Ecosystem services and water quality of turloughs, a form of intermittent karst wetland

Submitted to the University of Dublin, Trinity College
For the degree of
Doctor of Philosophy (PhD)

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June 2023

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SUMMARY

Ecosystem services (ES) can be defined as the conditions and processes through which natural ecosystems sustain and fulfil human life. These can be classified as provisioning, regulating, and cultural (water and raw material provision, flood risk attenuation, carbon sequestration, ecotourism). The quantification of ES can help analyse different scenarios linked to pressures on natural ecosystems (such as wetlands) like road drainage schemes, water supply and wastewater disposal. Turloughs, the focus of this study, are a kind of ephemeral lake/wetland which are present mostly in Ireland and show periodic inundation and lacustrine deposits. They are flooded for some periods across the year (typically in the winter) but usually dry up in summer months. Turloughs are protected under the Water Framework Directive (WFD, Directive 2000/60/EC) and the EU Habitats Directive (92/43/EEC). Their ES had never been quantified before.

The aim of this study was therefore to quantify the ES of turloughs and compare these to the literature on the ES of similar ecosystems.

Fifty-five turloughs were initially surveyed to assess their water quality and successively give an indication of their ES by applying the framework developed in this thesis. Seven turloughs (Blackrock, Lough Coy, Lough Aleenaun, Lough Gealain, Caranavoodaun, Skealoghan, Coolcam) were then selected from a previous study, to be representative of different hydrological regimes and a wide range of physico-chemical and chemical characteristics. They are located in the west of Ireland, in Counties Clare, Roscommon, Galway and Mayo. The majority of the fifty-five turloughs have mesotrophic waters (33), while 7 of them have oligotrophic waters, 11 have eutrophic waters and 4 hypertrophic. Water chemico-physical parameters (temperature, pH, dissolved oxygen, turbidity, and redox potential were measured in-situ, while others (alkalinity and colour), together with carbon and nutrient species (total phosphorus, soluble reactive phosphorus, total nitrogen, total oxidized nitrogen, dissolved inorganic carbon, dissolved organic carbon, colour) were determined by the appropriate laboratory methods. pH, carbon and nutrient species (total carbon and nitrogen, phosphorus and organic carbon) were also determined on soil samples taken from the turlough catchment during the dry phase. Greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) were determined using the closed chamber method during both the wet and dry phases of the turloughs. This study provides a quantification and valuation of the ES of turloughs, which had never been done before. The seven turloughs studied display a variety of hydrological characteristics, habitats, soils and vegetation and therefore ES of different quality and value; each ES was quantified using appropriate models. The most important ES for these turloughs are flood mitigation, habitat preservation and ecotourism. The calculated monetary values (from € 35,556 ha^{-1} yr^{-1} to € 122,150 ha^{-1} yr^{-1}) are in line with the literature on ES provision for similar habitats, but some of the turloughs show also significantly higher values. Though their ecohydrological condition has, in general, been assessed to be relatively stable compared to a previous study dating to about ten years ago, there are threats from anthropogenic activities and climate change that could cause a degradation of their habitats and the ES they provide. The monitoring of their waters to detect any nutrient enrichment is especially important for the oligotrophic ones, which have a high biodiversity value. There are opportunities to enhance ES values and thereby promote a better ecohydrological state for the rest of them, for example by lowering nutrient emissions in the zones of contribution of the turloughs. This could entail also the study of the socio-economical local situation, as turloughs are deeply integrated in the local socio-economical structure.

A framework has been proposed, which requires field data that can be integrated with literature data, depending on the availability and the level of depth of the studies. Indicators can be used when field data are not available. In particular, land cover, soil type, and vegetation cover are examples of parameters linked to the provision of ES and that can be acquired from existing literature or from remotely sensed images.

Due to the variability of several chemico-physical and chemical parameters, a single sample taken near the maximum flooded stage has been shown not to be representative of the whole variability during a hydrological year. Samples with at least a seasonal frequency should therefore be taken.

The study of further turloughs with the framework proposed in this thesis would help to have a more complete picture of the ES provided by these features which are almost unique to Ireland.

ACKNOWLEDGEMENTS

The last five years have been an amazing and intellectually stimulating adventure. Difficulties abounded in the field, laboratory and on the computer. The completion of this work would have not been possible then without the help and support of a number of people.

First of all, Laurence, my supervisor, who has been anything but supportive even in the most uncertain times, where it was not clear to me whether I should have completed the PhD. Though he left me free to choose how to develop the PhD he has always been there when help was needed, stimulating me to deepen my knowledge and go the extra mile.

A great thank you also goes to all the people in the Department who supported me in the field and in the lab. Pat, your help as a much more practical man in the field has been invaluable, together with sharing stories while sampling on a boat on top of those mystical places which are turloughs. Kevin, for introducing me to driving our van (which has been a faithful tool in the wild Irish west) to the streets of Dublin. Mark, who has improved my knowledge of chemistry, especially in its practical aspects. Mary, without whose practical sense and dedication to work I could not have (safely) completed those gas analyses. Eoin, who showed me how to professionally lead a soil lab and was never shy about giving help.

And last but not least my parents Enzo and Loredana, without whose material support I could not have gotten this far.

Per aspera ad astra,

Fabio Massimo Delle Grazie

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LIST OF ABBREVIATIONS

Name	Description
ALE	Lough Aleenaun turlough
AlluvMin	Mineral Alluvium soil
AlluvMRL	Marl alluvium soil
AlluvMRLPT	Marl with peaty soil
BLA	Blackrock turlough
BMinDP	Deep poorly drained mineral soil
BMinSP	Shallow poorly drained mineral soil
BMinSPPT	Shallow poorly drained mineral soils with peaty topsoil
BMinSW	Shallow well drained mineral soil
BMinVSP	Very shallow poorly drained mineral soil
BMinVSW	Very shallow well drained mineral soil
BOrgSW	Shallow well drained organic soil
BOrgVSP	Very shallow poorly drained organic soil
BOrgVSW	Very shallow well drained organic soil
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CARA	Caranavoodaun turlough
CH_4	Methane
CICES	Common International Classification for Ecosystem
CO_2	Carbon Dioxide
CO_{2eq}	Carbon Dioxide Equivalent
COOL	Coolcam turlough
COY	Lough Coy turlough
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
ER	Ecosystem Respiration
ES	Ecosystem Services
FenPT	Fen Peat soil
GEA	Lough Gealain turlough
GHG	Green House Gases
GPP	Gross Primary Production
GSI	Geological Service of Ireland
GWDTE	Groundwater Dependent Terrestrial Ecosystems
HEP	Habitat Evaluation Procedure
HGM	Hydro GeoMorphic Analysis
HSI	Habitat Suitability Index
ICP-MS	Inductively Coupled Plasma – Mass spectrometry
ICP-OES	Inductively Coupled Plasma – Optical E Spectroscopy

Lac	Lacustrine soil
MAES	Mapping of Ecosystem Services
MEA	Millennium Ecosystem Assessment
Mg	Magnesium
Mo	Molybdenum
N	Nitrogen
N_2O	Nitrous Oxide
Na	Sodium
NEE	Net Ecosystem Exchange
NHA	Natural Heritage Area
NPWS	National Parks and Wildlife Service
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PAR	Photosynthetically Active Radiation
PCA	Principal Component Analysis
PPFD	Photosynthetic Photon Flux Density
PtMRL	Peaty Marls soil
SAC	Special Area of Conservation
SEEA-EA	System of Environmental-Economic Accounting-
SKE	Skealoghan turlough
Sr	Strontium
SPA	Special Protection Area
SRP	Soluble Reactive Phosphorus
t	Metric tonne
TDS	Total Dissolved Solids
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
TN	Total Nitrogen
TON	Total Oxidized Nitrogen
TP	Total Phosphorus
UKNEA	UK National Ecosystem Assessment
WFD	Water Framework Directive
WTP	Willingness To Pay
Zn	Zinc
ZOC	Zone of Contribution

1 INTRODUCTION

1.1 Project Overview and motivation

Turloughs, the focus of this study, are intermittent wetlands that develop in karst rocks and are present mostly in Ireland. Hydrologically they show periodic inundation and lacustrine deposits (Naughton et al., 2012). Turloughs are flooded for some periods across the year (typically in the winter), but usually dry up in summer months (Figure 1.1). Turloughs are defined as Groundwater Dependent Terrestrial Ecosystems (GWDTE) and as such they are protected under the Water Framework Directive (WFD, Directive 2000/60/EC). As they host protected fauna and flora, they are also designated as a Priority Habitat in Annex 1 of the EU Habitats Directive (92/43/EEC) (Gill et al., 2013).

