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EPA Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Predicting ecological status in unmonitored lakes using catchment land use and hydromorphological characteristics

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Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The objective of the current study was to develop a method to predict the ecological status of unmonitored lakes to fulfil the requirements of the Water Framework Directive (WFD). Ecological status was assigned to 516 unmonitored lakes in Ireland, and departure from "high" status, or failure to fulfil the requirements of the WFD, was likely for another 43 lakes. Status was assigned using the available WFD chemical and biological assessment data for a large number of lakes (201), which were used to measure lake responses to eutrophication. These included total phosphorus concentration, chlorophyll a concentration and the status indicated by the EPA's macrophyte-based assessment method. Catchments were grouped by their hydrogeomorphological characteristics and land uses, providing a characterisation of Irish lake catchments and a framework within which lakes with similar settings and land use pressures can be assessed. Status was assigned by assuming that it was similar in lakes of equivalent settings and land use pressures. Monitored lakes in the group, therefore, predicted the status outcome for the unmonitored lakes.

Characterisation of lake hydrogeomorphological settings created 16 groups across WFD alkalinity and lake size categories. Wet inorganic subsoil, dry subsoil and peat subsoil characterised the settings across all alkalinity categories. Low alkalinity lakes overlaid poorly productive aquifers, groups of moderate alkalinity lakes were characterised by poorly productive and karst aquifers, while groups of high alkalinity lakes were characterised by productive, poorly productive and karst aquifers. For the low alkalinity lakes, settings characterised by peat and wet inorganic subsoil were identified; this was found for both large and small lakes. For the moderate alkalinity lakes, a setting characterised by wet inorganic subsoil was also found for both large and small lakes. There was also a setting characterised by peat that was identified for the moderate alkalinity small lakes. For the high alkalinity lakes, settings characterised by dry subsoil and wet inorganic subsoil were identified for both large and small lakes. Within the groups characterised by dry subsoil, two further settings were identified, one on dry subsoil overlying karst aquifers and one on dry subsoil overlying poorly productive aquifers.

The types and intensity of land use pressures increased in the moderate and high alkalinity lake groups. In these settings, the lake catchment groups characterised by dry subsoil tended to have higher ecological status classes than those on wet soil or subsoil. The type and intensity of pressure varied across the alkalinity categories, and the intensity of pressure associated with changes in status also varied with setting. These findings highlight how land use pressures can be mediated by the hydrogeomorphology of the catchment and lake, resulting in lakes with similar pressures having different status. Disentangling the effects of multiple stressors to generalise across groups for each individual pressure is not possible here. However, identifying those groups characterised by multiple pressures and their setting-specific response provides the knowledge required to assign likely status within those settings.

The framework was designed for the assessment of similarities between nutrient enrichment pressures on lakes, but the methodology could be employed with different land use pressure data to assess likely responses to, for example, hydromorphological alteration or inputs of artificial acidity. Furthermore, the designation of donor lakes may be updated with expert knowledge of donor suitability or future changes in status within groups. Further investigation of groups with no or few monitored lakes may increase confidence in these assignments, through field investigation, remote sensing, historical data or expert judgement.

1 Introduction

The Water Framework Directive (WFD; Directive 2000/60/EC) requires that all European Union (EU) Member States (MSs) implement monitoring programmes to assess the ecological status of their water bodies. The WFD outlines criteria for the inclusion of water bodies in the monitoring programmes, e.g. size and protection status, and requires that a subset of these water bodies be sampled for assignment of status. In the absence of sampling data, the status of the other water bodies in the monitoring programme must be extrapolated. The current project seeks to fill this knowledge gap and assist in the requirements of the EPA in assigning ecological status to unmonitored lake water bodies.

The goal of the project was to predict the likely biological status of unmonitored lakes based on relationships between the ecological status of monitored lakes and catchment land use, population densities and hydrogeomorphological characteristics. In order to achieve this, the project comprised a number of interlinked objectives:

- a review of important lake and catchment predictors of ecological status;
- a review of current practice in other EU MSs regarding unmonitored water bodies;
- prediction of the typology of unmonitored lakes;
- an assessment of the relationships between hydrogeomorphological and land use attributes and biological status;
- prediction of the status of unmonitored lakes.

All objectives of the project had to be met using map-derived characteristics, as it could not be assumed that in-lake measurements would be available for the unmonitored lakes.

The master lake list was downloaded from the EPA's geographical information system (GIS) portal (http://gis.epa.ie). Lakes were selected for inclusion in the reporting list, based on the size criteria specified by the WFD, to provide representative water bodies under pressure from nutrient enrichment, inputs of artificial acidity and abstraction, and to include lakes in protected areas. Lakes with catchment areas outside the Republic of Ireland were excluded from the analysis, as comparable catchment data for these lakes were not available. This selection process resulted in a list of 769 study lakes. The physical and hydromorphological characteristics of the lakes and the land uses of their catchments were derived from GIS layers (Table 1.1).

A number of methods were assessed for predicting ecological status, based on reviews of the scientific literature and of methods used in other EU MSs. Approaches taken differed depending on data availability and management needs. Not all MSs have developed prediction methods for unmonitored lakes, and few have published their methods. Approaches include prediction of in-lake conditions [e.g. total phosphorus concentrations, the use of regression analysis in Denmark (Nielsen *et al.*, 2012), development of chlorophyll a reflectance relationships using satellite imagery in Finland (O. Malve, Finnish Environment Institute, 24 May 2012, personal communication)], clustering techniques (e.g. GIS-based risk assessment in Scotland (W. Duncan, Scottish Environment Protection Agency, 7 February 2012, personal communication) and Austria (G. Ofenboeck, German Lebensministerium, 15 February 2012, personal communication) and expert judgement or a mixture of some of the above [e.g. England and Wales (Richard Hemsworth, UK Environment Agency, 12 June 2012, personal communication)].

A clustering approach was selected, as this method provides a characterisation of the lake setting that is independent of land use pressures, and allows similar lakes to be managed and assessed based on their particular features. The first grouping of lakes was carried out to assign lakes to their WFD typology (EPA, 2006) (Table 1.2). However, since the majority of the study lakes were unmonitored, the data necessary to assign typology were lacking, particularly for alkalinity and depth, as these are in-lake measures. To carry out WFD typology assignment, predictive models were created for these parameters.

