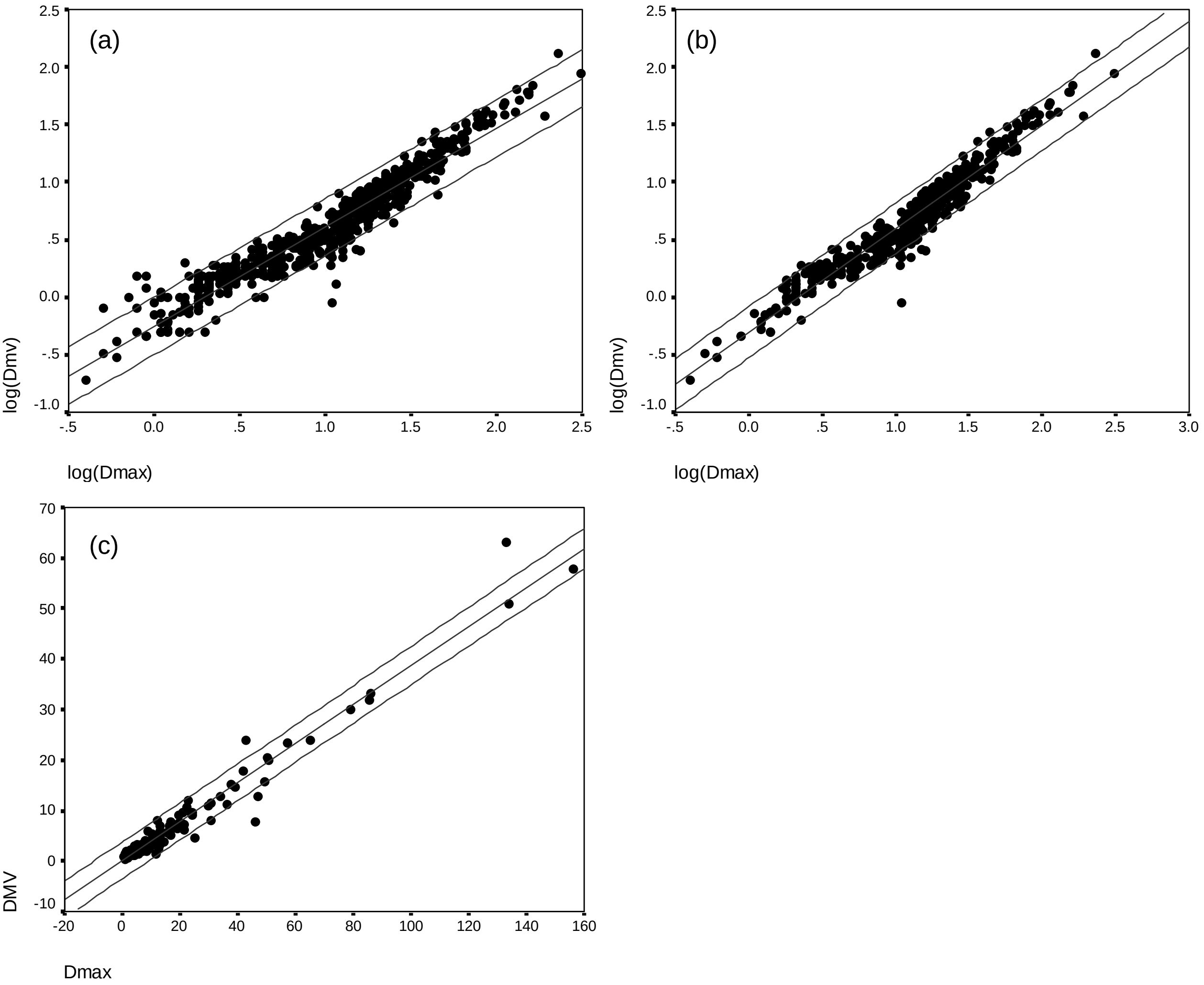

Fig. 2 Scatter plots between D_{max} and D_{mv} for transformed data for: (a) all lakes; and (b) natural lakes; (c) untransformed data for regulated lakes D_{max} and D_{mv}. 95% error bars are indicated (all units in metres).