***Figure 1.1**. Blackrock turlough, County Galway, (one of the turloughs present in this study) in the a) drained and b) filled phases (Photos by Laurence Gill, modified).*

One of the methodological concepts that have come to prominence in recent years and can be used to quantify the importance of wetlands in general (and turloughs in particular for this project) is that of ecosystem services (ES). ES can be defined as “the conditions and processes through which natural ecosystems sustain and fulfil human life” (Daily, 1997). These can be classified as provisioning, regulating, and cultural (raw materials production, flood risk attenuation, carbon sequestration, ecotourism) (Millennium Ecosystem Assessment, 2005). In light of the pressures on turloughs associated with road drainage schemes, water supply and wastewater disposal, the determination and valuation of ES can be important, especially when trying to choose between different management and development options.

Studies on the ecology and ecohydrology of turloughs are very limited (see Section 2) and a quantification of the ES of turloughs does not appear to have been attempted before: therefore existing models and tools had to be adapted to the dynamic hydrologic nature of these wetlands.

In general, studies on the ES of wetlands vary in scale and detail, with ~50% being desk studies (Delle Grazie & Gill, 2022). Hence, the present study on the ES of turloughs, gathering field information on many different aspects, is much more comprehensive than a purely desk-based one.

The ES quantified here are flood risk reduction, water purification, carbon storage and sequestration, habitat preservation, recreation value.

1.2 Research aims and objectives

The main overarching aim of this project was to quantify and value the ES of turloughs, while also comparing the estimates to other types of wetlands.

The aim stated above was accomplished through the following specific research objectives:

1. Select existing tools or develop ad hoc models for the quantification and valuation of ES and quantify the ES of chosen turloughs using the developed methodology and collected data;
2. Derive indicators of ES from hydrological, hydrochemical, soil, and biodiversity characteristics, that can be used for sites with more limited available data;
3. Describe a framework for the quantification and valuation of turlough ES;
4. Compare the value of the ES of turloughs with other temperate wetlands and grasslands to establish how they fit in a wider context.

These objectives were achieved through the following activities:

- Review of the existing knowledge on wetland ES and more specifically intermittent karst wetlands;
- Selection of the most important ES for turloughs from literature findings to support the development of an assessment framework;
- Once-off water sampling of 55 turloughs to derive the main physico-chemical and chemical parameters;

- Field sampling and measurement of water, soil and greenhouse gases at 7 selected turloughs;
- Quantification of the stocks of carbon in the soils from soils samples taken at the turloughs and derivation of indicators relating to ES quantification;
- Modelling of the greenhouse gas emissions measured at the turloughs and derivation of indicators linked to the provision of ES.

1.3 Thesis organisation

- Chapter 2 contains a review of the literature on temperate wetlands ES, on turlough ecohydrology and on ES quantification and valuation.
- Chapter 3 describes the research methods utilised.
- Chapter 4 presents the results of fieldwork, divided in water, soil and greenhouse gas emissions determination.
- Chapter 5 quantifies the ES of the turloughs studied.
- Chapter 6 discusses the results of Chapters 4 and 5 in light of the literature on wetlands ES.
- Chapter 7 presents the conclusions of the research in terms of its main findings and recommendations for future research in this area.

2 LITERATURE REVIEW

This chapter presents an overview of wetlands, their ES and on the tools to quantify and value said services. It then focuses on intermittent karst wetlands and in particular on turloughs. The chapter formed the basis of a review article titled *"Review of the Ecosystem Services of Temperate Wetlands and Their Valuation Tools"* (Delle Grazie & Gill, 2022).

2.1 Definition and characteristics of wetlands

Although there is not a universal agreement on the definition of a "wetland", the Ramsar convention provided one that is commonly accepted and defines them as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tides does not exceed six metres*" (Ramsar Convention, 1971, Article 1.1; Matthews, 1993). The definition was then expanded to include *"… riparian and coastal zones adjacent to the wetlands and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands."* (Ramsar Convention, 2010). This definition will be applied in this thesis and it includes turloughs.

The Ramsar definition does not contain information on vegetation and soils, even though one of the defining characteristics of wetlands is the presence of soils that are saturated for most of the year and home of a range of aquatic plants. A definition of wetlands that includes this information is: "*a community of hydrophytes and hydric soils*" (Environment Protection Agency, 2018). Wetlands must also be recognised as transitional (both in space and time) ecosystems, or ecotones, between terrestrial and aquatic ecosystems (Mitsch and Gosselink, 2015).

The Cowardin system uses the landscape position of a wetland (riverine, lacustrine, palustrine, tidal, maritime), while the U.S. Corps of Engineers uses a system based on their hydrogeomorphic character with subcategories based on hydrological features (Cowardin, 1979). Some of the hydrogeochemical and hydrodynamic gradients affecting wetlands are shown in Figure 2.1.

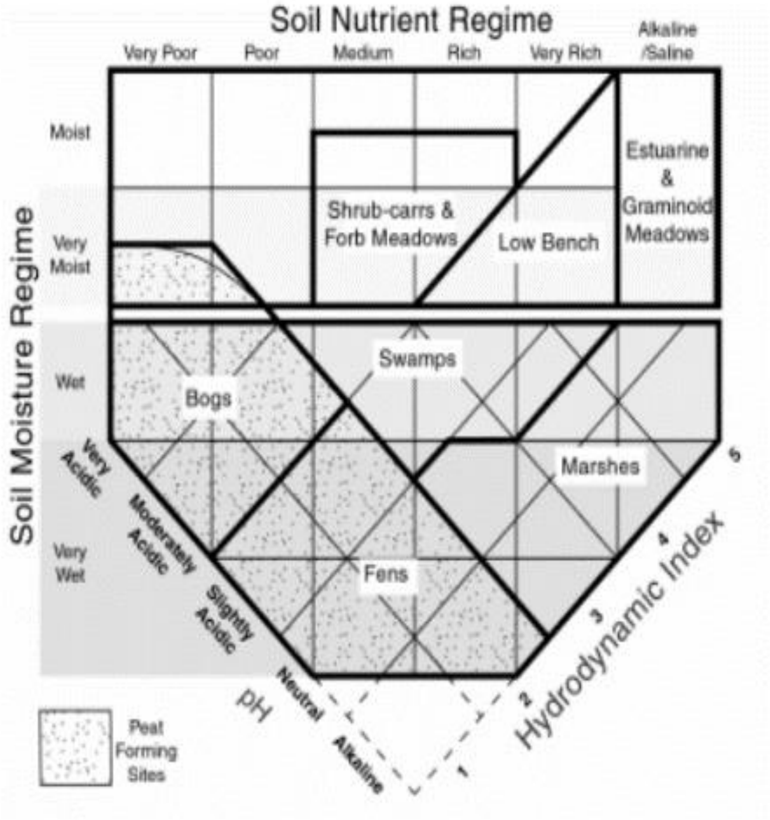


***Figure 2.1**. Major gradients affecting wetland ecosystems (MacKenzie & Banner, 2001).*

The Ramsar convention recognised 2,341 wetland sites in 170 countries worldwide, categorised into 42 types, divided into inland, coastal and man-made (www.ramsar.org).