Table 1.1. Lake and catchment characteristics derived from map-based sources with groupings for analysis, potential importance in describing in-lake conditions and literature source

Characteristic	Importance/description	Reference
Hydrology[a,b]		
Altitude (m)	Higher altitude lakes are likely to have reduced biological diversity	Palmer and White (1994)
SDI	Measures departure of shape from a perfect circle; convoluted lakes will have greater shoreline and littoral area than circular lakes, resulting in increased habitat availability	Håkanson (2005); Shilland *et al.* (2009)
Lake area (km^2)	Lake area and its relationship with lake volume can impact nutrient cycling through increased wind and wave action, varying stratification regimes and dilution	Håkanson (2005)
Catchment area (km^2)	Larger catchments are likely to have more heterogeneous land cover and land uses	Foy *et al.* (2003); Nõges (2009)
Lake:catchment area ratio	Proxy measure for lake retention time; larger, deeper lakes with longer retention times may have a greater potential to store nutrients	Free (2002); Canham *et al.* (2004); Koiv *et al.* (2011)
Mean catchment slope (°)	Catchment slope may help to describe the hydrology within the catchment, suggesting run-off potential and the importance of surface water pathways	Sobek *et al.* (2011); Greene *et al.* (2013)
Range of slope in near-lake buffer (°)	Describes slope of areas within 50 m of lake outline and may indicate steep lake littoral zones	Sobek *et al.* (2011)
Density of upstream lakes (km/km^2)	Upstream lakes can process nutrients as they are transported through a catchment	Kratz *et al.* (1997); Zhang *et al.* 2012)
Stream density/catchment (km/km^2)	Indicative of importance of surface water pathways; proxy measure for potential in-stream processing of nutrients	Venohr *et al.* (2005)
Geology[c,d]		
Igneous acid rock (%)	Potentially strong indicator of water alkalinity	Hem (1985); Meybeck *et al.* (1996)
Limestone (%)	Potentially strong indicator of water alkalinity; strong indicator of groundwater interactions	Hem (1985); Meybeck *et al.* (1996); Tedd *et al.* (2014)
Metamorphic rock (%)	Potential mediator of water alkalinity	Hem (1985); Meybeck *et al.* (1996)
Igneous non-acid rock (%)	Potential mediator of water alkalinity	Hem (1985); Meybeck *et al.* (1996)
Sedimentary rock (%)	Potential mediator of water alkalinity	Hem (1985); Meybeck *et al.* (1996)
Soil (%)	Wet soils are more likely to indicate overland flow; potentially a strong indicator of water alkalinity as peat releases humic acids into water bodies, affecting acidity and colour	Hem (1985); Meybeck *et al.* (1996)
Subsoil (%)	Potentially strong indicator of surface water alkalinity (wet peat, wet inorganic, dry/acid, basic)	Hem (1985); Meybeck *et al.* (1996)
Likelihood of inadequate percolation (%)	Determined by soil, subsoil and bedrock permeability; describes the likely subsurface conditions for pollutant transfer (low to very high, made)	Daly *et al.* (2013)
Aquifer category (%)	Strong indicator of groundwater interactions (poorly productive, productive, karst)	Hem (1985); Meybeck *et al.* (1996)
Agriculture[b,e,f]		
Livestock units/ha (cattle)	Proxy measure for nutrient loading from manures	Johnes (1996); Donohue *et al.* (2006)
Livestock units/ha (sheep)	Proxy measure for nutrient loading from manures and overgrazing	Johnes (1996); Allott *et al.* (2005); Donohue *et al.* (2006)
Arable (%)	Proxy measure for nutrient loading from inorganic fertiliser	Tedd *et al.* (2014)
Coniferous forestry (%)	Proxy measure for loading from inorganic fertiliser at planting, from filtering of acidifying anions from the atmosphere and from sedimentation at felling	McElarney *et al.* (2010)
Pasture (%)	Proxy measure for nutrient loading from manures and inorganic fertiliser	Jordan *et al.* (1999)

Table 1.1. Continued

Characteristic	Importance/description	Reference
Human[b,f]		
CSO	Potential point sources of pollutants	Johnes (1996); Matias and Johnes (2012)
Urban (%)	Proxy measure for nutrient loading from human wastes and altered surface drainage	Jordan *et al.* (1999)
Population/km^2	Proxy measure for nutrient loading from human wastes	Irvine *et al.* (2003)
UWWT	Potential point sources of pollutants	Bowman *et al.* (1993)
Septic tanks/km^2	Proxy measure for nutrient loading from human wastes	Arnscheidt *et al.* (2007); Withers *et al.* (2011)

[a]**Source: Ordnance Survey of Ireland.**

[b]**Source: EPA.**

[c]**Source: Teagasc.**

[d]**Source: Geological Survey of Ireland.**

[e]**Source: Department of Agriculture, Food and the Marine.**

[f]**Source: Central Statistics Office.**

CSO, combined sewer outflows; SDI, shoreline development index; UWWT urban waste water treatment discharges.

Table 1.2. The Water Framework Directive typology for Irish lakes

Parameters	Boundaries											
Alkalinity (mg/L $CaCO_3$)	<20				20–100				>100			
Depth (m)	<4		>4		<4		>4		<4		>4	
Area (ha)	<50	>50	<50	>50	<50	>50	<50	>50	<50	>50	<50	>50
Type	1	2	3	4	5	6	7	8	9	10	11	12

Source: EPA (2006).

2 Assignment of WFD Typology

The study lakes were divided into each of the three WFD alkalinity typology categories (Table 1.2) using a simple model that includes percentage catchment cover of limestone and peat soil (Figure 2.1). The model achieved a high percentage of correct classifications for the test and training data sets (80% and 87% respectively). Correct percentage classification was highest for the low alkalinity category (94%) and decreased for moderate (92%) and high (72%) alkalinity lakes. This may be due to issues such as the location of limestone within the catchment, whereby a small amount of limestone near a lake may have a significant effect on lake alkalinity. Assigning lakes to the WFD alkalinity categories using this model created three groups: 430 low alkalinity lakes, 147 moderate alkalinity lakes and 192 high alkalinity lakes.

It was not possible to predict depth to the precision necessary to group lakes by their WFD depth typology category (Table 1.2) using only map-derived data. The maximum depth was weakly correlated with the range in slope within 50 m of the lake shore (near-lake slope) and could be used to predict membership of groups with 12.3 m or 28.7 m depth. The lakes were then grouped according to their WFD size typology categories (Table 1.2). This provided a group of 74 large and 356 small lakes in the low alkalinity category, 44 large and 103 small lakes in the moderate alkalinity category and 76 large and 116 small lakes in the high alkalinity category.

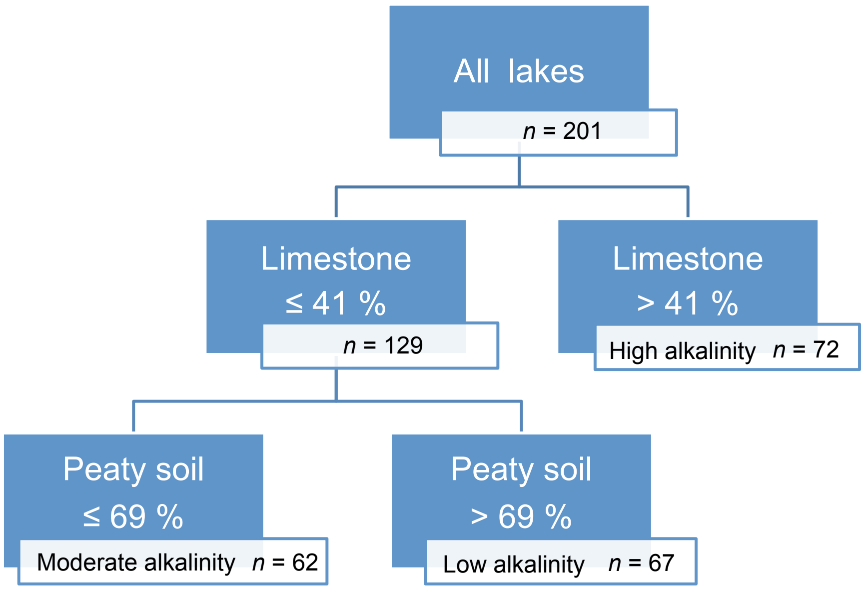

Figure 2.1. Model structure for the prediction of lake alkalinity group.

