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Estimating the effects of land-use and catchment characteristics on lake water quality: Irish lakes 2004-2009

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Abstract: This paper attributes the variation in water quality across Irish lakes to a range of contributory factors such as human population, septic tanks, urban waste water treatment, phosphorous excreted by livestock, as well as catchment soil and geology. Both linear and non-linear quadratic models were estimated in the analysis, which attempts to account for point and non-point sources of pollution affecting water quality in 216 lake catchments. The models show a clear link between activities within lake catchments (e.g. agriculture, population, etc.) and lake water quality, finding that the relationship is neither simple nor linear. The analysis also shows that it is important to account properly for the type of and intensity of land-use particularly in relation to agriculture.

Keywords: lake water quality; land-use; chlorophyll concentration.
JEL Classifications: Q15, Q53

1. INTRODUCTION

Surface water resources have a range of important functions. They provide drinking water, sustain biodiversity and constitute an important tourism and recreation resource. Poor water quality impacts on all of these and, thus, maintaining high water quality has a significant value.

Lake water quality is influenced by a variety of factors, natural and anthropogenic, with the latter often associated with detrimental impacts on quality but being more amenable to intervention. Preventing or remediating pollution damage is costly in resources, whether measured in abatement expenditures or opportunity cost. And while identifying the causes of point source pollution is usually easier than for diffuse sources, the most cost efficient approach to remediation may not necessarily be tackling point sources first. Therefore, understanding the relative contribution of various pollutant sources and their cost of remediation is a crucial input into efficient management.

In the European Union, the Water Framework Directive (CEC, 2000) requires member states to restore polluted water bodies to a minimum of ‘good status’ by 2015, as well as preventing deterioration in the quality status of all water bodies. The Water Framework Directive (WFD) incorporates concepts of economic efficiency by specifying that certain measures to deliver ‘good status’ be ‘cost effective’ or not ‘disproportionately costly’.

There is an extensive literature on lake water quality and it is generally acknowledged that phosphorus (P) is often the limiting nutrient determining algal growth in lakes (Schindler, 1977; Sondergaard *et al*., 2001; Moss *et al*., 2003). A significant correlation has been shown between soil P and P loss to surface water both internationally (Vadas *et al*., 2005; Pote *et al*., 1999; Sharpley *et al*., 1996) and in Ireland (Tunney *et al*., 2007; Watson *et al*., 2007; Styles and Coxon, 2006; Kurz *et al*., 2005; Daly *et al*., 2001). The loss of P from soils to water is complex and not all soils are equal in their capacity to lose P to water. For instance, mineral soils, particularly those high in iron and aluminium oxides, and soils with high organic matter are less susceptible to P loss (Jordan *et al*., 2005; Daly and Styles, 2005; Daly *et al*., 2001; Maguire *et al*., 2001).

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Agriculture, and in particular livestock farming, is often attributed as a primary source of P loss to water but the literature suggests that the relationship between stocking rate and P loss is site-specific, as is evident from the inconclusive nature of the relationship (Capece *et al*., 2007; Tunney *et al*., 2007; Schepers and Francis, 1982). Much of the knowledge of P loss to water is from field or small catchment based studies providing site-specific results and while this type of research has been used to develop nutrient cycling models, such as ANIMO, GLEAMS, DAYCENT, and MACRO, these models (or the necessary data) are not sufficiently detailed to model nutrient export at catchment scale in Ireland (Lewis and McGechan, 2002; Heathwaite *et al*. (2007); Doody *et al*. (2012)).

The use of multivariate statistical analyses is an alternative approach for investigating how activities within catchments affect water quality. Donohoe *et al*. (2006) used a spatial statistical analysis to link catchment characteristics with ecological status of rivers, finding that urbanisation, arable farming and the extent of pasturelands are the principal pressures at catchment scale that impact on ecological quality. From a policy perspective more refined explanatory variables than the percentage of catchments under urban, pasture and arable land is necessary to inform pragmatic policy initiatives. O'Donoghue *et al*. (2010) also combine spatial datasets to examine economic influences on the ecological quality of water and find that forestry, construction activity, population density, agricultural activity and wastewater treatment methods are critical factors affecting water quality. While O'Donoghue *et al*.'s results are intuitive (and not dissimilar from Donohoe *et al*. (2006)), two aspects of the analysis undermine the reliability of the quantitative results: the spatial unit employed in the analysis does not properly match with the water quality monitoring catchments; and secondly their model estimator ignores the spatial dimension of the data (see LeSage and Pace (2009) for a discussion of spatial estimators). Principal Component Analysis (PCA) is also frequently used to examine the effect of various nutrients on surface water quality (Wu *et al*., 2009; Fan *et al*., 2010; Zhao *et al*., 2012), however, the results of PCA analyses are generally more suited to developing predictive models of water quality than as a tool to identify the marginal impact of various sources or to inform the direction of policy.

The objective of this paper is to present a methodology for the assessment of the marginal contribution of various activities, (e.g. livestock, wastewater treatment, etc.) to lake water quality in Ireland. This information can subsequently be utilised by decision makers as an input into determining cost efficient programmes to achieve good status for water bodies.

Ireland, in common with many northern European countries, relies heavily on surface water as a source of drinking water, with 83% of drinking water being drawn from surface water sources. However, Ireland has a very fragmented water supply industry with many small rural supplies, with only basic treatment facilities. Consequently, the quality of surface water bodies is of particular importance in Ireland.

Furthermore, Ireland with extensive surface water resources has traditionally been a destination for angling tourism. Angling tourism has declined by 40% between 1999 and 2006, and importantly, a decline in water quality was cited as one of the contributing factors to this significant decline (Fáilte Ireland, 2009).

In this study we undertake a multivariate analysis using spatial data on lake catchments in Ireland and administrative data on agricultural and other catchment activity to estimate a model of lake water quality, which provides estimates of the marginal effect of various catchment activities on water quality.