The main classes of wetlands are swamps, fens, bogs, and marshes. Other distinctions are then drawn, such as tidal and non-tidal, coastal, inland, freshwater, brackish or salt, or according to their substrate type (rock bottom, unconsolidated, rocky shore, unconsolidated shore, streambed, reef. Cowardin, 1979).

The total area occupied by wetlands is still subject to debate and likely to be underestimated (Davidson & Findlayson, 2018). Recent estimates vary between about 12 x 10^6 and 17 x 10^6 km^2, with the lower value being probably the more accurate (Davidson & Findlayson, 2018). Being that tropical and subtropical wetlands reach an estimate of 4.7 x 10^6 km^2 and that Northern latitudes above 50°N contain 53% of the global wetland area (Aselmann and Crutzen, 1989), the extension of temperate wetlands (latitude between about 24° and 67° north and south) should be about 1 x 10^6 km^2, or around 8% of total.

The widest expanses of temperate wetland classes are bogs. The biggest in Europe is the Flow Country in Scotland, with 4,000 km^2. Another notable example is the Norfolk Broad with habitats ranging from the open water of shallow lakes to flooded reedbeds and from boggy marshes and fens to wet 'carr' woodland with willows and alders (www.plantlife.org.uk).

Blankespoor et al. (2014) estimated that with 1 m of sea level rise being predicted as a result of climate change, approximately 64% of the freshwater marsh, 72% of coastal wetlands, and 61% of brackish/saline wetlands in 86 developing countries are at risk. In light of these threats to wetlands, conservation efforts are being made worldwide and restoration is also underway for many different kinds of wetlands. One tool that can help with these efforts is the concept of ES.

Although covering only 6 to 8% of the global land space, wetlands account for a disproportionate amount of the total value of the ES of all biomes (possibly around 36% according to de Groot et al. (2012)). This testifies to the importance of these habitats, with valuations of their ES growing constantly worldwide (Delle Grazie & Gill, 2022). About half of global wetland areas have been lost and much of the remaining wetland areas are degraded (Zedler & Kercher, 2005). It is therefore crucial that we have accurate estimations of the value of wetlands, in order to be able to make a stronger case for their preservation.

2.2 Intermittent karst wetlands (turloughs/poljes)

Some wetlands are intermittent, due to the karst rocks on which they lie and which cause them to drain, at least partially, during spring/summer. Example of this are *polje* and turloughs.

Poljes are depressions in karst limestone which become flooded for some months of the year and are drained either by watercourses (open polje) or by swallow holes or ponors (openings where surface waters enter underground passages). They are present in many karst regions of the world and are common in the Dinaric Alps. An example and largest worldwide is Livanjsko *polje* in Bosnia. Water level fluctuation gives rise to disturbance to ecological succession, keeping these systems in an early productive stage of development defined as "pulse" or "water level fluctuation climax"(Dolinar et al., 2010). These fluctuations, together with number and extent of floods and changes in soil properties, give rise to specific vegetation patterns (Gaberščik et al., 2013, Dolinar, 2010). Several studies found that increases in temperature, solar radiation as well as intensity, timing and extent of floods, negatively affect primary production, life cycles of animals and mineralisation and decomposition (Dinka et al., 2008, Dolinar et al., 2010). Dolinar et al. (2010) investigating the Lake Cerknica polje in Slovenia, also found a gradual loss of seasonality of floods and droughts and an impact to primary productivity of common reed (*Phragmites australis*) due to changes in temperature and rain patterns. This can be important also for turloughs, in light of the ongoing changes brought by climate change.

Turloughs can be defined as "*a topographic depression in karst which is intermittently inundated on an annual basis, mainly from groundwater, and which has a substrate and/or ecological communities characteristic of wetlands*" (Tynan et al., 2007, in Waldren et al., 2015). They fill up mainly by rising groundwater levels (with some surface runoff) and empty from two different openings in karst rocks (a spring and a swallow hole, respectively), or from a single opening (called an estavelle). Turloughs occur mainly in Ireland, west of the River Shannon, where over 300 of them have been identified in Ireland (Geological Service of Ireland, (GSI), 2011) (Figure 2.2).

Figure 2.2. *Location of turloughs in the Republic of Ireland (www.epa.ie).*

They are ephemeral, meaning that they fill in winter and dry up in summer, therefore constituting unique features of the Irish landscape. They host both terrestrial and aquatic habitats, therefore they share traits with other wetlands, but also with terrestrial ecosystems like grasslands.

Hydrology is the primary driver of these unique ecosystems (Naughton et al., 2012), and so a rigorous understanding of the flooding regime is required in order to assess their conservation and future sustainability. Turloughs are hydrologically similar to polje for the period inundation and lacustrine deposits (Naughton et al., 2012)

Turloughs are also Groundwater Dependent Terrestrial Ecosystems (GWDTE) and as such they are protected under Directive 2000/60/EC (the Water Framework Directive, WFD) and since they host protected fauna and flora, they are also designated as a Priority Habitat in Annex 1 of the EU Habitats Directive (92/43/EEC) (Gill et al*.,* 2013).

This thesis follows on from a previous large-scale interdisciplinary research study titled, "Turloughs: hydrology, ecology and conservation" (Waldren, et al. 2015) which analysed 22 turlough bigger than 10 hectares, assessing their hydrology, water and soil quality, biodiversity, and conservation status. This research project was carried out at Trinity College Dublin in 2006-2015 and funded by the National Parks and Wildlife Service (NPWS) of the Department of the Environment.

Waldren et al. (2015) is therefore an important point of reference for this thesis and the turloughs investigated here were chosen from it. The data in Waldren et al. (2015) (together with other articles) that are relevant for this thesis were reviewed and analysed in this Section and the following ones.

2.2.1 Turlough geology and hydrology

Geologically, turloughs occur on Carboniferous limestone, a well-bedded, pure calcarenite, an example of it being the outcrops in the Burren (Coxon, 1987). Carboniferous limestone is the most common rock type in Ireland and it can be heavily karstified. Unlike the rest of Europe, many karst terrains in Ireland are lowland, with most of them lying under 100 m above sea level (Drew, 2008). Coxon (Coxon, 1987) surveyed 90 turloughs bigger than 10 hectares, though 30 were found to be drained.
Geological structures do not play a direct role in the location of turloughs, but rather an indirect one, via glacial excavation (Coxon, 1987). In County Clare the main

determinant of their occurrence is lithology (they are confined to areas of Burren Limestone outcrop), while in County Galway thickness of drift seems to play a more important role (they are absent where glacial drift is very thick or impermeable) (Coxon, 1987).

The different turloughs show a range of hydrological behaviours, from quickly discharging (i.e. flashy) shallow systems to ones which exhibit much longer duration flooding (Naughton et al., 2012). Such characteristics depends upon the topography of the basin, the quantity and characteristics of inflow and the outflow capacity. The hydrological characteristics of the different turloughs will be described in Section 4. Karst aquifers have three kinds of permeability: matrix (integranular), fracture (between mechanical joints), and conduit (through pipe-like openings) (www.gsi.ie). The flow is a mix of these three mechanisms and is variable spatially as well as temporally. The sources of recharge to the aquifer can be autogenic (within the karst aquifer) as well as allogenic (from outside the karst).

Two main models for the hydrology of turloughs have been proposed: the flow through and the surcharge tank (Gill, 2010). In the flow through model both inflow and outflow occur at the same time. Inflow can be from direct rainfall, surface runoff, epikarst (shallow groundwater) and deep conduits. In this model there is a constant flow of groundwater through the system and residence times are smaller than the other model. In the surcharge tank model the turlough acts as supplemental storage for groundwater. The turloughs described by the surcharge tank model, fill and empty either from two separate openings (a spring and a swallow hole), or from the same opening (called an estavelle). The relationships between turlough water and groundwater are regulated by their respective hydraulic heads. During filling periods there is no discharge from the turlough and during recessions turlough water is released back to the groundwater conduit.

