Natural capital: An inventory of Irish lakes

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Abstract: Lakes are important components of our landscape and along with networks of rivers and streams provide a range of important ecosystem services and natural capital. Estimates of lake numbers, particularly small lakes, have generally been under-represented historically as they did not appear on most printed maps. Accurate calculation of lake numbers is necessary in determining realistic estimates of their collective contribution to provisioning, regulating, supporting and cultural ecosystem services. A summary of the available lake data is vital to help shape research efforts to determine catchment and lake system contributions to biogeochemical processes, for example, carbon burial, pollution, filtration, and biodiversity. This is particularly important in the context of global climate change. In light of the most recent global inventory of lakes and an increasing recognition of aquatic ecosystem services, this paper summarises the publicly available spatial data on the lake population for the island of Ireland. A range of datasets of variable spatial resolution exists for the Irish ecoregion, which suggest varying lake populations of 360, 908 and 976 lakes greater than 0.1 km² surface area. Moreover, the most detailed dataset includes 12,205 lakes greater than 0.00001 km² in the Republic of Ireland (RoI). Additional complexities exist with access to lake data for Northern Ireland (NI). This creates confusion in efforts to valorise lake natural capital for the Irish ecoregion. This summary of the Irish lake population provides context for the selection of lakes for future study and highlights the variable nature of the spatial data.

Keywords: *lake inventories, digital datasets, natural capital, Ireland*

Introduction

Lakes have been described as temporary landscape features resulting from natural or human interferences in the drainage area (Reynolds, 1998; Downing, 2010). The number of lakes in the landscape varies with geography and the relatively permanent landscape morphological characteristics. Other influences include the more transient climatic conditions and increasingly anthropogenic catchment activities. For example, high altitude lakes often occur in glacially scoured basins and have outlets but no inlets and thus are described as headwater lakes. Valley lakes are invariably drainage lakes with

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both inlets and outlets (Håkanson, 2004). Other lake types include bogland, brackish, turloughs (temporary lakes) and artificial lakes (reservoirs, abandoned quarries, decorative lakes). The concept of lake landscape position (Kratz *et al.,* 2006) provides a basis for understanding lake characteristics and dynamics, while landscape limnology (Soranno *et al.,* 2010) is the spatially-explicit study of the interaction of freshwater with terrestrial and human landscapes to determine the effects on ecosystem processes.

Historically, numbers of lakes in the landscape were estimated using paper maps. Surveys in the early 1900s were essentially desk studies with careful scrutiny of maps and compilation of a list of lakes, noting lake name, position, area and altitude. In the past, early cumulative estimates of lake numbers were generally under-represented, mainly because small lakes were not depicted on most printed maps (Smith and Lyle, 1979; Lewis, 1996). A small lake or pond can be defined as a waterbody of between one square meter and two hectares (Biggs *et al.*, 2005). Halbfass (1914) and Thienemann (1925) attempted some of the first calculations of the number of world lakes. They estimated that lakes represented c. 1.8 % of the global land surface, and that a few very large lakes dominated this area. This contributed to the long-standing belief that large lakes were more important scientifically. In fact, lakes and ponds were generally thought of only as temporary reservoirs where water and materials are held for a short time before delivery to streams, rivers, and oceans (Downing, 2010). The first comprehensive global estimate of lakes was attempted by Schuiling (1977) and Herdendorf (1982), with estimates of 5-50 million lakes based on extrapolation of the frequency distribution of large lakes. Herdendorf (1982) estimated that large lakes accounted for approximately 90% of the total surface area and volume of water held in all world lakes. However, Lewis (1996) noted that small lake distribution was largely unknown or only available in raw form on maps. More recently, Kalff (2001) estimated that lake surface areas constituted between 1.3-1.8 % of the land surface. Lehner and Döll (2004) performed a full inventory of world lakes by using a geographic information system (GIS) of satellite imagery to count all of the world's moderate to large lakes. Smaller lakes and ponds (≤ 0.1 km²) were estimated using mathematical models. Downing *et al.* (2006) counted 304 million lakes covering an area of 4.2 million km² or 2.8% of the land area. This number was calculated using statistical extrapolation for smaller lakes and confirmed that small lakes dominate the total surface area of lakes, a view purported by Wetzel (2001). Wetzel (2001) examined the relationship between the number of lakes on Earth and their surface areas and water column depths and found that smaller lake systems cover a larger area than large lakes. In the most recent estimate of the global number of lakes, Verpoorter *et al.* (2014) utilising remote sensing, calculated 117 million lakes greater than 0.002 km² which have a combined surface area of about five million km². They estimate that this is 3.7% of the Earth's non-glaciated land area thus more than doubling Thienemann's (1925) and Kalff (2001) estimates and increasing estimates by Downing *et al.* (2006) by one third. The 2016 launch of the Sentinel-3 satellite carrying four Earth-observing instruments will have improved resolution and, therefore, allow a more accurate monitoring of inland waters and smaller lakes.