2. METHODS

2.1 Lake Water Quality Model

To explain the variation in water quality across the lakes in our dataset we estimate a linear model (Donohoe *et al*. (2006), O'Donoghue *et al*. (2010)) and also a non-linear quadratic variant. The linear model is specified in equation (1) below, where catchment activities affecting water quality are denoted by X_{itn}, where $i = 1$ to 216 lakes, t represents years 2004 to 2009, and $n = 1..N$ explanatory variables as described later. Other factors, either unknown or not measured, also affect water quality and are captured by the error term, ϵ_{it}. The vector of parameters to be estimated in the model is represented by β:

$$Water\ Quality_{it} = \beta X_{itn} + \epsilon_{it} \qquad (1)$$

In our non-linear model we allow for some quadratic terms in the explanatory variables rather than imposing linear relationships between the activities, such as phosphorus from livestock, and water quality. This model is specified in equation (2), where $Z_{itn} = (X_{itn})^2$ and β and γ are the parameter vectors to be estimated.

Quadratic terms are not included for all variables during estimation, for instance where the variables measure percentage shares.

$$Water\ Quality_{it} = \beta X_{itn} + \gamma Z_{itn} + \epsilon_{it} \quad (2)$$

As the lakes within the dataset are hydrologically independent we need not employ a spatial estimator, however, the panel format of the data (216 lakes with observations across years 2004-2009) necessitates using a panel estimator (see Arellano (2003) for a discussion of panel estimators). The dependent variable for both estimated models is the natural logarithm of maximum chlorophyll reading.

For the dependent variable we use Environmental Protection Agency (www.epa.ie) lake water quality monitoring data for the period 2004-2009 (EPA, 2008, 2010). Lake water quality in Ireland is assessed using a modified version of the standard OECD (1982) scheme based on the annual maximum *chlorophyll a* concentration. Chlorophyll levels indicate a level of phytoplankton in the water, which becomes elevated with higher levels of nutrients, primarily phosphorus. The growth in phytoplankton may lead to nuisance algal blooms, which reduce clarity (transparency), which in turn reduces the area colonised by submerged plants due to light exclusion and may ultimately eliminate plant growth. The data used in the analysis are lakes that had chlorophyll monitoring during the years 2004-2009. In total 216 lakes are included in the analysis, with maximum chlorophyll readings varying from a minimum of two to a maximum of six per lake. In total there are 1030 measurements of maximum chlorophyll across the 6 years, which are summarised in Table 1 across lake trophic categories.

Table 1: Trophic Status for 216 lakes, 2004-2009

Lake Trophic Category	Annual Max. Chlorophyll mg/m3	Level of Pollution	Max. Chlorophyll readings	%
Oligotrophic	<8	Very low	511	50
Mesotrophic	8<25	Low	339	33
Moderately eutrophic	25<35	Significant	60	6
Strongly eutrophic	35<55	Strong	56	5
Highly eutrophic	55<75	High	32	3
Hypertrophic	≥75	Very high	32	3
			1030	100

2.2 Catchment characteristics

In order to account properly for point and non-point sources of pollution it is important to conduct the analysis at lake catchments scale. A Geographical Information System (GIS) was used in the first instance to determine the catchments of the 216 lakes based on mapping topology layers. With lake catchments defined it was possible to calculate from existing GIS resources information on catchment geology, mean slope, and land cover (see the EPA's geoportal data site http://gis.epa.ie/).

Social or economic data are generally not available at lake catchment level in Ireland but it is possible using relatively simple spatial analytical tools to make catchment level estimates of relevant economic and social variables that potentially effect lake water quality within the catchment. To this purpose one can draw on data compiled as part of the census of population and the census of agriculture, which are available down to the so-called electoral district (ED) level. There are just over 3400 electoral districts in Ireland that range in area from 5 hectares to just under 13,000 hectares, in population from 39 persons to just over 16,000 persons. Geographically EDs do not match lake catchments, as lake catchments often comprise multiple EDs, or parts thereof. In order to construct catchment level data from data collected at the ED level a simple apportionment method is applied which is illustrated in Section 2.3.

2.3 Cattle and sheep

An agricultural census is undertaken every ten years in Ireland. Information on livestock populations and agricultural land use is published at ED level, with agricultural activity occurring in roughly 2800 EDs. The most recent censuses are 2000 and 2010, though ED level data for the 2010 census are not yet published.

Regional growth rates for livestock populations and land-use from annual agricultural surveys conducted by the Central Statistics Office (www.cso.ie) were used to estimate cattle and sheep populations by animal type and by ED for the years 2004-2009. Using a similar methodology as the EPA uses to estimate national emissions estimates for nitrous oxide and ammonia, estimates of phosphorus excreted by cattle and sheep by ED were calculated. To estimate P excreted by cattle and sheep within a lake catchment a simple spatial analysis tool was employed where the proportion of an ED within a lake catchment was applied to the ED's P estimate to calculate an ED's contribution or share of a lake catchment's cattle and sheep excreted P. Summing relevant catchment shares across EDs provided an estimate of P excreted by cattle and sheep within the catchment. Estimates of P excreted by cattle, sheep and pigs (discussed below) were summed to provide an estimate of P excreted by livestock within lake catchments.

2.4 Pigs

To preserve confidentiality Ireland's Central Statistics Office (CSO) only publishes details on pig population at county level (of which there are 26 compared to roughly 2800 EDs with agricultural activity). In contrast, information on larger pig producers, who have Integrated Pollution Prevention and Control (IPPC) licences issued by the EPA, is available on the EPA's website. IPPC licensed piggeries are required to submit Annual Environmental Reports (AER), which contain details on production activity. Where AER reports are either incomplete or not reported, information on maximum licensed activity is used to infer production volumes. Estimates of excreted P from pigs were calculated in a similar manner to that described for cattle and sheep following EPA's methodology. The location of IPPC licensed piggeries is known by map grid reference, which facilitated adding estimates of excreted pig P to the relevant catchment estimates for cattle and sheep P. IPPC licensed piggeries are a minority of total pig farms and the county level data from the CSO was insufficient to estimate the proportion of non-IPPC licensed piggeries that are located within lake catchments. CSO data on pigs (by animal type) within each county was used to estimate total P excreted, from which IPPC pig P already accounted for above was deducted.