In Waldren et al. (2015), three years of water level measurements and topographical data were integrated to compute variations in water levels, volumes, and surface area for 22 turloughs, as listed in Table 3.1. Two main models were developed to be able to predict water levels from precipitation and evapotranspiration data. The first one used linear regression to predict turlough volume from aggregated rainfall over a defined interval. The second one was a more refined reservoir model and was applied to a subset of the turloughs (Lough Gealain, Lough Aleenaun, Turloughmore, Lisduff, Ardkill, Coolcam, Croaghill, and Skealoghan). This approach conceptualised the turlough as a reservoir with the same physical characteristics as the turlough being modelled (stage-volume-area relationships), and where the hydrology of the turlough was controlled by the nature and functioning of the reservoir inflows and outflows. The objective of this modelling approach was to identify the characteristic equations governing the flow rates, and therefore the volume and stage, and to explain the relationship these hold with rainfall in order to accurately predict turlough hydrological regimes (Waldren et al., 2015). The models developed in Waldren et al. (2015) were used to obtain the water volumes in the 7 turloughs studied in depth in this thesis, and subsequently to calculate water nutrient masses, based on the water chemical analyses carried out (see Sections 3 and 4).

A lot of other research focussed on the hydrology of turloughs in the Gort lowlands, particularly in relation to the extensive areas of flooding that can occur in the winter time (Gill et al., 2013, McCormack et al., 2014, 2016). The hydrology of the linked network of turloughs in this area (Blackrock, Lough Coy, Coole-Garryland), was described and modelled using surcharge tanks (Gill, 2010); for example, evidence showed Lough Coy filling and emptying through a large estavelle. The Gort-Kinvarra system however, has a vast catchment area and very well developed conduit systems. Two of its turloughs also showed tidal influences. Evidence for the flow-through model was shown in Lough Aleenaun, where two different portions were simultaneously rising and sinking and in Lough Gealain, where a large spring was seen flowing in the north-east corner and above the high level water, therefore having no connection with the turlough stage. It was also shown to be highly likely that other turloughs are a combination of these two models. These models can then be used to derive ecohydrological models of the impacts of water level on plant and animal communities.

Ecohydrological indicators were developed to describe the hydrological characteristics that can influence biological communities (Waldren et al., 2015; Bhatnagar et al., 2021). Between them are flood duration, hydroperiod, flood frequency, wet/dry periods, areal reduction rate, flood velocity, and aggregation period. Hydroperiod uses a single variable to define the hydrological characteristics of a turlough. This can take the form of the duration of flooding before sampling, the longest continuous inundation in the period in which sampling took place, or the sum of the duration of single flooding events during a certain period. The choice of variables will depend on the application.

Flood frequency is the number of times that points above a certain elevation above turlough base have been inundated. Flooding is an event that disrupts terrestrial communities by changing conditions from dry to wet and aerobic to anaerobic. This change and the frequency with which it occurs determines species composition in turloughs. Species must be able to adapt quickly to frequent flooding events (Casanova et al., 2000). The season of occurrence is also important, as a flood in summer might have a higher impact than multiple floods in winter. This is also important for climate change considerations.

It is also important to consider the length of wet and dry periods, as well as the longest inundated and dry periods for vegetation relevé points. The areal reduction rate in m^2 day^{-1} gives an idea of the speed at which waters decrease between the time of maximum and minimum flooded area and may also have an impact on aquatic communities as waters recede. Finally, flood velocity can be calculated by dividing the distance between two sampling points by the time between samplings in order to define how fast the recession phase goes. The aggregation period is an indirect measure of flood duration and is basically a measure of how long water is retained in the system. A long aggregation period entails a long flood and recession periods (Waldren et al., 2015).

2.2.2 Turlough water quality

The nutrient parameters measured monthly in Waldren et al. (2015) can be found in Appendix A, Table A.1 and constitute a reference for this thesis. Total Oxidised Nitrogen (TON) and Soluble Reactive Phosphorus (SRP) are nutrients that can be easily utilised by algae and plants. Waldren et al. (2015) highlighted that most parameters are homogeneous among years, though there was some seasonal variation (Cunha Pereira et al., 2011). This thesis will provide further insight in inter annual changes and whether any significant changes took place.

The quality of waters in terms of nutrient status is mainly determined by total phosphorus (TP) and total nitrogen (TN) which measure the total nutrients potentially available for vegetation growth. Their ratio (TN/TP) gives an indication of the trophic state of the water body (oligotrophic, mesotrophic or eutrophic) (Waldren et al., 2015). Phosphorus was recognised as the limiting nutrient for algal growth, even though in situations of very low TN/TP nitrogen can become limiting (Phillips et al., 2008).

Water colour in turlough waters can be due to drainage of peat and is important ecologically because coloured waters have a lower potential for plant growth (Waldren et al., 2015).

Alkalinity is the measure of the ability of water to neutralise acids and is given by the sum of the bases in solution, expressed as ppm of $CaCO_3$ (Clesceri, 1969).

Chlorophyll α is photosynthetic pigment characteristic of green plants. Algae produce chlorophyll α, therefore this is a commonly used parameter to estimate algal biomass. Silicates are a fraction of silicon which is important for some algal groups like members of the class *Crysophyceae*, which includes diatoms.

The Gort lowland turloughs (Blackrock, Lough Coy, Caherglassan, Garryland and Lough Coole) were shown to be a peculiar group in several regards. First of all they receive surface water drainage from the Slieve Aughty mountains and therefore their waters have a deeper colour (due to drainage through peat) and a lower pH. They are also morphometrically the deepest and they are all connected hydraulically/hydrologically (Gill, 2010).

The spatial study of Caranavoodaun, Roo, Termon and Blackrock turloughs in Waldren et al. (2015), showed that most water quality parameters were spatially homogeneous throughout the area and depth of a turlough, except at the beginning and end of the flooding season for chlorophyll α near the shores. Chemical parameters were also homogeneous in the two years, with the exception of chlorophyll α in Blackrock in March and April 2008.

2.2.3 *Turlough soils*

Soils are an important medium through which nutrients are transported and sometimes immobilised and are therefore important for the plant communities present. They are also important providers of ES. The most frequent soil properties used in ES mapping studies are the soil organic carbon content, the available water capacity, the clay and silt contents (texture), the soil type, the soil depth and the bulk density (Greiner et al., 2017). Turloughs have inherently variable soils, therefore it is essential to have a clear picture of the different soils and their distribution. It is not clear, for example, whether nutrients in turloughs originate in the turlough basin (e.g. from grazing animals and farms) or they come from the groundwater which drains nutrients from elsewhere in the groundwater catchment, although some recent research has been carried out on the Gort lowland network of turlough in order to try to elucidate this (McCormack et al., 2016).

The soils of turloughs can be classified as hydric soils, defined as "soils that formed under conditions of saturation, flooding or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (Mitsch & Gosselink, 2015). They are generally poorly developed, shallow soils with simple profiles. They can also be classified according to the Irish Soil Survey as organic rendzinas and rendzina-like soils (loamy and sandy), which generally occur at the upper parts of these basins exceptionally exposed to flooding, grading to gleys (peaty and sandy), river silts and raw marl and peats.

Coxon (1986) identified five main soil groups related to duration and depth of inundation: marl (including marl and peat marl), peat (or peat and peat-marl), silt/clay, sand/silt or diamicton (poorly sorted deposits) and variable (a mixture of the previous groups). Turlough soils show a high variability both between and among them. Generally, organic soils can be associated with both mineral and alluvial soils, but mineral and organic soils are rarely found together.

Waldren et al. (2015) classified soils based on the EPA subsoil map and on the results of the soil sampling performed (6 sample points per turlough). In general, a distinction can be drawn between turloughs with predominantly mineral soils and turloughs with mainly organic soils. The soil classification carried out in Waldren et al. (2015)study can be found in Annex A.