3 Characterising Irish Lake Catchments across Alkalinity Categories

The low and high alkalinity lakes exhibited extreme values for many of the lake and catchment hydrogeomorphological characteristics described in this study. Lake and catchment size increased with increasing categories of alkalinity, while the near-lake slope, mean catchment slope and altitude all decreased as alkalinity categories increased. This suggests that there is a gradient ranging from smaller lakes (some of which were at higher altitude) with steeply sloping catchments and low alkalinity to larger lowland lakes with gently sloping shores and high alkalinity, with moderate alkalinity lakes falling between the two. Catchment stream density also decreased with increased categories of lake alkalinity. Low stream density can indicate an increased relative importance of sub-surface flow pathways, which is in agreement with the higher percentage cover of karst aquifers in the high alkalinity lake category (GSI, 2005). However, the high stream density observed for the low alkalinity lakes is due, in many cases, to the dominance of one or two small streams with very small catchments, rather than to intricate drainage patterns or long stream length.

The proportions of poorly productive aquifers, peat soil and areas classified as having a high likelihood of inadequate percolation all decreased with a rise from low to high alkalinity. Lakes of moderate and high alkalinity showed an increasing proportion of karst aquifers and dry subsoil. Moderate alkalinity lakes had the highest proportions of areas at a low likelihood of inadequate percolation, while high alkalinity lakes had the highest proportion of areas at very high likelihood of inadequate percolation. These changing settings suggest the greater importance of sub-surface flow pathways from low to high alkalinity lakes. The three alkalinity categories shared a number of similar characteristics: the shoreline development index (SDI) ranged between 1.84 and 7.66, but there was no pattern of increase or decrease across alkalinity categories. Density of upstream lakes also varied little across the alkalinity categories, but it reached its maximum in the catchments of Ireland's largest lakes within the high alkalinity category.

3.1 Hydrogeomorphological Clustering within Alkalinity Categories

The characterisation of lake hydrogeomorphological setting using K-means clustering created 16 groups across the alkalinity categories (Table 3.1). Clustering of the low alkalinity lakes resulted in five groups, two for large lakes and three for small lakes. All five groups were on poorly productive aquifers, with low percentage areas of dry subsoil and low upstream lake density. The catchments of the large lakes were an order of magnitude greater than the catchments of the small lakes. The majority of K-means cluster groups in this alkalinity category were at low altitudes (medians < 70 m), but the lakes of low alkalinity, small, K-means group 2 had a median altitude of 230 m. Clustering of the moderate alkalinity lakes by their hydrogeomorphological characteristics resulted in four groups, two for large lakes and two for small lakes. As with the low alkalinity category, the catchments in all four groups overlaid poorly productive aquifers. These lakes also had low mean catchment slopes and median altitudes below 87 m. Clustering of the high alkalinity lakes resulted in seven groups, four for large lakes and three for small lakes. All seven clusters were at low altitude and had a low near-lake slope and a low mean catchment slope. These characteristics suggest that high alkalinity lakes were, for the most part, lowland lakes. Three of the catchments in the high alkalinity cluster groups overlaid karst aquifers, two overlaid poorly productive aquifers and two overlaid mixed types of aquifer. In the high alkalinity category, the cover of productive aquifers was more common than in the low or moderate categories.

3.2 Patterns in Setting across Alkalinity Categories

Across alkalinity and lake size categories, wet inorganic, dry and peat subsoil characterised the settings. For the low alkalinity lakes, settings characterised by peat and wet inorganic subsoil were identified for both large and small lakes. For the moderate alkalinity lakes, a setting characterised by wet inorganic subsoil was

Table 3.1. Mean values for all K-means groups catchment characteristics

WFD alkalinity category	Low					Moderate				High						
WFD size category	Large		Small			Large		Small		Large				Small		
K-means group	llkm1	llkm2	lskm1	lskm2	lskm3	mlkm1	mlkm2	mskm1	mskm2	hlkm1	hlkm2	hlkm3	hlkm4	hskm1	hskm2	hskm3
K-means setting type	Wet, PP	Peat, PP	Peat, PP	Wet, PP	Peat, PP	Wet, PP/K	Wet, PP	Wet, PP	Peat, PP/P	Wet, K	Dry, PP	Wet, PP	Dry, K	Dry, PP	Wet, P	Dry, K
Range of near-lake slope (°)	**39.44**	*17.90*	**21.35**	**38.18**	*9.99*	*24.08*	*18.51*	**16.34**	*10.53*	*13.81*	*11.90*	**19.35**	*16.33*	*11.11*	**13.00**	*9.23*
Altitude (m)	72.39	51.21	**139.57**	**252.64**	52.48	40.16	**83.38**	99.99	59.57	52.10	54.47	36.40	54.71	45.14	**49.65**	43.66
SDI	2.01	**2.52**	1.56	1.44	**2.01**	2.44	2.87	1.47	1.64	1.86	2.25	**3.28**	2.10	1.49	1.46	1.56
Catchment:lake area ratio	25.35	25.44	24.17	36.89	**55.85**	42.45	83.61	**122.46**	13.69	44.24	25.03	**353.88**	23.94	**822.58**	34.64	268.98
Upstream lakes (m²/km²)	0.02	**0.04**	0.02	0.02	**0.07**	0.02	0.01	0.01	0.02	0.01	**0.17**	0.05	0.01	0.02	0.01	0.02
Catchment area (km²)	43.2	31.8	3.1	5.2	**6.7**	126.7	129.1	**18.1**	1.6	48.1	67.2	**1508.3**	35.8	**130.1**	5.0	27.8
Stream density (m/km²)	2046.5	1786.5	2143.1	2314.9	1983.1	1469.2	1163.9	**1613.8**	1611.4	1130.5	925.6	**1155.9**	511.9	**1457.0**	1159.3	587.8
Mean catchment slope (°)	**14.68**	5.87	**9.31**	**18.35**	3.39	5.65	4.31	**5.22**	2.43	3.17	2.10	**3.16**	2.42	3.09	**3.59**	2.78
Poorly productive aquifer (%)	91.13	88.62	88.06	**90.81**	88.45	81.39	**92.16**	**87.92**	36.25	15.19	**68.29**	**46.45**	11.28	**59.35**	35.43	6.84
Productive aquifer (%)	0.22	0.27	0.80	0.00	0.11	0.91	0.84	1.43	**35.98**	5.60	1.45	3.82	4.00	7.22	**31.46**	1.04
Karst aquifer (%)	0.38	0.09	0.08	0.00	0.00	**6.57**	0.30	0.28	0.08	**67.65**	13.60	42.87	**64.36**	25.11	20.31	**79.34**
Peat subsoil (%)	24.77	**63.94**	39.85	25.25	**78.29**	20.45	13.62	13.47	**31.23**	26.33	23.88	**28.48**	11.14	**28.07**	9.58	11.67
Dry subsoil (%)	**3.56**	1.57	**2.17**	0.49	0.11	27.64	19.04	22.68	26.27	8.92	**43.45**	19.38	**64.16**	**44.43**	2.05	**61.88**
Wet inorganic subsoil (%)	**63.39**	23.45	**46.85**	**65.08**	10.16	41.13	**60.37**	**53.04**	17.32	**52.99**	20.23	**45.65**	10.87	20.54	**75.32**	19.45
Very high inadequate percolation (%)	1.53	**25.89**	4.19	0.02	**33.16**	8.37	**56.38**	**33.11**	17.10	43.76	12.39	50.92	6.05	22.15	**77.28**	8.56
Low inadequate percolation (%)	0.68	0.34	**0.43**	0.00	0.00	**11.41**	0.76	2.26	**21.28**	6.16	**34.06**	13.53	**58.96**	35.58	0.28	**58.05**
High inadequate percolation (%)	52.75	59.65	**81.20**	5.60	55.19	**43.63**	22.92	**33.66**	18.46	1.66	**22.50**	**11.93**	1.49	**17.53**	0.79	0.27
Moderate inadequate percolation (%)	**36.75**	3.09	2.98	**85.18**	0.20	**25.66**	12.94	20.03	17.96	**36.64**	18.60	17.10	19.67	17.75	8.53	**26.09**
No. lakes in setting	28	46	114	68	174	25	19	84	19	21	14	30	11	26	46	44