2.5 Poultry

Ireland has a poultry population in excess of 11 million birds, with 83% located within just four counties: Monaghan, Limerick, Cavan and Waterford. Sufficiently detailed information was not available to enable estimation of excreted P from poultry within lake catchments. The most comprehensive information available comes from the 2000 and 2010 censuses of agriculture and in both instances information is only published at county level and in the case of the 2010 census only the total bird population was published, rather than population by bird type. Using this information and farm structure surveys from intervening years, county poultry populations for the years 2004-2009 were estimated.

2.6 Arable land and forestry

Ploughed land within a catchment has previously been found to have a negative effect on surface water quality (Donohue *et al*. (2006); Neil, (1989)). In a manner similar to cattle and sheep above, data from both the census of agriculture and annual agricultural activity surveys were used to estimate the area of ploughed land within each ED for the years 2004-2009, which in turn was apportioned to catchments in proportion to the area share of each ED within the catchment. A future refinement on the contribution of arable land to water quality might incorporate additional data on artificial fertilizer application rates to estimate total P applied to each crop, including pasture. CORINE land use data for 2006 were used to calculate the extent of forestry within catchments. Using data for just one year was considered reasonable, as forested area was unlikely to have varied considerably over the 2004-2009 period but more detailed information on forestry activities within catchments, such as clear felling forests, would provide better information to determine the effect of forestry on water quality.

2.7 Population, septic tanks and urban wastewater treatment

The 2006 population census is also published at ED level and similar to the methodology described earlier we were able to make population estimates for lake catchments. With GIS tools we were also able to identify urban populations located within catchments. The majority of rural households are not connected to public sewers and instead rely of septic tank technologies for wastewater treatment, which are considered to be a risk to water quality (Macintosh *et al*. (2011); Withers *et al*. (2011)). The census records households using septic tanks for wastewater treatment, which was used to estimate the number of septic tanks within lake catchments. The standard of urban wastewater treatment varies from primary to tertiary treatment with nutrient removal, however, in the present study our data did not distinguish between treatment plant types. We were able to distinguish, using dummy variables, between catchments with both urban centres and discharges from urban wastewater treatment plants (UWWT); catchments without urban settlements but with discharge points from UWWTs; and, catchments with neither urban centres nor discharges from UWWTs. The latter situation can be explained by an urban centre located in one lake catchment but whose UWWT discharges into an adjoining lake catchment. Being able to distinguish between these UWWTs enables us to statistically test for the effect of UWWTs on water quality.

2.8 Other P emission sources

The data discussed above accounts for the majority of anthropogenic activity that ultimately results in P emissions into surface waters but unfortunately it does not fully describe all P within catchments that has the potential to reach lake waters. It does not account, for example, for animal P in the form of manure or slurry that is imported or exported from catchment areas. In the case of non-IPPC pigs and poultry we use estimates of county level activity as a proxy for catchment activity, as detailed catchment level data is not readily available. We have no data on other activities that discharge P into the environment, for example, from the food processing sector or other industry. A summary of the data used in the paper in contained in Table 2.

Table 2: Summary statistics

Description	Units	Mean	Standard Deviation	Minimum	Maximum
Number of Septic tanks		568	2,512	1	28,940
Catchment urban population (towns >500 persons)		1,085	6,227	0	75,388
Share of catchments with no towns (>500 persons)	%	83.5	37	0	100
Share of catchments with UWWT discharge	%	15.1	36	0	100
Phosphorus excreted pigs (excl. IPPC licensed pigs) by county	Tonnes	87.9	142	0	511
Phosphorus excreted by cattle, sheep and IPPC licensed pigs within the catchment	Tonnes	92,733	482,045	12	6,090,462
Catchment area	Hectares	26,301	63,600	2002	748,027
Share of catchment forested	%	0.77	1.15	0	6
Share of catchment ploughed	%	0.04	0.19	0	2
Share of catchments with rainfall > 1500mm	%	29.4	46	0	100

3. RESULTS AND DISCUSSION

Table 3 shows estimates for both the linear and non-linear models based on a random effects, unbalanced panel generalised least squares (GLS) estimator with robust standard errors. A Breusch-Pagan Lagrange multiplier test for random effects (i.e. that a panel effect between lakes exists) confirmed the use of the random effects estimator. The pseudo R^2 for both models is 0.44, indicating the model explains 44% of the variance in the dependent variable (the logarithm of maximum chlorophyll), which is relatively good given the nature of the data and the extent and quality of the explanatory variables. The estimated non-linear model presented includes quadratic terms on just two variables; urban population and livestock P, as these were the only instances where a non-linear relationship appeared to exist. The parameter estimates from both models are discussed in turn below.

Table 3: Regression Estimates of Lake Water Quality Model

	Linear Model			Non-linear Model		
Observations Lakes Overall R-sq	1030 216 0.4469			1030 216 0.4495		
Variable	**Parameter Estimate**	**Standard Error**		**Parameter Estimate**	**Standard Error**	
LnSepticTanks	0.157	0.081	*	0.152	0.082	*
UrbanCatch:6550	0.501	0.192	**	0.447	0.234	*
UrbanCatch:30665	-0.723	0.202	**	-0.841	0.201	**
UrbanCatch:36657	1.565	0.152	**	1.694	0.161	**
UrbanCatch:36672	-0.354	0.147	**	-0.538	0.156	**
LnUrbanPop	0.287	0.079	**	1.758	0.635	**
$LnUrbanPop^2$				-0.092	0.038	**
Rural#UWWT 0#1	0.122	0.183		-0.008	0.197	
Rural#UWWT 1#0	2.129	0.589	**	7.933	2.580	**
Rural#UWWT 1#1	2.811	0.715	**	8.502	2.537	**
LncountyPigP	-0.114	0.023	**	-0.115	0.023	**
LnCountyPoultryPop	0.217	0.028	**	0.208	0.030	**
LnLivestockP	0.176	0.066	**	0.007	0.169	
$LnLivestockP^2$				0.012	0.011	
LnCatchArea	-0.419	0.102	**	-0.452	0.117	**
Forest06_den	0.079	0.045	*	0.073	0.045	
Ploughed_den	0.482	0.163	**	0.590	0.176	**
HighRainfall	-0.342	0.131	**	-0.317	0.138	**
SlopeDum	-0.293	0.159	*	-0.257	0.167	
s_aRend_Lith_Den	-1.678	0.958	*	-2.022	0.957	**
s_aPodzolics_Den	-2.945	0.707	**	-3.212	0.717	**
aRock_sediment_Den	-1.305	0.630	**	-1.321	0.612	**
aRock_metamorphic_Den	-5.599	1.353	**	-5.619	1.323	**
aRock_Ignesis_Den	-6.154	1.584	**	-5.934	1.653	**
Constant	0.094	0.855		-4.708	2.831	*
sigma_u	0.573			0.575		
sigma_e	0.699			0.694		
rho	0.402			0.407		