Turloughs with high proportions of mineral soils include Blackrock, Carrowreagh, Garryland, Rathnalluleagh, Caherglassan, Lough Coy, Turloughmore and Coolcam. Turloughs with non-alluvial soil types have till subsoils and a short duration of flooding. They also show coloured water and are relatively deep; an example of this category is Blackrock. This turlough is also characteristic in having high proportions of well drained soils in higher elevations, while Caherglassan and Lough Coy have high proportions of mineral alluvium on the basin floor. Coolcam is unique in having a high proportion of alluvium mineral soil and a low amount of grazed areas, together with high extension of standing water and longer hydroperiod and recession (Waldren et al., 2015).

Turloughs with non-mineral soils show complex associations of organic and marly soils, generally associated with long hydroperiods and recessions, and have limited extents of till subsoils. Fen peat is the most widespread organic soil type. Ardkill, Ballindereen, Caranavoodaun, Croaghill, Kilglassan, Lisduff and Skealoghan and Lough Aleenaun are characterised by organic soils. Ardkill and Ballindereen have high amounts of very shallow poorly drained soils while Caranavoodaun, Croaghill, Kilglassan, Lisduff and Skealoghan are characterised by fen peats. Lough Aleenaun is the only one with a high proportion of peaty marls and a relatively short hydroperiod and recession. These turloughs also have a higher amount of marls and lacustrine subsoils. Turloughs with organic soils are less grazed, especially the ones with marly sediments. An example is Lough Gealain which is ungrazed, while Termon, Tullynafrankagh and Knockaunroe have 20% grazed surface (Waldren et al., 2015).

Waldren et al. (2015) found that flooding, land use, vegetation, $CaCO_3$, pH and inorganic fraction were significantly interrelated. It also found that climate change might influence the amount of $CaCO_3$ in turlough soils, which in turn may influence phosphorus availability and vegetation community composition. The lower saturated zones were found to have higher levels of total P and total N, which could be due to nutrient drainage to the lower zones or to anaerobic processes. Turlough soils with relatively high inorganic P fractions did not seem to release significant amounts of soluble reactive phosphorus to the water column, though particulate phosphorus contributions from relatively phosphorus-enriched soils can potentially influence floodwater total phosphorus concentrations. Soil nitrogen and phosphorus dynamics, nitrification and mineralisation rates, and phosphorus retention capacities of turloughs soils still are subjects to be investigated. Finally, Waldren et al. (2015) suggested that a study of turlough trophic state should include the analysis of spatial and temporal nutrient variation (though a challenging task), soil humidity and redox potential, and information on the biological community composition data, as nutrient enrichment in soils can potentially influence floodwater concentrations.

Visser et al. (2006) propose a classification of turloughs based on a dry-wet continuum which is able to explain differences in soil and water nutrients. This classification is based on combinations of hydrology, geomorphology and elements of ecology. Wet turloughs are associated with shallow epikarst groundwater flow, nutrient-poor floodwaters and long hydroperiods (e.g. Lough Gealain). Dry turloughs on the contrary, have deep conduit groundwater flow, less alkaline floodwaters and relatively shorter hydroperiods (e.g. Blackrock).

Grazing pressure on turloughs, though extensive, has been reported as generally low therefore grazing should not represent a significant threat for turlough conservation. The kind of soil though affects grazing pressure, with mineral soils being under a higher grazing pressure.

Turloughs show a mixture of grassland and wetland communities, often surrounded by scrub and woods, with a great variation between each other. Grasslands are the dominant plant community in Ireland and have been found to sequester 0.5 t C ha^{-1} year^{-1}, while cropland is a net C source. Intact peatlands are carbon sinks while degraded ones are a strong carbon source. (Creamer & O'Sullivan, 2018).

The potential of grasslands as a sink for carbon is enormous in Europe. The EU (28 countries) currently has a permanent grassland area of about 60 million ha (d'Andrimont et al., 2020). Their correct management can therefore maximise carbon sequestration and therefore help with climate regulation.

Another factor of error in calculating carbon stocks is grazing by animals. While cows and sheep take away carbon in the form of grass, they partially return it to soil in the form of manure. Part of the carbon is lost from the system in the form of milk, meat and methane. McSherry and Ritchie (2013) carried out a review on the effects of grazing on soil carbon in grasslands. They showed that different studies found both strong positive and negative grazing effects on soil organic carbon (SOC), that could only poorly be explained and are highly context-specific.

2.2.4 Turlough biodiversity

Waldren et al. (2015) identified 28 different habitats in the turloughs, which range from grassland to semi-terrestrial, reed beds, fen wetland and open water. From a habitat point of view, turloughs can be distinguished in sedge- or grass and forb-dominated. The former group is dominated by *Carex panicaea* (Class *Scheuchzerio-Caricetea fuscae*), while the latter is characterised by a *Potentilla anserina* sward (Class *Plantaginetea majoris*) (O'Connell et al., 1984). The habitats are strongly linked to the fluctuation of water levels therefore historically they have been impacted by artificial drainage, damming and peat extraction. Similar to poljes, alterations of rainfall patterns and temperatures due to climate change, could have a significant impact on them.

Turlough habitats are very dynamic. Since water levels can vary in a matter of hours, vegetation has to adapt to such changing conditions if it is to survive. Hydrology therefore has a strong impact on biodiversity and determines plant species distribution and composition of plant communities (Casanova & Brock, 2000).

Turloughs have also been defined as temporal ecotones, meaning that they are a transition zone where two or more ecological communities transition in space and time (Kark, 2013). They contain priority habitats protected under the WFD. They host a variety of wet grassland and fen type vegetation. Due to their shallow waters, some of them are important sites for internationally significant winter wildfowl as well as a variety of water life, due to the normal absence of fish. This richness depends on the different hydrogeomorphological settings, as well as from the variety of grazing regimes. The main threat in the past has been drainage, but nutrient enrichment and the cessation of agriculture are new threats (Skeffington et al., 2006).

Twenty-eight plant communities were identified in the Waldren et al. (2015) study which can be seen in Appendix A, Table A.3. Some of them are of conservation importance (Appendix A, Table A.4). Beside frequency and duration of flooding another important factor for species distribution seems to be the total phosphorus (TP) concentration in the water column. As several species and communities show a strong link with flooding frequency and TP, these could work as ecological indicators. Examples of these can be found in Appendix A, Table A.5. Based on this concept, an index of ecological status based on the presence was developed during the Waldren et al. (2015) study which seems to be more robust than previous indicators which had been based on Ellenberg fertility values.

Several plants and communities are of conservation importance and some of the turloughs in the Waldren et al. (2015) study have been suggested as being of international importance. These are Lough Gealain (a very highly oligotrophic system with an important range of vegetation communites, which shows very low human impact), Knockaunroe (an oligotrophic turlough with a very wide range of typical turlough plant communities and several rare species) and Caranavoodaun, Roo West, Lisduff (which all contain communites and species typical of oligotrophic communities). Only two species of moss, *Cinclidotus fontinaloides* and *Cinclidotus antipyretica* are the only two plant species listed by the Habitat Directive manual as chracteristic of turlough though other species are nationally rare and require further study (Sheehy Skeffington et al., 2006).

Macroinvertebrates are also present in turloughs and their communities are highly distinctive. Season and water phosphorus levels have an important effect on communities. Hydroperiod and rate of areal reduction also affect them (Porst et al., 2012). Overall, the conservation of their ‘naturalness’ is crucial for invertebrate communities, especially low nutrient status.

2.2.5 Conceptual model of turlough ecological functioning

Flood duration, phosphorus concentration and grazing pressure were identified in Waldren et al. (2015) as the most important factors controlling the ecology of turloughs. Limited evidence in the study suggested that the drainage of phosphorus from soils to waters was not significant. Nonetheless, phosphorus levels exert an important influence on community assemblages. A conceptual model of turlough functioning can be found in Figure 2.3 (Waldren et al., 2015).