Table 2 Regression summary data for transformed and untransformed mean (D_{mv}) and maximum (D_{max}) lake depths for six geological lake types, UK.

	Geological type	r^2	n	Equation	F	p
All lakes	All	0.92	622	$\log D_{mv} = 0.9\log D_{max} – 0.3$	7565.4	<0.001
	P	0.87	44	$\log D_{mv} = 0.7\log D_{max} – 0.2$	261.2	<0.001
	LA	0.92	262	$\log D_{mv} = 0.9\log D_{max} – 0.4$	3191.7	<0.001
	MA	0.94	171	$\log D_{mv} = 0.9\log D_{max} – 0.3$	2839.9	<0.001
	HA	0.92	131	$D_{mv} = 0.3D_{max} + 0.4$	1434.0	<0.001
	Marl	0.97	6	$D_{mv} = 0.4D_{max} + 0.3$	117.0	<0.001
	B	0.94	8	$D_{mv} = 0.1D_{max} + 0.8$	95.5	<0.001
Natural lakes only	All	0.94	464	$\log D_{mv} = 0.9\log D_{max} – 0.3$	6984.8	<0.001
	P	0.87	37	$\log D_{mv} = 0.8\log D_{max} – 0.2$	2321.9	<0.001
	LA	0.92	209	$\log D_{mv} = 0.9\log D_{max} – 0.3$	2493.5	<0.001
	MA	0.95	147	$\log D_{mv} = 0.9\log D_{max} – 0.3$	912.1	<0.001
	HA	0.98	63	$D_{mv} = 0.4D_{max} + 0.2$	68.5	<0.001
	Marl	0.96	5	$D_{mv} = 0.4D_{max} + 0.2$	171.2	<0.01
	B	0.99	3	$D_{mv} = 0.8D_{max} – 0.4$	37.5	n/s
Regulated (modified natural and artificial lakes only)	All	0.96	158	$D_{mv} = 0.4D_{max} + 0.1$	3822.1	<0.001
	P	0.94	7	$\log D_{mv} = 0.7\log D_{max} – 0.1$	69.4	<0.001
	LA	0.97	49	$D_{mv} = 0.4D_{max} – 0.7$	1340.9	<0.001
	MA	0.99	23	$D_{mv} = 0.4D_{max} + 0.4$	1997.3	<0.001
	HA	0.74	68	$\log D_{mv} = 0.7\log D_{max} – 0.1$	191.9	<0.001
	Marl	–	1	–	–	
	B	0.94	5	$D_{mv} = 0.1D_{max} + 0.9$	43.1	<0.01

($p < 0.001$). Previous analysis by Gorham (1958) of 399 lochs from the Murray & Pullar (1910) archive found correlation coefficients (r) of 0.95 and 0.92 (r^2 of 0.9 and 0.85) for rock and drift basins, respectively. George & Maitland (1984) obtained an r^2 of 0.98 for a representative sample 65 lakes sampled in the Shetland Isles.

The relationships between D_{mv} and D_{max} for each of the core lake types are presented in Table 2. It is noticeable that the relationship for P lakes is weaker ($r^2 = 0.87$), probably due to the variable morphologies of blanket peat depressions and multiple mechanisms for peat lake emplacement. Better relationships are obtained for other lake types because of a greater commonality in mode of formation and consequently form, e.g. LA lakes are predominately located in the upland western and northern provinces of Great Britain where glacial scour into bedrock was most pronounced.

When only natural lakes are considered, the overall r^2 between D_{mv} and D_{max} rose to 0.94. With the exception of P lakes, r^2 either increases slightly, or remains constant when data are divided according to the typology. For regulated (and artificial) lakes r^2 values typically increased, particularly in the case of P lakes ($r^2 = 0.94$), but with such a reduced data set, this increase should be treated with caution. The relatively low r^2 value for regulated HA lakes ($r^2 = 0.74$) can (at least partly) be attributed to the relatively high proportion of artificially excavated pit lakes, particularly within the Broads of south-eastern England (Fig. 1(b)). Removal of Broads lakes from the regulated HA subset increased the r^2 value to 0.9, whilst the equivalent D_{max}:D_{mv} relationship for "Broads-lakes only" was extremely low ($r^2 = 0.26$), confirming their morphology is erratic depending on the excavation histories of individual sites.