3.1 Septic Tanks

The parameter estimate for the septic tank variable (LnSepticTanks) is statistically different than zero, allowing an inference that septic tanks contribute to poor water quality ($p<0.1$). The parameter estimate of 0.15 can be interpreted as an elasticity, as both the chlorophyll and septic tank variables are in logarithms: at the margin a 1% increase/(decrease) in the number of septic tanks within a catchment will increase/(decrease) the maximum chlorophyll level by 0.15%. We also estimated models substituting rural catchment population for septic tanks but the variable did not have any explanatory power.

Previous research established a nonlinear relationship between P concentration and chlorophyll levels in lakes (Dillon and Rigler, 1974), so a parameter estimate substantially less than one was not unexpected. For clarity it is worth emphasising that the parameter estimate is a measure of the effect of P from septic tanks on lake water quality, not an estimate of the proportion of P from septic tanks that enters lake waters. Existing research already demonstrated that septic tanks in Ireland have a detrimental impact on water quality (Macintosh *et al.* (2011); Withers *et al.* (2011)) but this is one of the few estimates that we are aware of that shows the marginal effect at catchment level of septic tanks discharges on water quality. O'Donoghue *et al*. (2010) estimated the marginal probability of a movement along a 5-point rating scale for river water quality associated with changes in the density of septic tanks within river catchments. In reality we would expect that the effect of septic tanks on water quality to vary by catchment characteristics such as drainage or even the number of septic tanks. In our data we did not find that to be the case. Nonetheless, the estimate shows that septic tanks are contributing to poor water quality and as such it is a buttress to policy action to improve the efficiency of septic tank treatment systems, which is relevant to policy proposals currently being considered in Ireland.

3.2 Livestock and Poultry

The effect of livestock and poultry on water quality is estimated through a number of variables in the models. In the case of poultry we find a statistically significant effect but as our variable (LnCountyPoultryPop) measures the logarithm of the county rather than catchment poultry population we cannot make a practical interpretation of the estimate. We know that all poultry within a county cannot affect water quality within a particular lake catchment but poultry production is highly concentrated in a few counties in Ireland and the parameter estimate suggests that poultry production is an important explanatory factor in the quality of lake water in those areas.

As discussed earlier, our data on pigs is split between larger IPPC licensed piggeries and the balance of the pig herd, the latter of which we have data at county rather than catchment level. Similar to poultry is it difficult to interpret the county pig population variable (LncountyPigP). In both estimated models the parameter estimate is unexpectedly negative (i.e. improving quality) and if pig production does have an effect on water quality we believe that it would be a deteriorating effect (i.e. positive parameter).

For the remainder of livestock within catchments we were able to sum excreted P from cattle, sheep and IPPC licensed pigs into a single variable to estimate a combined effect. In the linear model the parameter estimate on the livestock P variable (LnLivestockP) suggests an elasticity of 0.17; proportionately more livestock within a catchment leads to a proportionate deterioration in lake water quality. But livestock P was one of the variables that we found had a non-linear effect on lake water quality. While the parameter estimates associated with LnLivestockP and LnLivestockP^2 in the non-linear model are individually not statistically significant, when we calculate the marginal effect of livestock P on water quality the estimated effect is statistically significant. The marginal effect of livestock P on lake water quality in the non-linear model is given by the term 0.007 + 0.024*LnLivestockP. We used the delta method (Greene, 2000) to construct standard errors, which are presented in Table 4. Where the amount of livestock P within a catchment is relatively small, the estimated marginal effect is statistically insignificant. But at higher levels of livestock P the marginal effect is increasing and statistically significant. The marginal effects calculated in Table 4 cover the range of livestock P for the catchments within the dataset. For catchments with roughly 1800 tonnes of livestock P the estimated elasticity is 0.18, which is practically equivalent to the single elasticity estimate in the linear model. Within the dataset there are two catchments with annual excreted livestock P of roughly 1.4 million tonnes and one in excess of 5 million tonnes. The elasticity estimate in these catchments is 0.34 and 0.37 respectively, both significant at the 90% level.

Table 4: Estimated Marginal Effects of Livestock Excreted P on Lake Water Quality

Livestock P (tonnes)	Logarithm livestock P (LnLivestockP)	Estimated Marginal Effect (elasticity)	Standard Error	
12	2.5	0.066	0.119	
148	5	0.125	0.078	
1,808	7.5	0.184	0.070	**
22,026	10	0.243	0.101	**
268,337	12.5	0.303	0.148	**
1,468,864	14.2	0.343	0.184	*
5,389,698	15.5	0.374	0.212	*

3.3 Urban Centres

Urban centres emit P to lake catchments via urban waste water treatment plant (UWWT) discharges, unless plants have nutrient removal technology. In our dataset the majority of UWWTs do not have nutrient removal but we cannot identify the plants that do. We have used three approaches to capture the contribution of urban centres to lake water quality. The first approach uses the urban population within catchments from the 2006 census and we find that the marginal effect on water quality declines as urban centres increase in size. In the non-linear model parameter estimates on both variables (LnUrbanPop and LnUrbanPop^2) are statistically significant. The marginal effect, which can be interpreted as an elasticity, is given by 1.758 – 0.184* LnUrbanPop and calculated in Table 5 using typical urban populations within the dataset. We find that small towns have a proportionately higher effect on water quality with elasticity values varying from 0.19-0.58 depending on population size. In larger towns, greater than 6,000 population approximately, the estimate is not statistically significant. These marginal effect estimates contrast with the linear model, which had an elasticity estimate of 0.287 independent of population size.