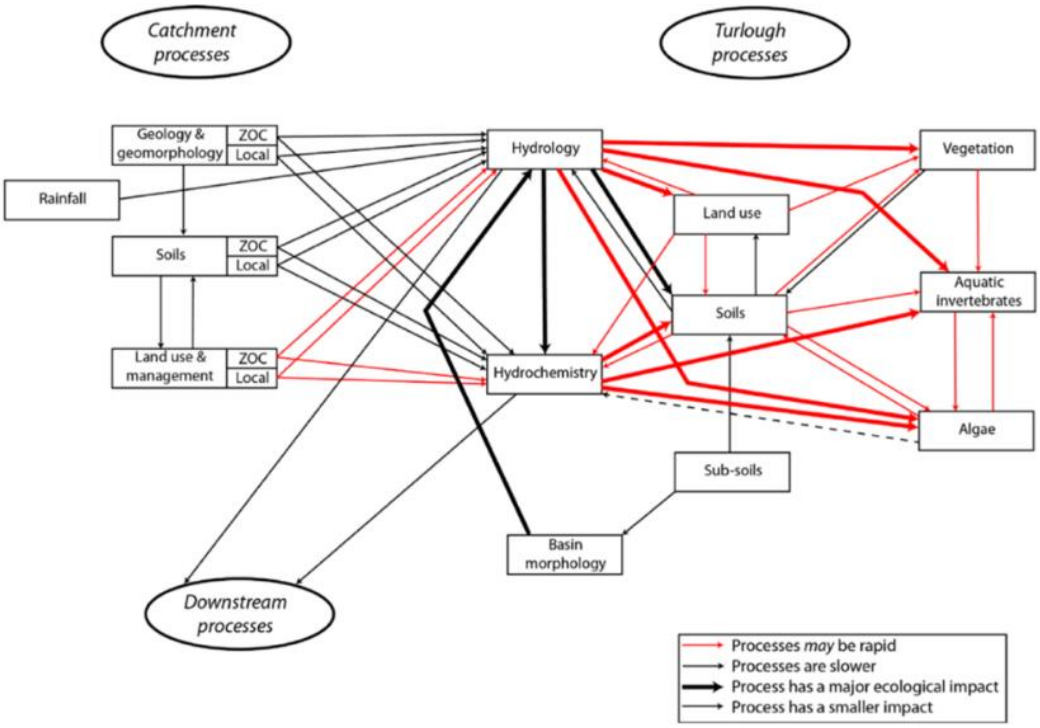


***Figure 2.3**. Conceptual model of turlough functioning (Waldren et al., 2015).*

2.3 Ecosystem service concept

ES were originally defined as the conditions and processes through which natural ecosystems sustain and fulfil human life (Daily, 1997) and were classified as provisioning, regulating, and cultural (raw materials production, flood risk attenuation, carbon sequestration, ecotourism) (Millennium Ecosystem Assessment, 2005)

The concept of ES originates from economic studies in the late 1970's which have become more mainstream with increasing interest in methods of quantifying their economic benefit (Gómez-Baggethun et al., 2010, Costanza et al., 1997). A common definition of ES as "the benefits that people obtain from ecosystems" has been provided by the Millennium Ecosystem Assessment (MEA, 2005), which offers the four categories of provisioning, regulating, supporting, and cultural ES. Another definition describes ES as the functions of ecosystems that provide benefits to people (Mace et al., 2012). A unifying classification system has been brought forward with the Common International Classification for Ecosystem Services (CICES), defined here as the contributions that ecosystems make to human well-being (Haines-Young & Potschin, 2013). This builds on the approach of the MEA, but with the difference that in the CICES classification supporting services are classed as intermediate services. The CICES classification uses three main categories with some sub-categories: provisioning, regulating and cultural ES. This classification is based on the cascade model which proceeds from the biophysical structures and functions of ecosystems, to produce the final services, which in turn generate goods and benefits, as shown in Figure 2.4.

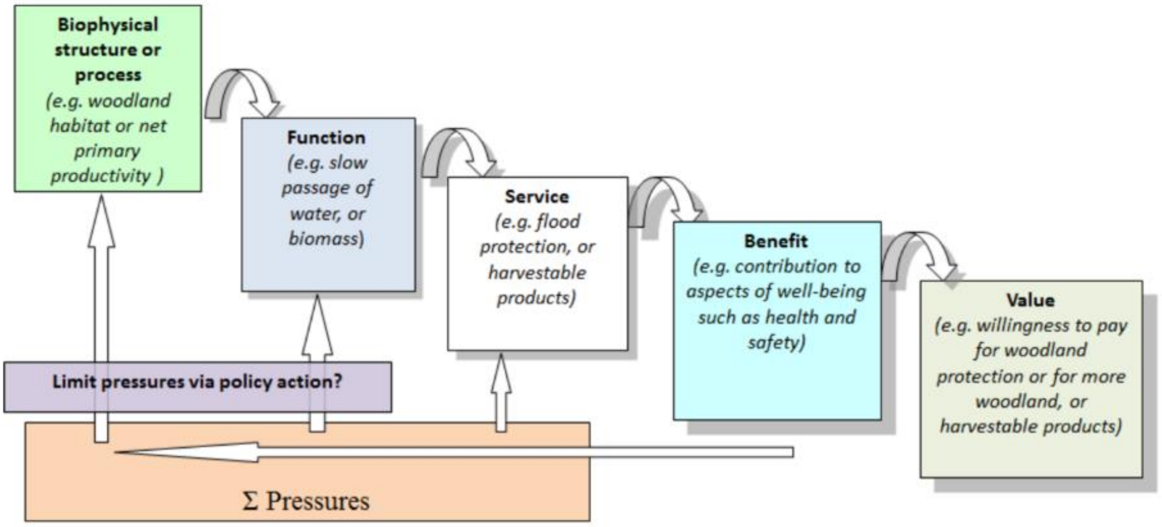


Figure 2.4. *The CICES cascade framework (CICES, Haines-Young and Potschin, 2013).*

The concept of ES has come under scrutiny and critique because of it being seen as anthropocentric in nature, promoting further exploitation of nature and undermining conservation efforts. It has been counter-argued that the concept of ES includes non-monetary and intrinsic values, which can help to reconnect humans with nature and it overlaps with the biodiversity concept (Schröter et al., 2014). Notwithstanding this debate, it is undeniable that the ES framework is being applied more and more in research as well as becoming mainstream in policy and planning; it provides increased awareness, communication, and participation, as well as spatially referenced knowledge. The ES concept can help compare different management and policy options and choose the one with the least impact or that which promotes the highest level of ES (Russi et al., 2012). Equally, it can be used to raise awareness about relative changes over a certain time frame (Reynaud et al., 2015).

The Economics of Ecosystems and Biodiversity (TEEB 2013, Russi et al., 2012) and the UK National Ecosystem Assessment (UKNEA 2011) both highlighted the danger of loss of ES, including for wetlands and peatlands in particular (van der Wal et al., 2011). The

Mapping of Ecosystems and their services (MAES) is also central to the European Biodiversity Strategy 2020 (Burkhard et al., 2018). Among the ES frequently associated with wetlands are water supply and purification, flood and erosion control, carbon storage and sequestration, and habitat preservation (Millennium Ecosystem Assessment, 2005, Barbier, 2011).

2.4 Key ecosystem services of wetlands

2.4.1 Provisioning services

2.4.1.1 Provision of biomass as food and for other uses

Almost all the freshwater species of fish and shellfish are dependent on wetlands during their life cycle, often spawning in in marshes around lakes or in riparian forests during floods. Many sea species spawn offshore, but they may migrate to coastal marshes during their juvenile stages (Mitsch & Gosselink, 2015).