The historical focus on large lakes meant that the study of small aquatic systems developed more slowly relative to large lake limnology over the past century (Downing, 2010). The revised upwards estimates of the number and spatial extent of smaller lakes and ponds globally has helped to confirm their importance. Small aquatic ecosystems now play an increasingly vital role in the context of global problems. For example, continental waters including lakes, store and process carbon as material buried in the sediments and through gaseous emissions (Tranvik *et al*., 2009) and the intensive activity of small aquatic systems can make them more dynamic in nature and time relative to large water bodies (Downing, 2010; Winslow *et al*., 2015). Moreover, littoral areas in small lakes are more important per unit area than larger lakes for biodiversity (Oertli *et al.,* 2002; Vadeboncoeur *et al.,* 2011).

More than a decade ago, the Millennium Ecosystem Assessment (MEA, 2005) highlighted the importance of ecosystem services (provisioning, regulation, cultural and supporting) and natural capital in maintaining human well-being and detailed persuasive evidence that human actions were leading to their decline (Aylward *et al.,* 2005; Guerry *et al.,* 2015). The concept of natural capital includes species, ecosystems and ecosystem products that future generations will need in order to live sustainably. This concept is core to the EU 7th Environment Action Programme (2013-2020) which aims to protect, conserve and enhance natural capital. Exploitation of aquatic services and natural capital has allowed human society to construct complex infrastructures necessary for human well-being (Mellino *et al.,* 2015). Natural ecosystem services, however, are being impaired globally (e.g. through intensive farming) with consequent water quality degradation, increased treatment costs, increased flood or drought risk and fisheries impairment. Lakes are important sentinels of these impacts (Williamson *et al.,* 2009) with concerning shifts from clear-water to turbid-water states. Clearwater systems generally have low phosphorus inputs, low phytoplankton biomass, and little recycling of phosphorus from sediments, in contrast to turbid systems, which can have abundant toxic cyanobacteria, anoxic events, fish kills and poorer ecosystem services (Folke *et al*., 2004). The integration of the value of natural capital into national accounting systems by 2020 is being increasingly promoted (Ormerod, 2014; EEA, 2015). Accounting for the environmental support provided by aquatic systems directly and indirectly can potentially help prevent natural capital being overexploited for present economic benefits, and thus comply with the EU strategy for smart sustainability and inclusive growth.

Water resource management is framed by the EU Water Framework Directive (WFD) (2000/60/EC), which was set up to regulate and protect water resources in Europe. The WFD requires that all lakes over 50 hectares (0.5 km^2) in surface area as well as smaller lakes associated with protected areas or drinking water abstraction are assessed and reported on. Additionally, the WFD requires the assessment of the hydromorphological status of lakes when physical alterations may influence aquatic ecology (WFD, Annex V 1.1.2). Countries across Europe have adopted different classifications of lake type to reflect the unique geographical settings. Irish lake types are classified into 13 groups based on physico-chemical descriptors including alkalinity (as a surrogate of geology), water

depth, surface area and altitude (EPA, 2005). Northern Ireland lake types are based on altitude, latitude, longitude, depth, geology and size (above and below two ha) (Rippey *et al.*, 2010). Pertinent geographical water management units for aquatic systems include catchment, hydrometric area and river basin district. Catchment areas are the immediate drainage area determined naturally by topography. Hydrometric areas comprise a single large river catchment, or a group of smaller sub-catchments, and adjacent coastal areas. For example, Ireland, north and south, is divided into 40 hydrometric areas for the purpose of hydrological classification. River basin districts (RBD) were established under the first cycle of the WFD (2009-2015) for the purpose of water management with eight river basin districts on the island of Ireland. This multiple RBD structure did not prove effective, and the second WFD cycle (2018-2021) has collapsed these into a single RBD for southern Ireland (DHPCLG, 2017). Lakes designated as Ramsar, Special Protection Areas (SPA) or Special Areas of Conservation (SAC) with aquatic interest are defined as high conservation status lakes. Additionally, a limited number of freshwater bathing waters are designated under the EU Bathing Waters Directive (2006/7/EC).

In light of the most recent global inventory of lakes, the increasing recognition of aquatic ecosystem services, and future increases in natural capital accounting, this paper summarises the publicly available spatial data on the population of freshwater lentic systems in the Irish ecoregion (EcoRegion number 17 under WFD, Annex XI). In terms of rivers and lakes, the whole island of Ireland and proximate smaller islands are designated as a single ecoregion. Historical estimates of the lake population are reviewed, lake numbers in publicly available digital datasets are detailed and the balance of large versus small lakes is summarised. This summary of the Irish lake population provides an important context for contemporary water quality monitoring, the proportion of high conservation status lakes, detail for selection of lakes for future study and helps identify data gaps. Furthermore, without knowledge of our lake resources, valorisation estimates of their ecosystem services and natural capital would be incomplete.

Methods

Publicly available GIS datasets and attribute data for lakes were accessed on global, European and Ireland (north and south) geographical scales. Digital hydrographical datasets exist at various scales and data are either available under restrictive license agreements only or are of limited detail. Lake attribute data also varies between datasets.