Table 5: Estimated Marginal Effects of Urban Centres on Lake Water Quality

Urban Population	Logarithm urban population (LnUrbanPop)	Estimated Marginal Effect (elasticity)	Standard Error	
602	6.4	0.584	0.168	**
992	6.9	0.492	0.138	**
1,998	7.6	0.363	0.106	**
2,981	8	0.290	0.096	**
4,915	8.5	0.198	0.096	**
13,360	9.5	0.014	0.135	
18,034	9.8	-0.041	0.152	
73,130	11.2	-0.298	0.245	

The location of urban centres and their UWWT discharge point do not always coincide within the same lake catchment. The second approach to capturing the contribution of urban centres on water quality is through dummy variables identifying the location of UWWT discharges. We use a combination of two one-zero dummies indicating whether the catchment is rural (i.e. does not contain a town) and whether there is an UWWT discharge point in the catchment. Using Wald tests we find that water quality in rural lake catchments (i.e. without urban centres) have poorer water quality when the catchments have UWWT discharge points ($p<0.045$). We also find that water quality in rural catchments (i.e. where no towns exist within the catchment) is lower than quality in catchments with towns regardless of UWWT discharges ($p<0.052$). This result suggests that rural pollution sources have a greater detrimental impact on lake water quality than urban source pollutants. Though the tests indicate the differences are statistically significant, the magnitudes of the differences are relatively small.

The third approach to capturing the contribution of urban centres to catchment water quality is through dummy variables identifying catchments with urban centres. Four lake catchments were identified that have water quality significantly different, either better or worse, than could be explained otherwise. One of the lake catchments with significantly poorer water quality was Lough Naglack (UrbanCatch:6550), which has the town of Carrickmacross within its catchment and a UWWT plant is located within 600 metres of its shore. Due to inadequate capacity this UWWT plant experienced many instances of storm water overflows and was implicated in several pollution instances at the lake, including fish kills[2]. Lough Mask (UrbanCatch:30665) is one of the lakes identified with significantly better water quality yet it has multiple urban centres located within its catchment.

[2] The 2011 Annual Environmental Report on the Carrickmacross waste water discharge licence (Monaghan County Council, 2011), highlights that over the period covered in our analysis the waste water treatment works which has a maximum capacity of 12,150 population equivalent had to cope with a load of up to 23,000 population equivalent. It also notes that the combined storm overflows are categorised as ‘at risk’ and that they are impacting on water quality, as they have been operating frequently due to the load on the WWTP.

3.4 Land Use and Catchment Size

Various types of land use have been recognised as contributing to nutrient enrichment of surface waters (Gibson (1976); Neil (1989); Donohoe *et al*. (2006); O'Donoghue *et al*. (2010)). For example, in the southeast of Ireland mean nitrogen loss from land to rivers was estimated at 76 kg/ha/yr for ploughed land compared to just 2.0 kg/ha/yr N for unploughed (Neil, 1989) ; whereas forestry in upland lake catchments has been attributed as the source of relatively high phosphorus concentrations (Gibson, 1976) . To investigate the effect of arable farming and forestry on lake water quality we included variables measuring the proportion of catchment land under these uses in the estimated model. In both instances we find a statistically significant effect; arable farming and forestry contribute negatively to lake water quality. In the case of arable farming we find that a one percentage point increase in the share of catchment land ploughed would contribute an estimated 0.48% increase in maximum chlorophyll (0.59% in the non-linear model). The effect of forestry is substantially smaller at 0.07%. The effect of arable land on water quality is not surprising given that nutrient guidance to farmers in Ireland has been based on fertiliser rates for economically optimal productivity, i.e. rates at which further fertiliser applications would not result in higher economic returns, with no distinction for soil types or crop requirements (Coulter, 2004). Elsewhere, there has been similar nutrient application guidance for arable and pasture crops (Withers *et al*., 2001; Oborn *et al*., 2003; Djodjic *et al*., 2005). The Irish guidance has recently been revised in response to new environmental legislative measures protecting water (Schulte and Lalor, 2008).

3.5 Soils, Geology and Catchment Characteristics

All catchments vary in terms of geology, topology, size, etc., and these characteristics can play an important role in the quality of water, independent of any pressures from industry, agriculture, or human population. For example, existing research shows that soil permeability, slope and rainfall intensity can affect the export of nutrients to water (Kleinman *et al*., 2004; Syversen, 2005; Ulen and Jakobsson, 2005). It difficult to fully control for such characteristics in estimation but nonetheless we find evidence that catchment characteristics play an important role in explaining lake water quality. We find that areas of high rainfall (>1500mm per annum), or catchments with a high mean slope (Slopedum) have better water quality than those with the converse. In the case of rainfall one could conjecture that the finding reflects some type of dilution or flushing process. We also find that larger catchments (LnCatchArea) generally have better water quality, with maximum cholorphyll declining by 0.42% for a 1% increase in catchment area. This result may reflect the fact that in larger catchments nutrient sources have a greater distance to travel and therefore a lower likelihood of reaching lake water. For example, if the nutrient pathway is through groundwater, the opportunity that phosphorus is bound in soils may be higher.

Soil types and underlying geology also play a role in water quality, whether inhibiting P export to water (e.g. binding in mineral soils or acting as a barrier) or transporting nutrients, for example in free draining soils. Ireland has a large number of soil types and underlying rock formations (Gardiner and Radford, 1980) and for tractability in model estimation we amalgamated soil and rock types into a number of categories. What we find is that lake water quality is generally higher in lake catchments with higher levels of rendzinas, lithosols and podzolic soils as well as sedimentary, metamorphic, and ignesis rock. In the model estimates presented in Table 3, we have excluded variables for rock and soil types that do not show significantly power in explaining lake water quality.