Wetlands have always contributed to the sustenance of mankind, providing fish that sustains a billion people worldwide today and rice as a staple food for more than half of world's population (International Rice Research Institute, 2013). In 2016 inland aquaculture provided 51.4 million tonnes of fish or 64% of total food fish production while coastal aquaculture and mariculture provided 28.7 million tonnes (FAO 2018). Among the most farmed finfish are carp like the grass carp (*Ctenopharyngodon idellus*) and Nile tilapia (*Oreochromis niloticus*). Tilapia, cultivated in small ponds around the world, is particularly suited to fish farming and produces a good amount of meat in a relatively short period of time, therefore is an important solution to food insecurity and source of income in various low-income countries (Potschin et al., 2016). Fish is also important for recreational activities and often conflict arises with commercial activities (Mitsch & Gosselink, 2015).

Molluscs are the next category of aquatic animals most farmed, with a total global production of 17.1 million tonnes, concentrated in coastal and marine aquaculture with ponds on or near the coast (constructed wetlands) being the norm. In fact, one of the most traditional types of aquaculture for centuries has been that of prawns in coastal brackish-water fish ponds in several countries of South East Asia.

Among the most farmed molluscs are bivalves like Cupped oysters nei, *Crassostrea spp.*

and Japanese carpet shell, *Ruditapes philippinarum* amounting to 53% of the total farmed. Crustaceans are the next most farmed, with a prevalence of ponds on or near the coast compared to inland aquaculture. One of the most farmed crustaceans is shrimp and among them Whiteleg shrimp (*Penaeus vannamei*), with nearly 75 to 85% of the production in Asia/Pacific and Latin America and a clearly growing trend in total crustaceans production (FAO, 2018).

Algae are also an important product which is partly harvested from the wild or grown in open waters and provide a big input to economies worldwide. The most important species are *gusô* (*Eucheuma* spp.) used for the production of carrageenan and as food in southeast Asia and Japanese kelp (*Laminaria japonica*) widely eaten in East Asia and most found in shallow waters. *Ascophyllum nodosum* is also harvested in Norway and Iceland and is a brown seaweed closely related to *Fucus* and used for the production of alginic acid, as high-quality animal meal and as fertilizer (www.seaweed.ie). The two other important species harvested in Ireland are *mäerl* (*Phymatolithon calcareum* and *Lithothamnion corallioides*) for agricultural, horticultural, food, and cosmetics uses and kelp (*Laminaria* spp.) (Werner & Kraan, 2004).

Wood is an important raw material sourced from wetlands. Wood as fuel charcoal from wetland trees is used in countries like Panama and Nicaragua, where mangrove trees provide 7400 m^3 of charcoal and 400 tonnes of bark for tanning in the former while in the latter 80% of households use wood for cooking (Lacerda, 1993).

Peat is also an organic material sourced from wetlands and used for energy generation or as planth growing medium, however its use is not sustainable, given the slow rate of peat accretion.

2.4.1.2 Provision of water

The provision of water for different uses comes from the function of wetlands of recharging aquifers and also contributing to surface water flows. Some of the benefits are direct, like provision of domestic and irrigation water or indirect, like the maintenance of groundwater levels. There are also non-use values like the maintenance of water supply for future generations. Other benefits are the prevention of land subsidence and saline water intrusion near coastal areas.

The provision of water is also recognised as one of the most important ES of wetlands by the MEA (MEA, 2005). Throughout history people have relied on wetlands for water provision. It is likely for example that the first Homo sapiens in Africa relied on wetlands (Kingdon, 1993), for example oasis in deserts. Wetlands provide storage of surface and/or groundwater and also help by improving water quality. Since they occur in a range of hydrological, geological and topographical settings though, their role in water supply is not simple (Maltby & Barker, 2009). Evapotranspiration from wetlands, for example, can significantly deplete downstream water resources, especially in the tropics (Maltby & Barker, 2009). An example is the Okavango swamp, where the downstream flow from the wetland is just 3% of net flows entering upstream (Scudder et al. 1993). In some situations, where there is an open water surface, evaporation is not constrained by the amount of water present, unless the water table is very shallow. The role of plants must also be considered. Some studies have found of the effect of wind turbulence on vegetation increases the amount of water that would otherwise evaporate without any vegetation present (Gavin & Agnew, 2000). Water from wetlands is also important for both wild fauna and livestock (e.g. cattle) sustenance, especially in tropical regions. In Bangladesh, for example, cattle during dry seasons use water in perennially inundated areas called *beels*.

2.4.2 Regulating services

2.4.2.1 Flood attenuation/prevention

Though flood prevention has been determined as the ES with highest monetary value by de Groot et al. (2012), the actual flood attenuation/prevention of the different kinds of wetlands is not univocal and flood attenuation estimates should be made on a case-by -case basis. Bullock & Acreman (2003) also state that the same wetland type might both reduce and enhance flood risk in different environmental settings or at different times of the year.

Flood attenuation might be due more to the resistance to water movement linked to vegetation cover (Woltemade and Potter, 1994) than to the actual storage of water in the wetland. For example, Grayson et al. (2010) found that re-vegetated wetlands provide a slowing of surface runoff and a reduction in flood peaks at catchment scale. Clear cases of flood risk reduction come from coastal wetlands with salt marshes and mangroves acting like giant storm buffers (Barbier et al. 2019, Mitsch & Gosselink, 2015).

In general, wetlands that are in the lower part of any catchment tend to provide flood risk reduction, while the flood attenuation performance of wetlands in other areas tends to be more complicated to quantify (Bullock & Acreman, 2003). That is the case for example, of riverine wetlands lower in the catchment (with e.g. fifth-order streams) as opposed to wetlands further up in the catchment (Ogawa & Male, 1986). Other important factors are the size of the wetlands, the severity of the flood, the encroachment on wetlands and the lack of upstream storage areas (Ogawa & Male, 1983).

A hazard is defined as a source of potential harm, a situation with the potential to cause damage or a threat/condition with the potential to create loss of lives or to initiate a failure to the natural, modified or human systems (Tsakiris, 2007b).

Groundwater flooding is a significant source of flood risk in the west of Ireland, where prolonged flooding can occur from turloughs (Irish Government, 2019). The winters of 2009 and 2015/2016 were the worst for flooding in recent years. In the Gort lowlands several properties and services were impacted. For example, in the Skeanagh area close to Blackrock turlough, seven properties were impacted by the floodings in 2009 (Naughton et al., 2017). The transportation network in the Gort lowlands area was also affected, with 13.2 km of roads were flooded, with over 100 households with restricted or prevented access.

In general wetlands can both alleviate and exacerbate flood risk, depending on different factors, like position in the catchment and time of the year. Excess floodwater in winter is temporarily stored within turloughs, which provide attenuation of the more variable river and rainfall inputs (Naughton et al., 2017).

The flood attenuation of wetlands which are not in the lower parts of a catchment may be complicated to calculate (Bullock & Acreman, 2003). This is particularly true for turloughs, which show a great diversity of hydrological functioning and positions along the flood basin. Factors that can be considered when assessing this ecosystem service are the turlough position, basin volume, vegetation, encroachment of the basin

(Vegetation that can slow the flow of water), past flooding events and upstream storage areas. The hydrological regime of the turlough is also important, as the ones with the more flashy responses will in general pose a bigger threat (i.e. Blackrock and Lough Aleenaun).

Climate change is expected to exacerbate flooding and make it more frequent, therefore threatening the delicate ecosystem equilibria. Plant species would also be forced to start their vegetative period later therefore having a reduced effect on the rising of flood waters (Morrissey et al., 2020).

Hedges, dry stone walls and areas of long grass and vegetation also work to slow the flow of water down the hill. Therefore, controlling grazing by animals and ensuring an appropriate vegetation cover can also aid in slowing down flood waters.

2.4.2.2 Erosion and sediment retention

Wetlands can trap sediment thereby reducing damage to habitats by reducing turbidity of waters thereby benefitting aquatic ecosystems both within the wetland as well as downstream. This is testified by the creation of artificial ponds for the purpose of retention of sediments (with the associated nutrients). Sedimentation in fact, has adverse impacts on flood risk (by reducing channel capacities), diffusion pollution (due to the nutrients associated with sediments) and biomass production and biodiversity, thereby linking this service to habitat protection (Robotham et al., 2021).