Catchment characteristics which were significant ($\alpha < 0.05$) in characterising groups are given in bold text. K-means groups are abbreviated using the first letter to indicate alkalinity group, the second to indicate size and the number to indicate the K-means group, e.g. llkm1 is low alkalinity large K-means group 1. Aquifer types are abbreviated as follows: PP, poorly productive; P, productive; K, karst.

Figure 3.1. Lough na Cuige Rua (WE_31_78), Galway, an unmonitored WFD lake (photograph: Sean Hyland).

found for both large and small lakes. There was also a setting characterised by peat that was identified for the moderate alkalinity small lakes. For the high alkalinity lakes, settings characterised by dry subsoil and wet inorganic subsoil were identified for both large and small lakes. Within the groups characterised by dry subsoil, two further settings were identified, one on dry subsoil overlying karst aquifers and one on dry subsoil overlying poorly productive aquifers.

3.2.1 Setting characterisation: wet inorganic subsoil

Catchments on wet inorganic subsoil were the only setting type found across all three alkalinity categories. These catchments were for the most part at moderate risk of inadequate percolation and had a low percentage area at low likelihood of inadequate percolation. The highest median value for dry subsoil area within these groups was 20% and the highest median value for peat soil area was 29%. Wet inorganic subsoil tended to overlie poorly productive aquifers, except in the large high alkalinity lake catchments in which karst aquifer cover was most prevalent. Mean catchment slope followed the pattern described above of decreasing across the low to high alkalinity groups. This pattern of decrease was observed across alkalinity categories, but none was observed within the alkalinity categories, i.e. there was no difference in mean catchment slope whether on peat, wet inorganic or dry subsoil. However, near-lake slope tended to be higher around lakes on wet inorganic subsoil (except the large moderate alkalinity lakes). Where stream densities were lowest (i.e. within the high alkalinity lake category), they were higher in the setting of wet inorganic subsoil than on dry subsoil, reflecting the increased likelihood of surface water pathways dominating where the subsoil is waterlogged. Group mean catchment size, catchment:lake area ratio, density of upstream lakes and SDI all varied between groups and did not follow a pattern that was explained by alkalinity category or setting (except catchment size, which increased across the alkalinity categories).

3.2.2 Setting characterisation: dry subsoil

The setting characterised by dry subsoil was present only within the high alkalinity category. This setting occurred across both large and small size classes and, within each, was represented by one group with dry subsoil on karst aquifers and one group with dry subsoil on poorly productive aquifers. Across both size categories, catchments with dry subsoil tended to be smaller and, consequently, to have smaller catchment:lake area ratios. These catchments may be much larger in reality, due to the increased importance of sub-surface flow pathways in these settings. However, mapping of sub-surface catchments is not currently available. Stream network density was lower for catchments with dry subsoil on karst aquifers, which underlines the importance of sub-surface pathways in these settings. These catchments also had a lower mean catchment slope, but there was a pattern of change in the near-lake slope based on size within the settings on dry subsoil. Catchments on karst aquifers also had a higher median percentage of dry subsoil area than those on poorly productive aquifers. Catchments on poorly productive aquifers had lower median percentages of peat soil and wet inorganic subsoil areas, and, consequently, lower median percentage of cover with low likelihood of inadequate percolation.

3.2.3 Setting characterisation: peat subsoil

The setting characterised by peat was present only within the low and moderate alkalinity categories. This setting occurred across both size classes for the low alkalinity lakes, but only in the small, moderate alkalinity lakes. Peat subsoil was present in the high alkalinity lake groups, but no group had a median higher than 29%. It might be expected that peat subsoil cover would be related to alkalinity, as peat soil cover was used to predict alkalinity, but soil and subsoil types do not always match in the Irish landscape, due to its glacial history. Although peat subsoil cover was found to be correlated with alkalinity, it was not as strong a predictor as either peat soil or limestone cover.

These settings tended to have median cover of < 30% of areas with low and moderate likelihood of inadequate percolation. The median percentage cover of dry subsoil overlying karst aquifers within all peat settings was zero, and the median cover of poorly productive aquifers was lowest in the small, moderate alkalinity lakes on peat. Median mean catchment slope and near-lake slope were low for all groups characterised by peat (< 6° and < 17° respectively) and stream network densities were similar across size and alkalinity categories (range of medians 1325–1856 m/km^2). There was a narrow range of upstream lake density in the study catchments, but the highest median group values were found for low alkalinity lakes in peat settings. As with the higher stream network densities found in the lower alkalinity lakes, this higher density of upstream lakes was often due to the presence of one small lake upstream dominating a small catchment. Across all settings, larger lakes tended to have larger catchments, but the group with the smallest median catchment area was characterised by a peat setting (moderate alkalinity, small, K-means group 2 lakes).

3.3 Land Use Patterns within Alkalinity Categories

The median value for all land use pressures in the low alkalinity category, except sheep and cattle densities, was zero (Table 3.2). Median values for certified sewer outflows (CSO), urban waste water treatment (UWWT) discharges and arable land cover were zero for all alkalinity categories, but their mean increased across the alkalinity categories. Densities of population, septic tanks and cattle had their highest median value in the moderate alkalinity lake category, sheep densities, pasture and forestry cover had their highest median value in the high alkalinity lake category, while the highest median value for coniferous forestry cover was in the high alkalinity category where the maximum value was 28.75%. The highest median value for coniferous forestry cover was greater than 90% in both the moderate and the low alkalinity groups; mean values were highest in the low alkalinity group, decreasing with increasing alkalinity category.