Table 3 Results of stepwise regression analysis, determining D_{max} for natural lakes based on catchment variables using A (lake surface area), dh (altitudinal range of drainage area), L_o (shoreline length), and ADA (drainage area).

Geological type	R^2	n	Equation	F	p
All	0.67	464	$D_{max} = 3A + 0.3dh + 18.2\log L_o - 8\log ADA - 0.6$	237.1	<0.001
P	0.50	37	$D_{max} = 8.2\log A - 0.2ADA - 0.01dh + 14.8$	14.9	<0.001
LA	0.71	209	$D_{max} = 2.5A + 22.8\log L_o + 0.2dh - 7\log ADA + 1.4$	127.5	<0.001
MA	0.82	147	$D_{max} = 12.6A - 0.3ADA + 0.04dh - 1.2L_o + 8$	166.4	<0.001
HA	0.50	63	$D_{max} = 0.04dh + 1.9L_o - 7.4\log ADA - 1$	15.1	<0.001
Marl	0.93	5	$D_{max} = -26.2\log dh + 68.4$	39.5	<0.1

Table 4 Results of stepwise regression analysis, determining D_{max} for regulated lakes based on catchment variables.

Geological type	R^2	n	Equation	F	p
All	0.62	153	$D_{max}=0.6L_0 + 0.04dh + 1.6A - 4.2\log ADA + 1.4$	61.1	<0.001
LA	0.49	49	$D_{max} = 28.4\log L_o - 10.2\log ADA + 1.5A + 0.03dh - 0.05$	35.4	<0.001
MA	0.96	23	$D_{max} = 6.4A + 7.2\log dh - 7.9$	254.0	<0.001
HA	0.46	68	$D_{max} = 0.3dh = 2.8\log L_o + 1.8$	28.1	<0.001
B	0.99	5	$D_{max} = 18.5A - 0.9ADA = 0.9$	959.0	<0.01

Note: P and Marl lakes excluded from analysis because of small sample numbers.

Predicting D_{max} from catchment variables

Stepwise multiple regression was undertaken to assess the utility of map-derived parameters to predict form factors such as D_{mv} and D_{max} (Tables 3 and 4). Prediction of D_{max} for LA and MA lake types was exceptionally strong, with R^2 values of 0.71 and 0.82, respectively. For Marl lakes the R^2 was high (0.93), but the relationship was not statistically significant because of the very low sample numbers ($n = 5$). Prediction of D_{max} for P and HA lakes were less strong, with the R^2 falling to 0.5, though both relationships remained highly significant. The most important parameters used to model D_{max} and D_{mv} were A, ADA and dh, which accords with the results of Håkanson & Peters (1995). Within the UK, low and moderate alkalinity lakes are typically glacial in origin (generally rock scoured, basins, knock and lochan, and to a lesser extent kettle-holes). P and HA lakes are typically situated in (or dammed by) drift, and basins are formed either through moraine-damming and blanket-bog depression or solution processes.

Stepwise analysis was also undertaken for the regulated lakes and the predictive power generally dropped, with the exception of MA lakes, where an R^2 of 0.96 was obtained despite a reduced dataset ($n = 23$) and using only two independent predictor parameters.