Datasets

The Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004) combines data from the best available sources for lakes on a global scale and includes large lakes, reservoirs and smaller water bodies (www.worldwildlife.org/pages/global-lakes-and-wetlands-database). Level 1 (GLWD-1) comprised world lakes with an area ≥50 km² and reservoirs with a storage capacity ≥0.5 km³, and included extensive attribute data. Level

2 (GLWD-2) comprised permanent open water bodies (including lakes, reservoirs and rivers) with a surface area ≥0.1 km².

All European countries provided digital data sets containing drainage basins, rivers and lakes to the European Commission in 2004 in compliance with obligations under the WFD (Vogt *et al.*, 2007). These data informed the Joint Research Commission's River and Catchment Database for Europe (CCM Version 2.1), a pan-European database of river networks and catchments (http://ccm.jrc.ec.europa.eu). Lakes included in this dataset have surface areas ≥0.1 km2.

The Irish Environment Protection Agency (EPA) in conjunction with Ordnance Survey Ireland derived a Web enabled GIS system, which included a digital lake network based on the 1:50,000 scale maps. This data was downloaded from http://gis.epa.ie/Envision and included lakes with surface areas ≥0.0001 km2. The key publicly available lake data for Northern Ireland were available from the Department of the Environment, Northern Ireland at https://www.spatialni.gov.uk/geoportal/. Downloaded data included lakes with surface areas ≥0.1 km². Other datasets associated with Northern Ireland Environment Agency (NIEA), and the CEDaR Lake Survey were restricted access. A 1:50,000 scale water dataset which consists of points, lines and polygons associated with water bodies and systems for all of Northern Ireland was available from the Ordnance Survey Northern Ireland (OSNI) with a charge of 220 GBP in 2017.

QGIS Version 2.10, the free and open source GIS, was utilised to display the geo-referenced data for lakes. The data for the Irish ecoregion was extracted from the GLWD and CCM datasets. The attribute data for Irish lakes included in global, European and national digital datasets were assembled and summary statistics were calculated in Excel.

Results

Global Dataset

The global dataset GLWD incorporated a total of 360 lakes for the island of Ireland with surface areas greater than 0.1 km² (Figure 1). The distribution of lakes according to logarithmic surface area class intervals (>0.1 km², >1 km², >10 km² and >100 km²) is illustrated in Table 1. The majority of lakes (n=232) ranged between 0.1 km² and 1 km². Additional lake attribute data included perimeter length and latitude and longitude. The cumulative GLWD lake area for 360 lakes was 1,791.8 km² (or 2.1% of the land area) (Table 2), while lake perimeters ranged from 1.3 km (unnamed) to 179.6 km (Lower Lough Erne). The dataset contained seven large lakes with surface areas >50 km² incorporating additional attribute detail including lake name, altitude, catchment area, and mean inflow into lake in m³/s.
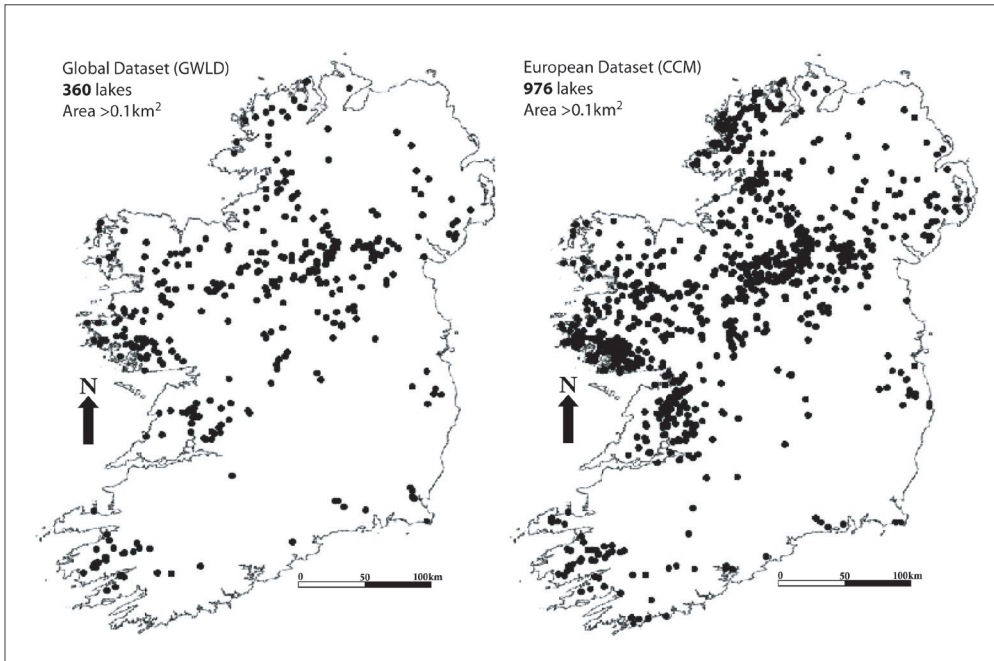
Figure 1: Lake with surface area >0.1 km² in the GLWD (global) and CCM (European) lake datasets