In the low alkalinity category, low-intensity agricultural activities, such as forestry and sheep farming, had their highest mean levels. Cattle densities and pasture cover were lowest in this group and arable cover was absent. Although not common in any of the lake catchments characterised, arable cover increased with increasing alkalinity category, with a maximum of 13.60% in the high alkalinity category. Human and cattle densities

Table 3.2. Summary statistics for land use characteristics of catchments by predicted alkalinity category

Alkalinity category	Low (*n* = 440)			Moderate (*n* = 147)			High (*n* = 197)		
	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
No. sewer outflows	0.00	0.05	0.00	0.22	0.89	0.00	2.49	10.42	0.00
No. UWWT discharges	0.00	0.10	0.00	0.75	2.06	0.00	4.94	22.42	0.00
Population/km^2	3.02	9.97	0.00	23.35	29.62	17.26	27.83	38.64	17.22
Septic tanks/km^2	1.66	5.33	0.00	10.98	12.09	9.64	10.41	8.33	8.52
Forestry (%)	7.40	16.75	0.00	6.46	12.53	1.12	4.24	5.70	1.88
Arable (%)	0.00	0.00	0.00	0.12	0.54	0.00	0.28	1.42	0.00
Pasture (%)	2.81	10.22	0.00	54.28	32.57	58.98	59.70	22.33	61.95
Cattle density (LSU/ha)	0.10	0.12	0.07	0.60	0.41	0.67	0.59	0.25	0.57
Sheep density (LSU/ha)	0.08	0.06	0.06	0.05	0.06	0.03	0.05	0.06	0.04

LSU, livestock unit; SD, standard deviation.

had their maxima in the high alkalinity category, but median values were higher in the moderate alkalinity lakes. Septic tank densities were highest in the moderate alkalinity category, probably reflecting the greater abundance of sewer outflows and UWWT discharges that attended the higher population densities in the high alkalinity category.

3.4 Patterns in Land Use Pressures across Alkalinity Categories

Land use pressures were lowest in the low alkalinity lake group (Table 3.2). There was only one catchment in this category characterised by CSO and UWWT discharge pressures (Table 3.3). Catchments containing arable land were found only within the high alkalinity lake category and this was not common within those catchments. Mean pasture percentage cover within lake catchments increased across the alkalinity categories, although cattle density did not follow the same patterns. Cattle density was highest in lake catchments in the moderate alkalinity category. Within the low alkalinity category, sheep and cattle densities did not follow the same pattern as pasture cover, indicating the grazing of these animals on unproductive land cover types. As large inputs of inorganic fertiliser in these agriculturally “marginal” settings are not likely to be intensive or widespread, pasture percentage cover may not be a good indicator of these nutrient loadings in that setting either, especially if there is a relationship between intensity (livestock density) and likelihood of fertiliser use. In the moderate and high alkalinity categories, it was more common for groups to be characterised by both higher cattle densities and pasture cover.

For land use pressures, such as population and septic tank densities, identification of patterns across settings was more complex. Densities of both population and septic tanks were lowest in the low alkalinity category. Mean and maximum population densities were lower in moderate alkalinity catchments than in high alkalinity catchments. Although population and septic tank densities were linked in the low alkalinity category, the very high population densities in the high alkalinity category were associated with urban areas. These are more likely to have connections to sewered systems, and this is indicated by the lower septic tank densities in this alkalinity category. Population and septic tank densities were usually associated with agricultural pressures. In addition, as indicated, higher population densities were often associated with CSOs and UWWT discharges. There were no catchments dominated by human waste and population pressures in the same way that some catchments were dominated by agricultural pressures.

In the low alkalinity setting, a pattern emerged that was repeated in some of the moderate and high alkalinity land use groups. High ecological status was associated with lower levels of all pressures apart from sheep density. Across settings and alkalinity categories, the percentage cover of coniferous forestry greater than 10% was associated with a departure from high status. For land use groups characterised by arable land cover, there were few monitored representatives to allow status assignment. Across all settings, the addition of human and cattle population pressures (including septic tanks, CSOs and UWWT discharges) to sheep and forestry pressures was associated with failure to meet WFD objectives (i.e. worse than good status). This was potentially mediated in some settings in the

Table 3.3. Land use groups significantly characterised by land uses across alkalinity and size categories and hydrogeomorphological setting

WFD alkalinity category	Low					Moderate				High						
WFD size category	**Large**		**Small**			**Large**		**Small**		**Large**				**Small**		
K-means group	**llkm1**	**llkm2**	**lskm1**	**lskm2**	**lskm3**	**mlkm1**	**mlkm2**	**mskm1**	**mskm2**	**hlkm1**	**hlkm2**	**hlkm3**	**hlkm4**	**hskm1**	**hskm2**	**hskm3**
Broad setting	**Wet, PP**	**Peat, PP**	**Peat, PP**	**Wet, PP**	**Peat, PP**	**Wet, PP/K**	**Wet, PP**	**Wet, PP**	**Peat, PP/P**	**Wet, K**	**Dry, PP**	**Wet, PP**	**Dry, K**	**Dry, PP**	**Wet, P**	**Dry, K**
No. groups in setting	7	10	6	23	40	3	4	9	5	8	4	16	2	7	6	6
No. sewer outflows	a					a		a			b	f		a, b		
No. UWWT discharges	a					a		a, d, e		d, f, g	b	f		a, b		b
Population/km²	a, c, e	b, j	a, d	a, t, v, w	a, b	b, c	b, d	a, c, g	a, e	h		a		a, c, f	b, f	d
Septic tanks/km²	c, e	b, j	a, d	a, t, v, w	a	b, c	b, d	a, c	e	h		a		c, g	b, f	d
Forestry (%)	d	d, f	b	u	d, zh, zl		a, c	b	e	g		o		d	e	c
Arable (%)														a		a
Pasture (%)	a, e	a, d	a	a, w	b, zm	b, c	d	h	e	f, g	d	b, g		g	a, f	f
Cattle density (LSU/ha)	a, c, e, g	c, d	c, d, e	a, b, c, k, s	c, zi–zl	a, c	d	h	e		d	b, c, f		d	a, c	a, f
Sheep density (LSU/ha)	b, e	d, e	f	j, k	zn	a, c	a	f, i	a, b	a		c, p	a, b	e	d	
High status	e, g	h, i, j		t	e–zg				c, d				a, b			
Good status	c, d	a, c, d, f, g	d,f	d–j, u, w		c		b, c, i	b	b–f	c, d			e	e	f
Moderate status			c	a, b	c	a, b		f, g	e	a, g	b	a, e, f, h–n, p		d, f, g	b, c, d	b, e
Poor status	a						a, b, d	h				d, o		c		
Bad status							c			h		g			f	
Unassigned	b, f	b, e	a, b, e	c, k–s, v	a, b, d, zi–zn			a, d, e	a		a	b		a, b	a	a, c, d

Only significant positive relationships are presented. K-means groups are abbreviated using the first letter to indicate alkalinity group, the second to indicate size and the number to indicate the K-means group, e.g. llkm1 is large low alkalinity K-means group 1. Aquifer types are abbreviated as follows: PP, poorly productive; P, productive; K, karst. Letters indicate land use groupings, identified by cluster analysis and described in full in the project final report, available at http://www.epa.ie/pubs/reports/research

LSU, livestock unit.

moderate and high alkalinity categories by groundwater interactions. In lakes with high levels of groundwater inputs, the available data may not reflect the whole picture (surface and groundwater catchments do not overlap perfectly) and/or groundwater inputs may dilute incoming nutrient-rich water or transport it from the lake basin. In these settings lakes tended to be of higher status than their level of land use pressure might have indicated.