4. CONCLUSIONS

The purpose of this paper is to present an approach for the assessment of the marginal contribution of various catchment activities to lake water quality, which will assist water managers in relation to actions to improve water quality. Previous catchment level statistical analyses, similar to that used in this paper, have assumed a relatively simple relationship between the share of catchment land in specific land uses and water quality. The analysis here shows that the relationship is neither simple nor linear. Donohoe *et al*., (2006), for instance, relied solely on broad land use shares to explain water quality. The analysis here shows that models of water quality need to incorporate all aspects of anthropogenic activity, though the non-availability of data will limit the extent to which this is practically possible.

Detailed spatial data on activities likely to impact water quality, where it exists, generally does not match river and lake catchments and is therefore often of limited use. Our approach, using spatial data based on administrative boundaries to estimate catchment level activity, could be used more extensively. A simple spatial algorithm was used to map administrative data into catchment boundaries producing quite plausible results. In future analyses of Irish lake water quality it is hoped that this approach can be applied to other administrative datasets, for example on forestry activities, to improve the explanatory power of the model.

An extensive literature has shown that various activities and enterprises (such as wastewater treatment, livestock and arable farming) contribute to nutrient loading and hence affect water quality of surface waters. We now have estimates of the marginal effects of catchment level activities on water quality. While the empirical results are applicable to Ireland they show that the relationship between pollutant source and water quality can be a complex one. For example, we find that the marginal impact of urban populations on lake water quality is disproportionately greater for smaller towns. An implication for water policy in this instance is that growth in small towns will have disproportionately greater impact on water quality than growth in larger towns given existing waste water treatment systems. Our results also show a clear relationship between the level of excreted P within catchments and lake water quality. Not unexpectedly, we find that the larger the P loading from livestock within a catchment, the greater the marginal impact on water quality.

While our model controls for some catchment characteristics it is not yet sufficiently complex to fully understand the interrelationships between activities and catchment characteristics with respect to water quality. For instance, we show that an increase in livestock P loading within a catchment will more than proportionately reduce water quality; but in our current model we cannot say how this effect varies depending on catchment characteristics or the intensity of agricultural activity. These are areas for future research.

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FIRST VOTE OF THANKS PROPOSED BY CATHAL O'DONOGHUE,[18] TEAGASC RURAL ECONOMY AND DEVELOPMENT PROGRAMME

I would like to the thank the society for the opportunity of being a discussant for John Curtis and Edgar Morgenroth's paper "Estimating the effects of land-use and catchment characteristics on lake water quality: Irish lakes 2004-2009". I found it a very interesting paper, which conducted an analysis attempting to estimate marginal impact of the different human activities on the water quality of the lakes in Ireland using econometric linear and quadratic estimations. While many studies of the impact of human economic activity on water quality focus on the relationship at a local or catchment scale (O'Dywer *et al.*, 2013), this study allows for a spatial relationship at wider national level similar to those employed by O'Donoghue *et al.*. (2010) and Donohue *et al.*. (2006).

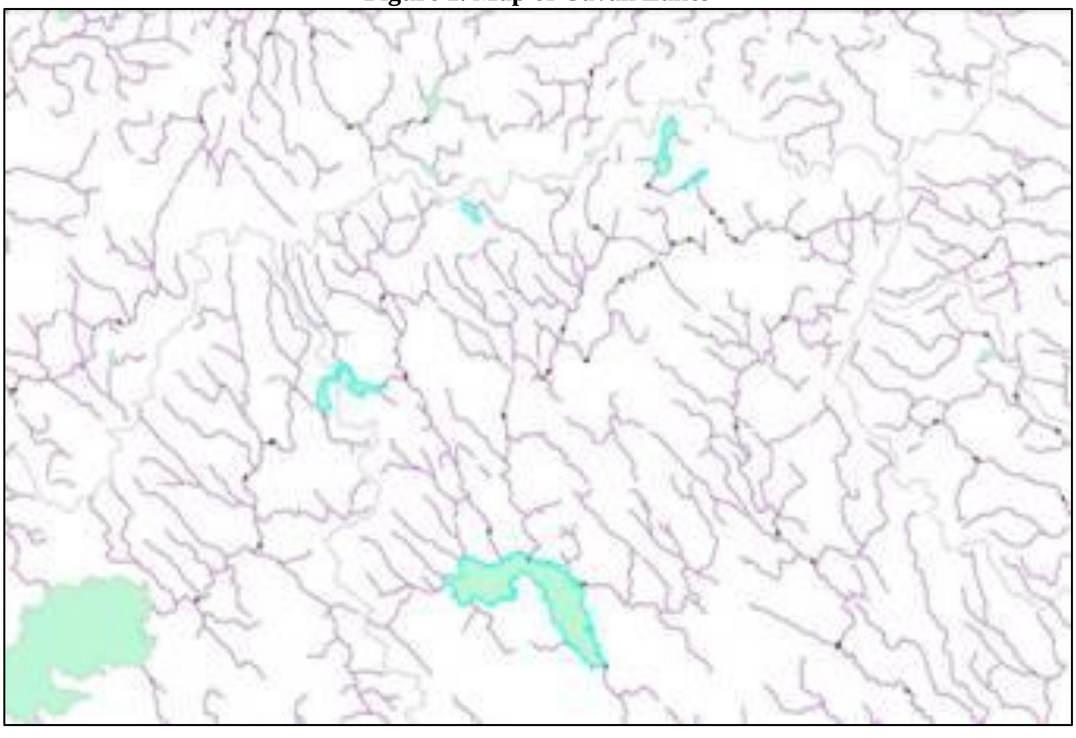
The authors are to be commended on the effort they put into the analysis, which involved bringing together a substantial volume of data from different sources as part of their analysis. The paper used a number of interesting data-matching techniques that helped them to overcome data limitations and gaps. For example, some data is available on the ED level only, so they were able to match the ED data to the lake catchments.