Lake size classes (>km²)	Global (GLWD) Irish Ecoregion	European (CCM) Irish Ecoregion (NI in brackets)	Republic of Ireland (RoI) (EPA)	Northern Ireland (NI) (DoE)
0.0001	–	–	3053	–
0.001	–	–	5399	–
0.01	–	–	2873	1
0.1	232	819 (101)	772	16
1	101	131 (7)	94	4
10	22	21 (2)	14	2
100	5	5 (2)	3	2
Total no. Lakes	**360**	**976 (112)**	**12,208**	**25**

Table 1: Comparison of lake numbers for Ireland using different publicly available datasets

European Dataset

The European CCM dataset includes a total of 976 lakes with surface areas greater than 0.1 km² for the Irish ecoregion (Figure 1; Table 1). The substantial difference between the Global and European datasets is related to the smaller lake size class (>0.1 km² and ≤1 km²), with the European dataset incorporating 819 lakes compared to just 232 for the GLWD dataset. The CCM dataset had an estimated cumulative lake surface area for the Irish ecoregion of 2,040.7 km² or 2.4% of the land area (Table 2). The CCM dataset incorporated attribute information including lake name, upstream area, shape length (perimeter) and altitude. Close to one third of the dataset (n=365) had associated lake names.

	Global (GWLD)	European (CCM)	Ireland (RoI EPA + NI DoE)
Number	360	976	995 (883 +112)
Area (km²)	1791.8	2040.7	1781.8 (1172.1 + 609.7)

Table 2: General characteristics for lakes >0.1 km² in the Irish ecoregion, using different digital datasets

Irish Datasets

The Irish EPA downloadable digital records for southern Irish lakes, encompasses 12,205 lakes with an area greater than 0.0001 km² (equivalent to 0.01 ha or 0.247 acres) (Table 1). The majority of these lakes are small with 93% of the lake population less than 0.1 km² in surface area. Very small lakes or ponds in the range of 0.0001-0.001 km² (100-1,000 m²) constitute a quarter of all lakes. The total cumulative lake surface area is 1,288.1 km² or 1.8 % of the RoI. Lake attribute data includes name, hydrometric area, class and shape length. 62% of the lakes (n=7,597) have been classified as lake, reservoir or pond, while 38% are unclassified (Figure 2). One third of the lakes (n=4,407) have associated names. Many lakes share the same name and the most frequently occurring names are Doo (n=64), Black (n=64), and Beg (n=48). According to the Irish dataset, 883 lakes have a surface area of greater than 0.1 km² which, when compared with the total of 976 European dataset, suggests that approximately 93 lakes with surface areas greater than 0.1 km² are in Northern Ireland. The geographical distribution sees the greatest number of lakes in northwest Mayo (EPA Hydrometric area No. 33) (n=1,923) and the Western River Basin District (n=5,655). The critical WFD reporting cut off for lake water quality monitoring is 50 ha or 0.5 km². Only 207 lakes in the RoI fulfil this criterion which constitutes just 0.017% of the total population of lakes >0.1 km².
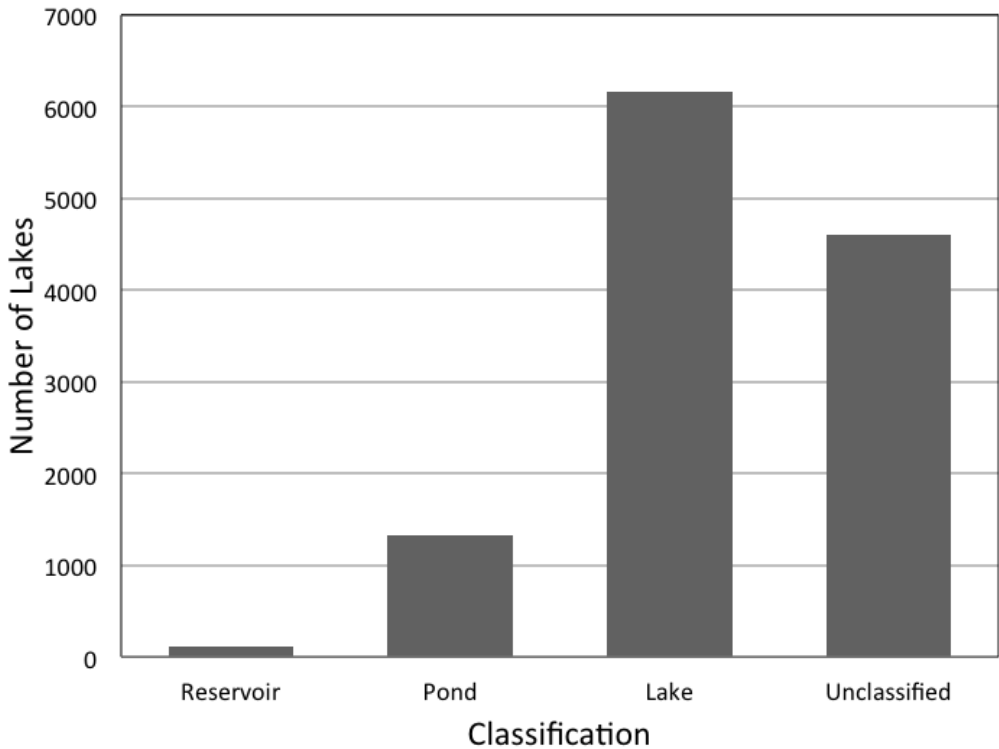
Figure 2: Number of lakes classified as reservoir, pond, lake, or unclassified in the Republic of Ireland (n=12,205). Source www.gis.epa.ie/Envision