Morphometric analysis yields insights into hydromorphological sensitivity

An illustration of the potential of morphometric analysis to yield insight into the sensitivities of lakes to respond to different pressures such as nutrient loading or water

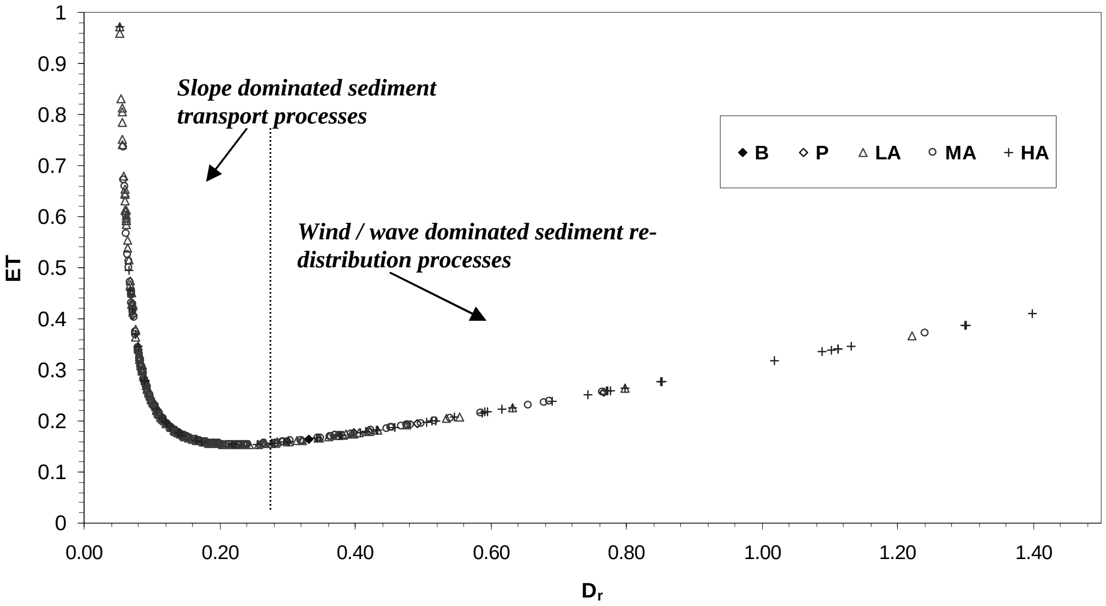

Fig. 3 Relationship between the dynamic ratio (D_R) and the fraction of a lake bed dominated by erosion and transportation processes (ET) for five geologically-defined lake types.

abstraction is shown in Fig. 3. The parameter ET, which is the proportion of the lake bed where fine grained sediments are likely to be eroded and transported (Håkanson, 2005), is plotted against D_R. In this scheme when $D_R = 0.25$, the ET areas will occupy 15% of the lake bed; if D_R is higher than 0.25, then wind generated wave action is likely to dominate, due to a relatively large surface area (and hence effective fetch) combined with relatively shallow water. When D_R is low, particularly below 0.1, then ET increases rapidly because small surface areas relative to high D_{mv} result in steeper bed slopes and an increased role for slope processes such as turbidity currents. The large number of points on Fig. 3 display a high degree of scatter, yet it is clear that a population of LA lakes (typically small, deep, cirque glacial lakes) exhibit very high ET levels equating to pronounced sediment focussing in the deepest sections of the lake. By contrast, HA lakes (characteristically low lying, large, but relatively shallow) dominate the high D_R range resulting in frequent and extensive re-suspension due to wave action (peaking at over 40%), with resultant implications for the release of eutrophication-linked nutrients such as phosphorus.

CONCLUSIONS

The need for reliable lake bathymetric data is widely considered as a prerequisite for practical lake management and is vital to enable effective compliance with the WFD. When such data are lacking it is necessary to make estimates based on empirically derived relationships from map-derived parameters, and models of varying degree of performance were demonstrated. The regression analysis presented in this paper demonstrates that strong statistical relations exist between maximum and mean water depth for most *natural* and *regulated* lake types in Great Britain. The strengths of the relationships are such that considerable insight into the morphometric character of a previously un-surveyed lake can be achieved with only a modest investment to determine D_{max}, and, once derived, D_{mv} can be used estimate key size factors such as V, influencing stratification behaviour and T. Form parameters relevant to the structure and function of lake ecosystems (e.g. D_{mv}, D_{rel}, D_R, etc.) can also be calculated, which in turn can be used to predict limnological state variables directly, e.g. productivity (TP), transparency (Secchi depth) and pH, through "step-by-step prediction" with empirically-derived relationships (Håkanson, 2005).

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