The authors focused water quality as measured by nutrient enrichment, specifically Phosphorus, in lakes in Ireland by regressing chlorophyll concentrations on the dependent variables that would be normally associated with Phosphorous contributions into the environment. The limitation of the paper in terms of the enviro-economic insight is that it is limited to the phosphorus analysis and lakes. The Water Framework Directive requires a more comprehensive approach to the issues of the water pollution. Water pollution is a complex phenomenon with contributors from many different sources and via a range of different pollutants that pose a problem to the environment in addition to P.

I have a couple of queries in relation to the data. The data used to calculate the extent of forestry within catchments, CORINE land use data for 2006 may have a tendency to misrepresent forestry in Ireland, (Black *et al.*, 2008). In relation to the statistical model, the two models estimated yield similar results with the quadratic model having slightly higher predictive power; however, this could be due to multi-colliniarity that can be present when the quadratic term of the same variable is introduced into the regression.

One may query the statement that "As the lakes within the dataset are hydrologically independent we need not employ a spatial estimator." As we can see the in Figure 1, a map of the first 5 Cavan lakes in the EPA 2007-2009 database of lakes sampling we can see that most of them are linked via rivers - indeed most Irish lakes have an inlet and an outlet.

Figure 1. Map of Cavan Lakes



[18] I am grateful for the expert advice of my colleagues Ger Shortle, Stuart Green and Aksana Chyzheuskaya in preparing this note.

The HighRainfall variable shows a negative sign on the coefficient. This could be explained that in lakes the high rainfall would dilute the nutrients in the water. Usually high precipitation is positively associated with the nutrients and other pollutants in the stream due to overland and street runoff.

Intensive human/agricultural activities in the catchment are associated with the higher concentrations of chlorophyll in the lake.[19] The results of this paper are consistent with the situation until the mid-2000s. However as O'Dwyer *et al.*. (2013) highlight despite continued levels of Agricultural activity, there is evidence that since 2007 as a result of Agri-Environmental policies and related mitigation measures on farms that the impact has reduced.

The timing of the study, relying primarily on 2000 Census of Agriculture Data may have a specific impact on the results as there have been likely changes in the period since 2000. Lalor *et al.*. (2010) report a reduction in soils with excessively high levels of P over that period; At the national level, P fertiliser use has declined by 6 kg ha-1 (55 %) for grassland and 5 kg ha-1 (16-30 %) for arable crops between 2003 and 2008. The proportion of tested soils with excessive P (Index 4) has declined from 30 % to 22 % between 2007 and 2011 (Lalor *et al.*., 2010), falling to 18% in 2012. Research on Teagasc's Agricultural Catchment Programme (ACP) has shown that on 5 catchments, between 6 and 26 % of soils had excessive P status, showing the legacy of historic P surpluses (Wall *et al.*., 2012). Large spatial variability was found at farm and field scale, indicating scope to correct imbalances with better nutrient management.

Later data that is now available from the 2010 Census of Agriculture could usefully add to our understanding of these processes. However it may be difficult to observe the impact of the reductions in high levels of P in the period since 2007 as there are significant lags in relation to the impact of changes on farm to changes in water quality. Schulte *et al.*. (2010) used a 'Soil P Decline' model to evaluate this expectation for 4 ACP catchments. At a field P deficit scenario of -7 kg P ha^{-1} it was predicted that an average of between 5 and 20 years would be required for all Index 4 soils to reach Index 3.

Paradoxically there is a concern that more recently below optimum, with increases in the proportion of land with Phosphorous Index 1 and 2 increasing from 40% in 2007 to 59% in 2012, which will lead to reduced farm level productivity (Shortle, 2013).

Overall, I found this paper made an excellent attempt at what is a highly complex question, involving a variety of different data sources. It is one more building block in our understanding of the human-environment relationship, can make a useful contribution to policy development in this space and points in the direction of future research in this area.

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[19] The opposite relation however is true for pig's P production, which could be explained that the authors had no access to the data on the pigs activities in the data and had to estimate it using various techniques and assumption. It should be noted that the 2010 Census of Agriculture data has district level pig numbers.

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SECOND VOTE OF THANKS PROPSED BY DEIRDRE TIERNEY, ENVIRONMENTAL PROTECTION AGENCY

This paper highlights the importance of lakes as a multi-user resource of significant value both economically and socially. It establishes that there is a link often more complex then perceived between catchment activities, catchment characteristics and water quality. The fact that a statistical significance was found is an achievement in itself given the difficulty in compiling the relevant data. And the authors are to be commended for their endeavour.

Whilst many would assume that it is evident that many of the pressures identified: human population, septic tanks (DWWT), UWWT, livestock numbers and effluent, effectively agriculture and forestry and modelled in the paper would negatively impact water quality in the absence of good management practices, it is nonetheless important that evidence of the impact or adverse effect on water quality is published. And little has been published in this respect for lakes in an Irish context.

The findings, grounded in science, support existing policy such as septic tank inspection to improve ground water and thereby protect human health. Other policies underpinned by the paper are the requirement for nutrient management plans, the upgrading of wastewater treatment facilities, and the establishment of drinking water protection zones. Although some of these initiatives are driven by legislation to protect and improve water quality in effect they are protecting human health.

The findings presented generally reflect what the EPA has been publishing in its water quality reports for many years, namely that the pressures and impacts on surface water quality in Ireland come from all aspects of society.

While water quality in Ireland compares favourably with that in other EU countries, we still face considerable challenges tacking both diffuse and point source pollution to meet the objectives of the WFD. In the period 2008 – 2010, only 47% of the monitored lakes achieved the targets of the WFD.

In order to combat this, a cross-sectorial approach engaging all stakeholders will be necessary; the programmes of measures being implemented in each water catchment will need to ensure compliance with the Urban Waste Water Treatment and Waste Water Discharge Regulations to tackle point sources of pollution and the environmental impacts from forestry and domestic waste water discharges (septic tanks) in addition to compliance with the Good Agricultural Practices (Nitrates) regulations.