The publicly available dataset from the Department of the Environment Northern Ireland contains just 25 lakes >0.1 km² as well as Cashel Lough Upper (0.06 km²) (Table 1). This compares with 36 lakes in the GLWD dataset and 112 lakes in the CCM dataset for Northern Ireland. This confirms that the European CCM Dataset is the most comprehensive publicly available dataset for Northern Irish lakes. The 112 CCM lakes included have surface areas greater than 0.18 km² and similar to the RoI, 90% of the lakes are <0.1 km² in surface area. Northern Ireland also contains the two largest lakes in Ireland and Britain, Lough Neagh and Lower Lough Erne.

A comparison of accuracy in surface area across the global, Europe and Ireland datasets for the seven largest lakes (>50 km²) on the island of Ireland (Neagh, Corrib, Derg, Erne Lower, Ree, Mask, Conn) revealed discrepancies across the three datasets (Table 3). If it is assumed that the local datasets are the most accurate, this suggests that greater surface areas are assigned by both the European and Global datasets for five of the seven lakes. The greatest deviations in area were found for Erne Lower and Ree. A comparison of three smaller lakes in each digital dataset is illustrated in Figure 3. The smallest lake, Ballyallia, Co. Clare, measures just 0.33 km² in the EPA dataset and is more than triple this surface area in the European CCM dataset. Ballyallia lake water fluctuates substantially between

winter and summer. The CCM dataset captures a more representative measure of high water levels while the EPA and GWLD boundaries encapsulate low waters. Lough Gur in Co. Limerick is more evenly represented across the three datasets (average area 0.83 km^2 – standard deviation 0.17 km). Lough Inchiquin in Co. Clare deviates in area and perimeter by almost 15% between datasets.
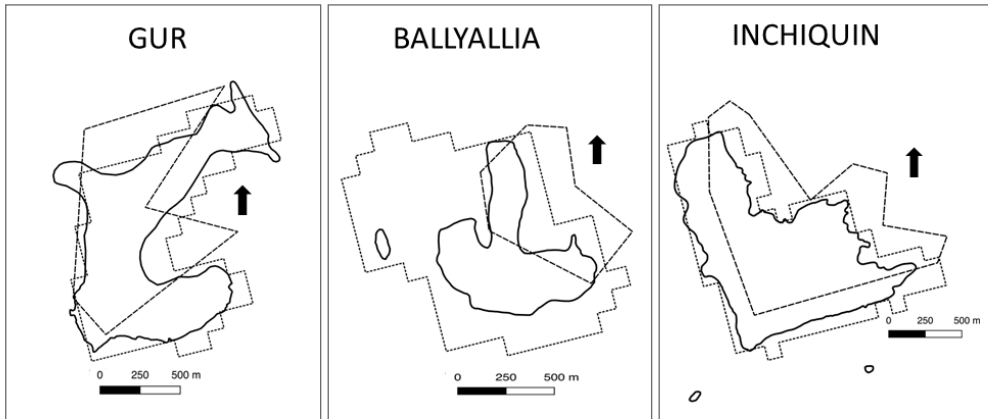
Area (km^2)			
	Gur	**Ballyallia**	**Inchiquin**
GWLD	0.7	0.4	1.2
CCM	1.02	1.09	1.44
EPA (RoI)	0.78	0.33	1.08
Perimeter (km)			
GWLD	4.5	2.5	5.4
CCM	6.39	5.2	7.19
EPA (RoI)	6.35	3.45	5.93

Figure 3: Lake boundaries for Gur, Ballyallia and Inchiquin lakes according to the in Global (GWLD – dashed line), European (CCM – dotted line) and Ireland (EPA – solid line) digital datasets as well as lake area (km^2) and perimeter (km) distance

Lake Name	km²		
	Global (GLWD)	European (CCM)	Ireland (⁺EPA, *DoE NI)
Neagh	380.3	386.49	*381.79
Corrib (Lough)	176.7	178.33	⁺166.31
Derg (Lough)	121.1	122.28	⁺120.06
Erne Lower	120.3	112.96	*103.84
Ree (Lough)	107.9	117.8	*103.54
Mask	87.0	85.75	⁺82.18
Conn	53.4	49.62	⁺57.28

Table 3: Comparison of the seven largest lakes (>50 km²) across datasets

Lakes in SACs

There are 498 SACs in the RoI. Of these, 226 SACs contain approximately 4,746 lakes or 38% of the total lake population. The majority of the lakes in SACs are found in counties Mayo (n=1,610) and Galway (n=1,329). The SACs with the largest number of surface water bodies are the Connemara Bog Complex SAC (49,218 ha) in Galway with 968 lakes and the Bellacorick Bog Complex SAC (9,523 ha) in Mayo with 534 lakes. In contrast, the Maigue River catchment in lowland Limerick is impoverished in terms of both lake features and also SACs with just three lakes (Gur, Bleach and Dromore) and six SACs.