The effects of multiple land use pressures and their association with failure to meet the requirements of the WFD were also mediated in some settings in the moderate alkalinity category by co-location of pressures with pathways to surface water (e.g. wet inorganic subsoil). In such settings, it was not possible to discern patterns or thresholds in the cumulative impacts of multiple pressures and groups of moderate, poor and bad status. This may be due not only to the different combinations and levels of pressures present but also to the highly variable hydrogeology of the catchments in these settings. For this reason, a number of groups were identified for further investigation. Increasing the number of monitored lakes in these groups may clarify their appropriate status using the current methodology. If further analysis does not clarify status assignment for this group, it may be appropriate to conclude that this approach is restricted to the prediction of three status end points: high, good and moderate, or worse.

3.4.1 Pressure characterisation: peat subsoil

In settings dominated by peat there were few land use pressures, which is probably a result of challenges posed by the unproductive and waterlogged nature of the subsoil. Coniferous forestry cover was more common on peat than on wet inorganic subsoil. While the age of a plantation is important in understanding the risk of eutrophication, lakes with higher proportions of forestry in the catchment area tended to have lower than high status. In the only peat-dominated group in which population, septic tank and cattle densities were higher (moderate alkalinity small K-means group 3), the combination of these pressures resulted in failure to meet the objectives of the WFD (moderate status or worse).

3.4.2 Pressure characterisation: wet inorganic subsoil

Within the low alkalinity lake category, sheep density was higher in the catchments dominated by wet inorganic subsoil than in those dominated by peat subsoil. This is probably due to the increased productivity of those subsoils. The association between higher sheep densities and high status groups suggests that current sheep densities are not negatively contributing to eutrophication pressures on lakes, but rather that issues of overgrazing are important for rivers and potentially for hydromorphological impacts on lakes (Allott *et al.*, 2005; May *et al.*, 2005). Such habitats may be uniquely susceptible to changes in agricultural policy. Across the moderate and high alkalinity categories, land use pressures on lake groups dominated by catchments with wet inorganic subsoil increased in number and magnitude. In wet inorganic settings overlying poorly productive aquifers in the moderate alkalinity group, increases in population, septic tank and cattle densities were associated with groups of moderate status or worse. In wet inorganic settings in the high alkalinity groups, increases in population and cattle densities, CSO and UWWT discharge numbers were also associated with lakes of moderate status or worse. An exception to this is the case of the group that overlaid karst aquifers in which land use pressures were likely to be mediated by groundwater interactions and the majority of water bodies were assigned good status.

3.4.3 Pressure characterisation: dry subsoil

In settings dominated by dry subsoil, population and cattle densities were higher. This is probably due to the productive nature of these soils and their easier trafficability. These settings were also at lower altitudes, where human settlements are more likely to occur. In these settings, where dry subsoil overlaid karst aquifers, impacts were potentially mediated by groundwater interactions, but settings overlying poorly productive aquifers still had groups of good status. This may be due to the attenuation of nutrients in these settings, rather than the probable direct runoff in more waterlogged settings (Archbold, 2010).

4 Conclusions

The grouping of catchments by their hydrogeomorphological characteristics and land uses provides a broad-scale characterisation of Irish lake catchments and a framework in which lakes of similar setting and pressure can be assessed. The current study provides ecological status assignments for 516 unmonitored lakes and indicates likely departure from high status, or likely failure to meet the requirements of the WFD for another 43 lakes. This study focused on elements of status for which data were available for a large number of lakes, and that encompassed the WFD's inclusion of biological assessment methods. This framework is suitable for the assessment of similarities between nutrient enrichment pressures on lakes, but the methodology could be employed with different pressure data to assess likely responses to, for example, hydromorphological alteration or inputs of artificial acidity. Furthermore, the designation of donor lakes may be updated with expert knowledge of donor suitability or future changes in status within groups.

The types and intensity of land use pressures increased in the moderate and high alkalinity lake groups: the groups with settings characterised by dry subsoil tended to have higher status classes than those with wet soil or subsoil. The types and intensity of pressures varied across the alkalinity categories, and the intensity of pressure associated with changes in status also varied with setting. These findings highlight how pressures can be mediated by the hydrogeomorphology of the catchment and lake, resulting in lakes with similar land use pressures having different status. Disentangling the effects of multiple stressors to generalise across groups for each individual pressure is not possible here. However, identifying those groups characterised by multiple pressures and their setting-specific response provides the knowledge required to assign likely status within those settings.

4.1 Potential Limitations of the Study

There were a number of settings in which the relationship between the land use pressures and the group status was unclear. This was related to the approach taken to grouping the lakes. The analyses formed groups that were statistically significantly different from each other, but not necessarily significantly ecologically different. This arose because the approach was not predictive in a statistical sense, and there was no explanatory variable informing the cluster formation. Groups could be created that were significantly ecologically different, either in their hydrogeomorphology or in their pressures. In groups where there were ecologically significant differences between settings or pressures, resulting in different status assignments within the group, splitting of these groups for status assignment and donor selection, or for further investigation of group status, would be necessary.

The inclusion of data on lake setting and pressures was limited by the need to incorporate only data that were available for all lakes. This necessitated the use of a number of proxy variables. Indeed, all of the pressure data included are used as proxies for their likely contribution to lake nutrient loads, and all lake and catchment data are used as proxies for their likely effects in mediating nutrient transport and processing or biological response to those nutrients. While all data are consistent and comparable across all catchments, there are inherent assumptions associated with the use of such data. For example, the use of agricultural census data makes assumptions about the location of livestock in relation to the farmer's dwelling. Furthermore, the use of data summarised by catchment does not take into account proximity to the lake. This can be important for hydrogeomorphological characteristics, as well as for pressures. The location of small amounts of carbonate-rich rock close to a lake can have a disproportionately large impact on lake alkalinity. Similarly, under the critical source area concept, where high cattle densities are coincident with areas in the catchment with a very high likelihood of inadequate percolation, transport of nutrients to surface waters is more likely (Strauss *et al.*, 2007).