The paper however, highlights the difficulty in compiling relevant data at the appropriate level and detail. The identified gaps and data difficulties provide direction for future work which with better data availability would lead to a more targeted and thus more effective and cost efficient programme of measures under the WFD. Some of this work is already underway and will be referred to later.

I would like to focus on some of the issues some of which were alluded to in the paper:

1. Availability of data and at the appropriate scale, in this case catchment level. Some useful datasets available (although not necessarily widely available) since the paper's inception include:

a. Land Parcel I Scheme under the Department of Agriculture compiled from the single payment scheme. This shows the farm outlines of all land held by farmers who have applied for support payments from the European Union and current usage. This is currently being used to update CORINE landcover data being undertaken by the EPA.

b. Forestry Maps held by Coillte and the Forest Service

c. Nutrient plans and import/export of slurry possibly an explanation as to why pig numbers did not have an adverse effect on water quality?

d. Percolation map for septic tanks – Map illustrating susceptibility categories for inadequate percolation summarising the relevant hydrogeological parameters that characterise the surface pathway in the source to pathway

e. Defining the catchment could be an issue

2. Other sectors not accounted for - Food Industry,

3. Why smaller urban areas exert a greater influence?

4. Why did rural catchments seem to have poorer lake quality?

5. One not addressed was the impact of Zebra Mussel on chlorophyll levels – were these excluded? Zebra Mussel pose another layer of complexity.

6. Although chlorophyll was used as an indicator of water quality largely due to the fact that this was the best available data at the time, WFD ecological status is more complicated and includes general physical components status, biological status (4 elements assessed), whether or not there are alien species and in the case of lakes that are high status for both biology and general physical components, an assessment of hydromorphological condition is necessary.

Whilst the paper acknowledges that the model is not sufficiently complex for a full understanding of interactions or variation due to catchment or pressure intensity, it does further support the need to identify critical source areas on a catchment by catchment basis.

Current Relevant Research

There are a number of projects currently underway outlined in the STRIVE publication - http://www.epa.ie/downloads/pubs/research/water/EPA%20Water%20Research%20Leaflet%202012.pdf under *Improve our Knowledge on State of Water Resource and Pressures* that are relevant to the paper presented tonight and are attempting to address some of the issues highlighted in the paper to the catchment level.

Katherine Webster: Integrating hydromorphology into typology to improve risk assessment of Irish lakes. University of Dublin, Trinity College (TCD)

This project aims to develop a hydromorphology classification of Irish lakes to include morphology, hydrology and landscape setting; a nutrient-loading models to assess permissible loading rates for inflowing rivers and to assess lake sensitivity to abstraction.

Caroline Wynne: Predicting ecological status of unmonitored lakes based on relationships between status, hydrogeomorphological and landuse characteristics. University of Dublin, Trinity College (TCD)

This project aims to quantify the relationships between hydrogeomorphological and landuse attributes and ecological status to include quantification of relationships between anthropogenic pressures (including land use, human populations, industry, etc.), lake chemistry (e.g. TP), biology (chlorophyll a, species richness, fish abundance etc.) and metrics of ecological status (WFD metrics for different elements) in different hydromorphological settings (which includes lake typology but also scale-related attributes, e.g. position of a lake in the landscape). It involves extensive collation of data layers and year 1 is now complete.

Raymond Flynn: PATHWAYS Assessing, modelling and managing water and contaminant movement along pathways (underground and over-ground) from the land surface to aquatic receptors, including the roles of contaminant transport and attenuation. Queen's University Belfast

'Identification of significant hydrological pathways within RBDs;
Quantification of flows along the identified hydrological pathways;
Identification of the significance of these pathways for diffuse pollutant transport and attenuation, with particular emphasis on the attenuation of nutrients (nitrogen and phosphorus species), and particulate matter (pathogenic micro-organisms and sediments);
Identification of critical source areas contributing diffuse pollutants to groundwater, surface water and relevant ecological receptors; and
Development of a CMT employing data collected during the study in line with the requirements of the end-user.
The project literature report aims to provide an overview of current understanding and knowledge gaps in relation to diffuse contaminant flow and attenuation pathways and the assessment of the impact of these contaminants on aquatic receptors in rivers and streams.'

DOLMANT
DOLMANT is a cross border project which will develop lake management tools to assist in creating programmes of measures to meet EU legislation. It is funded through the European Union's European Regional Development Programme, INTERREG Iva. AFBI is the lead partner with five project partners involved. Project funding is £1.2 million. It aims to develop lake management tools that integrate the biological, hydromorphological and physiochemical properties of lakes with lake and lake catchment variables in cross border catchments, to improve and maintain the ecological status of lakes. The modelling tools will enable the development of targeted catchment management to conserve ecological status required for Water Framework Directive compliance. They will help predict changes in biological groups due to catchment changes and this will be beneficial to environment agencies in implementing the directive.'

There are two questions for the authors. One not addressed was the impact of Zebra Mussel on chlorophyll levels – were these excluded? Zebra Mussel pose another layer of complexity. The other concerns what effect would the distribution of max chlorophyll values have on the models – skewed towards better quality end?

DISCUSSION

Judy Osborne: Would it be possible to include peat cutting as a land use In any future extension of the research? Commercial and domestic turf cutting covers very wide areas and is known to have a detrimental impact on water quality. Following an earlier question on the significance of industrial development on water quality I would like to add that at a previous seminar on septic tanks, organised by Engineers Ireland, it was suggested that many of our rivers were currently at full capacity for pollutants permitted by discharge license. It is conceivable that this could ultimately constrain further industrial development in some areas. This would seem to indicate that it would essential to also include industrial development as a land use in order to get a clear picture of the situation in a catchment area.

Keith Walsh: I thank the speaker for an interesting paper. I note the lack of a variable for industrial activity is a shortcoming and suggest that fuel laundering dump points can be a possible new data source.

Thomas Conefrey: Given the significant exchequer and CAP-funded expenditure on schemes to improve farm buildings, for example the 2008 farm waste management scheme, would it be possible to include as additional explanatory variable to test the impact of these schemes on water quality? For example, could an explanatory variable such as the share of total capital grant payments by county be added to the regression?