Lake publications

A search of published material on Irish lakes in Web of Science, JStor and Science Direct revealed 428 publications in 130 Journals (the majority international) on lake ecosystems in Ireland between 1970 and 2016 (Figure 4). Lough Neagh features most prominently with over 40 international publications. The number of publications has increased each decade, with acceleration in numbers after the establishment of the EPA in 1993 and the implementation of the WFD in 2000. The maximum number of publications was 21 in 2007 at the juncture of National Development Plan funded research programmes ERTDI 2000-2006 and the first STRIVE programme 2007-2013. Most publications are individual lake studies containing primary data, while research topics concentrate for the most part on biological elements, including fish and to a lesser extent on physico-chemistry and lake sediment records (i.e. palaeolimnology).
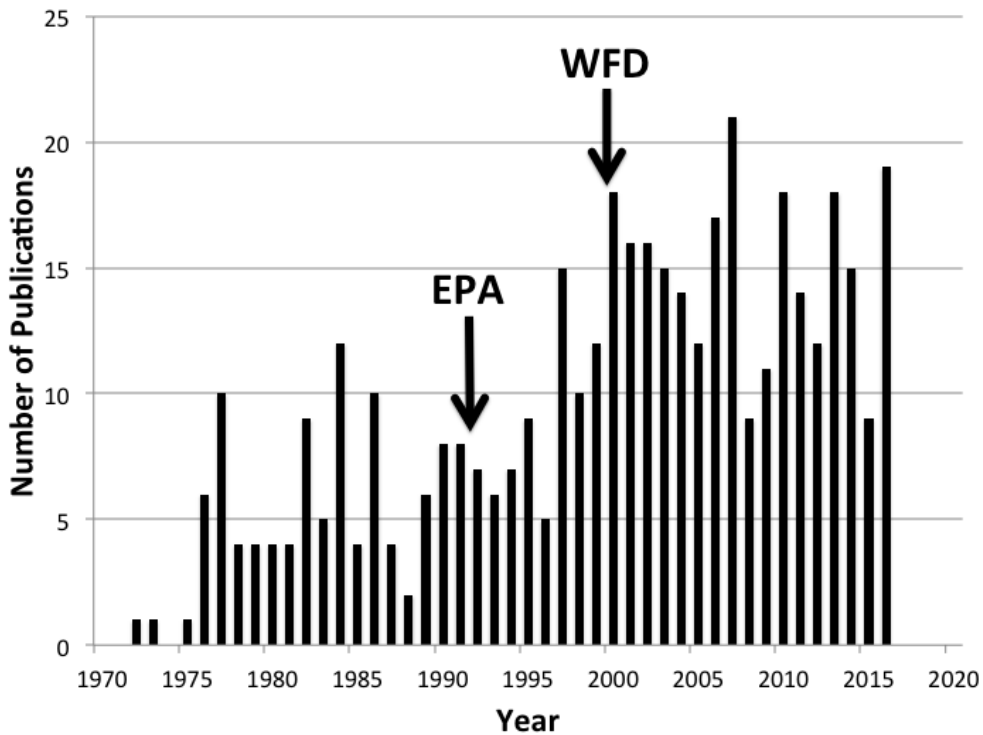
Figure 4: Journal publications on Irish lakes between 1970 and 2016 (total number 428).

Discussion

Digital Access and Accuracy

Calculation of the global freshwater lake resource has changed through time with the transition from paper to digital accounting. The increased assessment powers of remote sensing and GIS have resulted in more accurate quantification of the lake resource. This has meant that regional and local assessments are also potentially more accurate. This transition is illustrated in the Irish ecoregion where, as recently as 2000, no inventory of lakes, or classification of lake sizes, existed for the RoI (Aherne *et al.,* 2002). Prior to recent digital developments, Reynolds (1998) described some 4,000 lakes greater than five ha (0.05 km^2) in surface area for Ireland while Irvine *et al.* (2001) estimated a lake population of 5,000 of less than 50 ha (0.5 km^2). If we use the current EPA dataset, just 1,478 lakes have areas greater than five ha while some 11,950 have areas less than 50 ha, of which 9,500 are <2 ha (0.02 km^2).

Cumulative lake surface area calculations, using the range of datasets publicly available for the Irish ecoregion, illustrate major anomalies. The discrepancy between Global and European datasets likely reflects the number of lakes included, 360 and 976 lakes respectively, despite supposedly similar spatial resolution (lakes >0.1 km^2).