4.2 Recommendations

4.2.1 *Management*

- A number of cluster groups did not have any monitored representatives, while, in some groups, every lake was monitored. Consideration could be given to including some of these water bodies in the national lake monitoring programme in the setting types described in the current study. This approach was taken in Scotland, where the monitoring programme was designed around the WFD lake types as settings and cluster groups based on pressures. While this was not possible in Ireland when the monitoring programme was initially designed (data were not available to type all lakes), inclusion may be possible based on the groups presented here. A risk-based approach might suggest that lower levels of monitoring in groups with lower pressures (e.g. the low alkalinity lakes) and a higher monitoring intensity in groups with higher pressures is appropriate. However, in light of the difficulties in protecting high-status water bodies (Ni Chathain *et al.*, 2012), reduced monitoring may not be appropriate.

- Prediction of WFD type based on depth was not possible for the unmonitored lakes, as a reliable model for predicting lake maximum depth to the resolution required for WFD typology (< 12/> 12 m) could not be created based on existing lake and catchment characteristics. Lake bathymetry surveys have been carried out for a large number of lakes on the monitoring programme. As these additional data become available, it may be possible to improve the accuracy of the predictive model. Alternatively, bathymetric surveys of the remaining unmonitored lakes could be prioritised. Carrying out the bathymetric surveys would be more expensive and time-consuming, but would provide additional data on lake volume and hypsometry, which could be used for calculating residence times, and for understanding lake nutrient loading and the impacts of abstraction pressures.
- For a number of groups, groundwater interactions may be mediating the impacts of eutrophication on surface water quality. However, nutrients entering groundwater will ultimately impact either groundwater quality or that of connected water bodies. Integration of water quality management across surface and groundwater bodies will be required to address this issue.
- Further analysis or investigation into some of the groups generated by the cluster analysis will be required to assign status or to increase confidence in the status assignments made. For some groups, more detailed information on the nature and type of pressures present, their location in relation to the lake and knowledge of in-lake characteristics such as depth or littoral area may help to understand discrepancies between status classes within groups.
- For groups in which few or no monitored representatives are present, one-off investigative monitoring might provide increased confidence in status assignments or, alternatively, remote sensing of these lakes could be explored. While efforts were made during this project to use recent data that derived from WFD-compliant assessments, there are other sources of information, including occasional or historic monitoring events, local authority laboratories and group water schemes, that could be used to indicate departure from high status for unassigned groups.

4.2.2 Research

- The absence of arable cover in the majority of study catchments is related to the natural distribution of lakes throughout Ireland. Lake density is lowest in the south and east of the country, where the temperature and soil conditions are most suited to arable farming. In river catchments in that part of the country, arable cover can reach 80%. However, there are few lakes in these locations. If a risk-ranking approach is taken to further lake status investigations, the low number of lakes under pressure from arable farming may mean that they are not a high-risk category. As such, this may be better posed as a research question.
- Invasion of the zebra mussel, *Dreissena polymorpha* (Pallas, 1771), can bring about changes in lake nutrient processing, with increased water clarity, decreased water column nutrient concentrations and decreased frequencies of algal blooms all reported (Burlakova *et al.*, 2011; Baranowska *et al.*, 2013; Cha *et al.*, 2013; Greene *et al.*, 2015). It was hypothesised that invasion by *D. polymorpha* might explain variations in status within groups of otherwise similar lakes. This was not found to be the case. Further research into the ecological impacts of *D. polymorpha* in Ireland is required (Lucey *et al.*, 2008), but, in particular, research into its effects on Irish lakes at different spatial scales may be required to understand how lake nutrient processing is being impacted across the landscape. This may require investigation of

the seasonal dynamics of these effects as well as their impacts at site, water body and catchment scale.

- It was hypothesised that abstraction pressures might explain variation in status within groups of otherwise similar lakes. This was not found to be the case across all groups, although the clustering method did group together many reservoirs, e.g. those in the south-east. Further investigation of the magnitude of abstractions and timing of maximum drawdown on a range of lake types might provide a better indication of which lakes are most likely to be affected by these hydromorphological pressures.
- Disentangling the effects of multiple pressures on ecosystem health remains a challenge in aquatic ecosystem management. The current study identifies groups of lakes subject to similar types and magnitudes of pressures, providing a framework in which further research into the relative importance of these pressures and their magnitude to lake status may be investigated.

The final report for the project is available for download at http://erc.epa.ie/safer/reports, along with the full list of lakes included in the study, their catchment and land use characteristics and the results of the status assessment for the lakes monitored during the project.

References

Allott, N., McGinnity, P. and O'Hea, B., 2005. Factors influencing the downstream transport of sediment in the Lough Feeagh catchment, Burrishoole, Co. Mayo, Ireland. *Freshwater Forum* 23: 126–138.

Archbold, M., 2010. *Contaminant Movement and Attenuation Along Pathways from the Land Surface to Aquatic Receptors: a Review*. STRIVE Research Report No. 56. EPA, Johnstown Castle, Ireland.

Arnscheidt, J., Jordan, P., Li, S. *et al*., 2007. Defining the sources of low-flow phosphorus transfers in complex catchments. *Science of the Total Environment* 382: 1–13.

Baranowska, K., North, R.L., Winter, J. *et al*., 2013. Long-term seasonal effects of dreissenid mussels on phytoplankton in Lake Simcoe, Ontario, Canada. *Inland Waters* 3: 285–296.

Bowman, J.J., McGarrigle, M.L. and Clabby, K.J., 1993. *Lough Derg: an Investigation of Eutrophication and Its Causes.* Part I. Environmental Research Unit, Dublin.

Burlakova, L.E., Karatayev, A.Y. and Karatayev, V.A., 2011. Invasive mussels induce community changes by increasing habitat complexity. *Hydrobiologia* 685: 121–134.

Canham, C.D., Pace, M.L., Papaik, M.J. *et al*., 2004. A spatially explicit watershed-scale analysis of dissolved organic carbon in Adirondack Lakes. *Ecological Applications* 14: 839–854.

Cha, Y., Stow, C.A. and Bernhardt, E.S., 2013. Impacts of dreissenid mussel invasions on chlorophyll and total phosphorus in 25 lakes in the USA. *Freshwater Biology* 58: 192–206.

Daly, D., Sweeney, L., Byrne, C. *et al*., 2013. *A Risk-Based Methodology to Assist in the Regulation of Domestic Waste Water Treatment Systems.* Guidance Document. EPA, Johnstown Castle, Ireland.

Donohue, I., McGarrigle, M.L. and Mills, P., 2006. Linking catchment characteristics and water chemistry with the ecological status of Irish rivers. *Water Research* 40: 91–98.

EPA (Environmental Protection Agency), 2006. *A Reference Based Typology and Ecological Assessment System for Irish lakes*. ERTDI Research Report No. 2000-FS-1-M1. EPA, Johnstown Castle, Ireland.

Foy, R.H., Lennox, S.D. and Gibson, C.E., 2003. Changing perspectives on the importance of urban phosphorus inputs as the cause of nutrient enrichment in Lough Neagh. *Science of the Total Environment* 310: 87–99.

Free, G., 2002. The Relationship between Catchment Characteristics and Lake Chemistry in the Republic of Ireland. Unpublished PhD thesis, Trinity College, University of Dublin, Dublin.