However, the picture becomes even more complex when the most comprehensive local EPA dataset from the RoI is combined with the most detailed dataset for Northern Ireland (CCM). These combined Irish ecoregion datasets give a cumulative lake surface area of 1,897.8 km², based on 12,317 lakes and ponds and yet falls far short of the combined surface area of 2,042.7 km² calculated using the CCM Irish ecoregion dataset with just 976 lakes. If only Irish ecoregion lakes greater than 0.1 km² are included, the shortfall is even greater with a cumulative surface area ranging from 1,781.8 km² (EPA and CCM) to 2,040.7 km². Additionally, cumulative lake perimeters range from 3,708.6 km (GLWD) to 6,594.0 km (CCM) (Table 2). While some perimeter and surface area differences can be attributed to the time of measurement (winter versus summer), the differences are anomalous.

Ireland and Northern Ireland share 11 cross-border river basins, which results in added complexity in terms of data access. Just 25 lakes are included in the publicly available local digital dataset for Northern Ireland (Department of the Environment) spanning a cumulative lake surface area of 570 km². The UK Lakes Portal (eip.ceh.ac.uk/apps/lakes) contains two additional lakes (Carn and Lattone) for Northern Ireland (Hughes *et al.,* 2004). This contrasts with a total of 112 lakes downloadable in the European CCM dataset with a cumulative surface area of 609.68 km². Moreover, a 1988-1991 survey of lakes using the 1:50,000 Ordnance Survey maps of Northern Ireland (Gibson *et al.,* 2002) determined a total of 1,670 water bodies totalling 622 km² or 4.4% of the land area. This full NI dataset is only available through purchase.

Lakes in Ireland north and south are predominantly small in surface area or size. Some 9,500 lakes in the RoI are less than two ha and are thus defined as small lakes or ponds (Biggs *et al.,* 2005). In contrast, just seven lakes exceed 50 km² in area (Neagh, Corrib, Derg, Erne Lower, Ree, Mask and Conn) and cumulatively constitute 1,028.81 km² or 54% of the total lake surface area in the Irish ecoregion (RoI and NI). 78% of the lakes are less than two ha (RoI only) and account for just 36 km² or just under 3% of the total lake area. However, small lake perimeters contribute 2,267 km or 23.5% of all lakes, confirming their enormous potential contribution to ecosystem services (Oertli *et al.,* 2002; Tranvik *et al.,* 2009). Small lake shorelines are dominated by edge-effects in contrast to large lakes which have less shoreline relative to their water surface area (Vander Zanden and Gratton, 2011). The lake edge or littoral environment is a critical habitat for many fish and invertebrates within lakes. However, it is also a zone of human interactions and is often highly modified for diverse human uses (Vadeboncoeur *et al.,* 2011). The potential concentration of species richness in the littoral zone emphasises the need to focus more research effort toward small lakes.

Some of the first bathymetric or lake basin contour maps of Irish lakes were published in the 1960s (Charlesworth, 1963). Depth soundings and Admiralty charts were utilised to produce maps of five lakes on the central plain: Erne, Ree, Derg, Corrib and Mask. Since then a range of lake bathymetric surveys have been undertaken as part of a variety of projects – Taylor *et al*. (2006) surveyed 26 lakes as part of the EPA INSIGHT project; 104 lakes were surveyed by Western Regional Fisheries Board personnel (WRFB, 2006);

lake bathymetries were mapped for 33 lakes as part a characterisation study of aquatic resources in two potential fracking case study areas (Moe *et al.,* 2016). In 2010, MERC Consultants, in association with Compass Informatics, conducted bathymetric surveys of over 180 lakes in Ireland on behalf of the EPA. The EPA currently has bathymetries for some 555 lakes. It would be very useful if the repository for this data was publicly accessible.

Lake Research Effort

The first efforts to gather coordinated information on water quality in the RoI only commenced in the late 1960s and 1970s with An Foras Forbartha, the Environmental Research Unit, Local Authorities and Inland Fisheries. These agencies, along with the Office of Public Works (OPW) who were responsible for river gauging, began monitoring water resource states. Up until this point, Irish freshwaters were considered relatively pristine as a result of low population density and non-intensive agriculture (Reynolds, 1998). The first national survey of lakes was undertaken in the mid-1970s (Flanagan and Toner, 1975) when 53 lakes were examined. A historical focus on stream and river management meant that information on lakes was not routinely collected. The monitoring of lakes, prior to the establishment of the EPA in 1993, was sporadic and often focused on those lakes for which there were perceived water quality problems, for example, Lough Gur in Co. Limerick (King and O'Grady, 1994) and Lough Leane in Co. Kerry (Twomey *et al.,* 2000). By 1998, some 1,380 river gauges, 4,200 river sampling points, and 200 lakes were being investigated. However, Irvine *et al.* (2001) noted that lake monitoring was much less extensive compared to river monitoring and there was no integrated strategy.

The 2001-2003 EPA water quality report includes information on 492 lakes but with data of variable sampling frequency and parameters measured (Toner *et al.,* 2005). The WFD lake monitoring programme commenced in 2007 with a more comprehensive assessment of a smaller number of lakes, with a focus on lakes >50 ha. Some data have been collected for a total of 812 lakes for EPA reports, but comprehensive monitoring is now only conducted on 216 lakes and nine reservoirs (EPA, 2017) which are considered representative of the national lake population. The ecological status of these lakes in 2013-15 was: High 25 (11.1%), Good 78 (34.7%), Moderate 75 (33.3%), Poor 28 (12.4%), and Bad 19 (8.4%). In an assessment by the EPA of pressures and the risk of water bodies not meeting the requirements of the Water Framework Directive, 822 lakes were evaluated and 18% were identified as being At Risk, 32% are currently Under Review, while 50% were deemed to be Not at Risk.

Many data gaps remain in relation to Irish lakes. While some of the limitations regarding lake types (including surface area) have been addressed, data on lake depths and volume are limited. There is poor site-specific monitoring information on remote upland lakes, while hydromorphology classification is still in its infancy and a large proportion of unmonitored lakes require review. Additionally, the exclusion of small lakes and ponds from statutory monitoring precludes potentially important freshwaters and vulnerable resources from assessment (Irvine, 2012). It is also telling that few Irish

lakes are included in international monitoring programmes. No Irish lakes are included in the International Long Term Ecological Research (ILTER) network, set up in 1993 to monitor environmental change impacts on ecological and socioeconomic systems. The World Lake Database http://wldb.ilec.or.jp/ contains just six Irish lakes (Loughs Neagh, Beg, Erne (Upper and Lower), Derg and Ree) while the Global Lake database (http://www.worldlakes.org/lakes.asp) includes 12 Irish lakes (Ballyallia, Beg, Corrib, Derg, Ennell, Erne (Upper and Lower), Gara, Neagh, Oughter, Owel, Ree). Six Irish lakes (Feeagh, Namanchree, Corbet, Kernan, Neagh, Erne) feature in the Global Lake Ecological Observatory Network (GLEON) (http://gleon.org/), while Neagh and Erne feature in the UKLEON (http://data.ecn.ac.uk/ukleon/). Lakes in Ireland fare little better in the GloboLakes database (http://www.globolakes.ac.uk/), which was set up to provide a basis for investigating the state of lakes and their response to climatic and other environmental drivers of change, using a combination of in-situ and remotely sensed data: of a total of 991 lakes in the database, three (Corrib, Melvin and Derg) are located in Ireland.

Natural Capital

The importance of lake ecosystem services and natural capital is increasingly being recognised (Ormerod, 2014; Guerry *et al.,* 2015). Many key processes scale with lake size (Håkanson, 2004; Winslow *et al.,* 2015), including carbon burial and biodiversity. Irish lakes, similar to their counterparts in Britain, are predominantly small but act as important wildlife refugia in the landscape, while river networks provide corridors for exchange of material, energy and species. The presences of these green networks are core to landscape limnology studies and they potentially act as important buffers to climate change. Early studies of Irish lakes noted that they were mostly natural compared to other parts of the world (Reynolds, 1998). However, there is increasing recognition of the importance of hydromorphological condition. Physical modification or damage to habitat and natural river/lake processes and functions are a significant pressure in water bodies at risk (DHPCLG, 2017). These characteristics are particularly important in terms of small lakes as they account for some 24% of the interface between lentic environments and terrestrial ecosystems. Most Irish lakes (68% in RoI) are located in non-protected areas and the achievement of sustainable water quality has been hampered by poor integration between environmental objectives (e.g. WFD) and agricultural targets (e.g. Food Harvest 2020 and Food Wise 2025) (DHPCLG, 2017). This highlights the need for more monitoring, conservation or restoration, and better agency integration to avoid further aquatic system degradation. Getting the balance right between use, protection and enhancement of lake natural capital firstly requires accurate information on the current extent and status of the aquatic resource. The need to quantify trends in a variety of different lake ecosystem elements or 'stocks' of genes, species, ecosystems and ecosystem products is vital for future generations to live sustainably. Recognition of lake ecosystem services and natural capital that benefit our resource-hungry species could potentially provide an important addition to more traditional conservation approaches.

Ireland is an excellent region to further explore the role and contribution of smaller waterbodies because it has large numbers of small, shallow lakes which are currently under researched.

Conclusion

Accurate enumeration of the lake water resource has enormous implications for the evaluation of the associated natural services provided by lakes. Lake inventories provide a basis for investigating the state of lakes and their response to climatic and other environmental drivers of change. A total of 13,875 lakes (12,205 in RoI, 1,670 lakes in NI) exist in the Irish ecoregion covering 6.2 % (1.8 % RoI, 4.4% NI) of the landscape. While the tools available to undertake estimations of the lentic resource have become more powerful in recent years, data accessibility and accuracy remains an issue. Enumeration and general classification of small lake types have been achieved. However, their exclusion from statutory monitoring precludes potentially important freshwaters and vulnerable resources from assessment, and thus highlights the need for more research on these sites. Despite important advancements in lake studies, valorisation of their overall contribution to natural capital is still potentially being underestimated.

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