Greene, S., McElarney, Y.R. and Taylor, D., 2013. A predictive geospatial approach for modelling phosphorus concentrations in rivers at the landscape scale. *Journal of Hydrology* 504: 216–225.

Greene, S., McElarney, Y.R. and Taylor, D., 2015. Water quality effects following establishment of the invasive Dreissena polymorpha (Pallas) in a shallow eutrophic lake: implications for pollution mitigation measures. *Hydrobiologia* 743: 237–253.

GSI (Geological Survey of Ireland), 2005. *Groundwater Body Descriptions*. Geological Survey of Ireland. Available online: https://www.gsi.ie/Programmes/Groundwater/Projects/Groundwater+Body+Descriptions.htm (accessed 9 December 2015).

Håkanson, L., 2005. The importance of lake morphometry for the structure and function of lakes. *International Review of Hydrobiology* 90: 433–461.

Hem, J.D. 1985. *Study and Interpretation of the Chemical Characteristics of Natural Water*. Water Supply Paper No. 2254. United States Geological Survey.

Irvine, K., Donohue, I., Wemaëre, A. *et al*., 2003. Connecting land-use with water quality: sources, sinks and time-bombs. Diffuse Pollution and Basin Management: Proceedings of the 7th IWA International Conference, Dublin. University College Dublin, Dublin.

Johnes, P.J., 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. *Journal of Hydrology* 183: 323–349.

Jordan, C., McGuckin, S.O. and Smith, R.V., 1999. Deriving phosphorus export coefficients for CORINE land cover types. *Water Science & Technology* 39: 47.

Koiv, T., Noges, T. and Laas, A., 2011. Phosphorus retention as a function of external loading, hydraulic turnover time, area and relative depth in 54 lakes and reservoirs. *Hydrobiologia* 660: 105–115.

Kratz, T., Webster, K., Bowser, C. *et al*., 1997. The influence of landscape position on lakes in northern Wisconsin. *Freshwater Biology* 37: 209–217.

Lucey, F.E., Minchin, D. and Boelens, R., 2008. From lakes to rivers: downstream larval distribution of *Dreissena polymorpha* in Irish river basins. *Aquatic Invasions* 3: 297–304.

McElarney, Y.R., Rasmussen, P., Foy, R.H. *et al*., 2010. Response of aquatic macrophytes in Northern Irish softwater lakes to forestry management; eutrophication and dissolved organic carbon. *Aquatic Botany* 93: 227–236.

Matias, N.-G. and Johnes, P.J., 2012. Catchment phosphorous losses: an export coefficient modelling approach with scenario analysis for water management. *Water Resources Management* 26: 1041–1064.

May, L., Place, C., O'Hea, B. *et al*., 2005. Modelling soil erosion and transport in the Burrishoole catchment, Newport, Co. Mayo, Ireland. *Freshwater Forum* 23: 139–154.

Meybeck, M., Friedrich, G., Thomas, R. *et al*., 1996. *Rivers*. Water Quality Assessments: a Guide to Use of Biota, Sediments and Water in Environmental Monitoring UNESCO/WHO/UNEP, London.

Ni Chathain, B., Moorkens, E. and Irvine, K., 2012. *Management Strategies for the Protection of High Status Water Bodies*. STRIVE Research Report No. 2010-W-DS-3. EPA, Johnstown Castle, Ireland.

Nielsen, A., Trolle, D., Søndergaard, M., *et al*., 2012. Watershed land use effects on lake water quality in Denmark. *Ecological Applications* 22: 1187–1200.

Nõges, T., 2009. Relationships between morphometry, geographic location and water quality parameters of European lakes. *Hydrobiologia* 633: 33–43.

Pallas, P.S., 1771. *Reise Durch Verschiedene Provinzen des Russischen Reichs.* Theil 1. Physicalische Reise durch verschiedene Provinzen des Russischen Reichs im 1768 und 1769sten Jahre. Kayserliche Akademie der Wissenschaften, St. Petersburg.

Palmer, M.W. and White, P.S., 1994. Scale dependence and the species-area relationship. *The American Naturalist* 144: 717–740.

Shilland, P., Gaston, L. and Moe, H., 2009. *Revised Risk Assessment Methodology for Surface Water Abstractions from Lakes*. Eastern River Basin District – Abstractions National POM/Standards Study No. 39325/AB40/DG51. Dublin City Council, Dublin.

Sobek, S., Nisell, J. and Fölster, J., 2011. Predicting the depth and volume of lakes from map-derived parameters. *Inland Waters* 1: 177–184.

Strauss, P., Leone, A., Ripa, M.N. *et al*., 2007. Using critical source areas for targeting cost-effective best management practices to mitigate phosphorus and sediment transfer at the watershed scale. *Soil Use and Management* 23: 144–153.

Tedd, K.M., Coxon, C.E., Misstear, B.D.R. *et al*., 2014. An integrated pressure and pathway approach to the spatial analysis of groundwater nitrate: a case study from the southeast of Ireland. *Science of the Total Environment* 476–477: 460–476.

Venohr, M., Donohue, I., Fogelberg, S. *et al*., 2005. Nitrogen retention in a river system and the effects of river morphology and lakes. *Water Science and Technology* 51: 19–29.

Withers, P.J.A., Jarvie, H.P. and Stoate, C., 2011. Quantifying the impact of septic tank systems on eutrophication risk in rural headwaters. *Environment International* 37: 644–653.

Zhang, T., Soranno, P., Cheruvelil, K. *et al*., 2012. Evaluating the effects of upstream lakes and wetlands on lake phosphorus concentrations using a spatially-explicit model. *Landscape Ecology* 27: 1015–1030.

Abbreviations

CSO	Combined sewer outflow
EU	European Union
GIS	Geographical information system
MS	Member State
SDI	Shoreline development index
UWWT	Urban waste water treatment
WFD	Water Framework Directive

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:

- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha);*
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol (*m.sh. Timpeall an Tí, léarscáileanna radóin).*
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:

- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- An Oifig um Cosaint Raideolaíoch
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 181

Predicting ecological status in unmonitored lakes using catchment land use and hydromorphological characteristics

Authors: Caroline Wynne and Ian Donohue

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Identifying pressures • Informing policy • Developing solutions

Identify pressures

Hydrological, geological and morphological characteristics (i.e. lake setting) of Irish lake catchments were used to group lakes based on their similarities. This characterisation allowed the description of the impacts of different land uses on lakes, providing a framework for assessing lakes of similar setting and pressure. This process identified an increase in the type and intensity of pressure across the lakes groupings based on alkalinity. The research also highlighted that understanding a lake's setting is important in predicting the effects of land use pressures on lake water quality.

Inform policy

The current study provides a framework to predict ecological status for unmonitored lakes for the purposes of the Water Framework Directive (WFD). Our findings highlight how the impacts of similar pressures differ depending on hydrogeomorphological characteristics of a catchment and lake. This knowledge can be incorporated into land use planning policies to assist in meeting our water quality objectives under national and EU legislation.

Develop solutions

Prediction of water quality across a greater number of Irish lakes using this method would also assist in the planning and resource allocation for programmes of measures required to improve water quality through catchment management.

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