Siltation of water supply infrastructure is also reduced. This is due to the ability of wetlands of reducing water velocity, with factors being the slope of the wetland, the roughness and holding capacity (Turpie, 2010).

It has been estimated that small wetlands along streams retain one third of the sediments entering from the streams, roughly 160 t/km for gullied agricultural catchments of 0.08–9.8 km^2 in area (Zierholz et al. 2001) and help prevent erosion for gullied catchments up to 300 km^2.

Some wetlands, like mires, have antagonistic effects on erosion. For example, bogs, on one hand prevent substrate erosion when they are undrained, but on the other can generate surface erosion, peat slides and bog bursts if artificially drained (Bragg, 2002).

2.4.2.3 Global climate regulation

This ES is performed by the influence that ecosystems have on the concentration of greenhouse gases (GHG) on the temperature of the atmosphere, in particular by fixing CO_2 in plant tissues and soil organic matter and by the emission of CH_4 and N_2O by soils (which can be considered a disservice). Wetlands are in fact significant emitters of methane and are estimated to account for around 20 to 25% of current global anthropic emissions (Mitsch et al., 2015). However, overall wetlands act as net C sinks and even newly created wetlands become net carbon and radiative sinks within 300 years of establishment (Mitsch et al., 2013).

Similarly, lakes and impoundments are significant emitters of GHG. It has been found that lakes and impoundments amount to about 20% of global fossil fuel CO_2 emissions (Le Quere et al., 2018). The emission rates of the different GHG have been found to vary with lake size and productivity, though the effect is different. CO_2 has an inverse relationship to lake size, while CH_4 emissions are directly related to productivity. CH_4 emissions may be of disproportionate importance due to lake productivity and the high global warming potential of this gas. Chlorophyll α and TP were also found to explain CO_2emission rates. N_2O emission rates also have a positive relationship with lake size and chlorophyll α. The relative importance of the difference gases was found to be 73% for CH_4 emissions, 22% for CO_2 ones and 5% for N_2O ones (Del Sontro et al., 2018).

Although covering only about 5-8% of land's surface, wetlands store up to a third of the total 2,500 Pg of soil carbon and almost as much as all the terrestrial vegetation (Maltby & Barker, 2009). Wetlands have been accumulating carbon for hundreds of thousands of years, with a peak around 12 to 7 thousand years ago (Smith et al., 2004), with most continuing to do so today. The wetlands with highest C sequestration rates are in the tropic, but they are followed by wetlands in temperate and boreal climates (Villa & Bernal, 2018).

Current anthropogenic carbon emissions from wetlands are about 11 Pg C yr^{-1} (Zou et al., 2022) compared to an overall global sequestration of about 830 Tg C yr^{-1}, with an average of 118 g-C m^{-2} yr^{-1} (Mitsch et al., 2013), mostly in tropical and subtropical wetlands. Wetlands are thus an important global carbon sink.

Rates of carbon sequestration vary according to wetland type and local climate, primary productivity and decay rate being strong factors (Mitsch et al., 2013). Boreal peatlands and coastal wetlands are large C sinks, while the rest (including all temperate and tropical freshwater wetlands) have not been studied as well as the former ones (Villa & Bernal, 2018).

A distinction must be made between the preservation of carbon stocks (which is not considered an ES) and carbon sequestration. Carbon stocks can be defined as "*the absolute quantity of carbon held in a habitat pool at any specified time" (*www.epa.ie*),* while carbon sequestration can be defined as "*the process of transferring* CO_2 *from the atmosphere into the soil of a land unit through plants, plant residues and other organic solids, which are stored and retained in the unit as part of the soil organic matter (humus)"* (Lal et al., 2015).

The total stock of carbon will be the sum of the above-ground biomass, the below-ground biomass, the carbon in dead wood, litter, and soil. As wetlands also emit methane, this source of carbon must be assessed and balanced with the carbon sequestered. In general, the terms of the equation are Net Ecosystem Exchange (NEE), methane emissions, nitrous oxide emissions, as well as any aquatic losses in the form of Dissolved Organic Carbon (DOC).

Carbon sequestration can be expressed as the product of bulk density, carbon concentration, and accretion rate (Villa & Bernal, 2018). The methods to determine accretion rates can be defined as short-term and long-term. An example of a short-term method is the determination of the net ecosystem exchange (NEE), based on the use of eddy covariance towers (Saunders et al., 20014) or on the closed chamber method (Murphy et al., 2022). These methods entail the analysis of a period of one or few years.

The accretion rate can also be measured on a long-term basis, either directly (using benchmarks like an artificial marker horizon or a sediment accretion table) or by dating methods (based on radiometric readings) (Villa & Bernal, 2018).

2.4.2.4 Habitat preservation

Wetlands can be considered as hotspots of biodiversity (Maltby & Barker, 2009). Many species of insects, reptiles, amphibians, birds, and fish are dependent on wetlands at different stages in their lives, either being resident of wetlands or migrating there.

The biodiversity of plants in wetlands reaches 31% of total plant species in the United States and 20% of the total species diversity in the Amazon basin (Junk et al., 2006). While biodiversity is in general higher in tropical wetlands, some temperate wetlands like fens, floodplain and forested wetlands have a rich floristic diversity (Gopal & Junk, 2000).

The function of providing a habitat for birds by wetlands has been known since prehistory as humans depicted birds in wetlands on the walls of caves. Birds use wetlands to breed, nest, and rear young, rest, feed, shelter and as places of social interaction. This strong link is testified by the direct relationship between wetness and population of birds (Stewart, 1996). This also indicates that climate change will have an adverse impact on populations if dry years become more common (Mitsch & Gosselink, 2015). The area of wetland can also be an important factor for certain species (dabbling ducks etc.), in order to satisfy their requirements for food and shelter (Webb et al., 2010). Depth of water is another important factor for bird distribution in wetlands, as diving species require enough water for their feeding strategy. Hydrology ultimately controls vegetation distribution in wetlands and this also affects species distribution, as many waterfowl prefer to be able to see predators approaching. Vegetation is also required for feeding though, so that the combination of these two factors often regulate the density of birds (Webb et al., 2010).

Climate change is expected to cause biodiversity loss with respect to vulnerable plant species in wetlands. For example, in Ireland 34 species have been mapped in peatlands, which will be threatened by climate change, including Marsh Saxifrage (*Saxifraga hirculus*), Cloudberry (*Rubus chamaemorus*), Violet (*Viola persicifolia*), and Bog Orchid (*Hammarbya paludosa*) (Malone & O'Connell, 2009).

Many reptiles and amphibians are also dependent on wetlands and the terrestrial habitats surrounding and connecting them (Gibbons, 2003).

Among the mammals present in wetlands some are commercially important for their fur. The main species involved are the muskrat (*Ondatra zibethicus*) and the nutria (*Myicastor coypus*). Other species of lesser economic importance are beavers (*Castor canadensis*), mink and otters. Alligators are also harvested for their skins in the USA, in Louisiana and Florida. After being threatened by hunting pressures, populations have now rebounded and also contribute to a market for their meat and skins (Mitsch & Gosselink, 2015).

Important regulating ecosystem services linked to habitats and biodiversity are genetic diversity conservation, habitat preservation and pollination.

2.4.2.5 Pollination

Pollination is the transfer of pollen from the male anthers to the female stigma of angiosperms to cause fertilisation. The main vectors of pollination are biotic (mainly insects and some mammals). Among the abiotics wind is the main one. This pollination vector is for example common in wetland grass species, conifers and many deciduous trees. In some wetland plants pollen is released in the water, which becomes the vector for pollination (McInness, 2018).

This ES is in jeopardy globally as pollinator populations are decreasing, primarily due to habitat loss and degradation. Pollinator insect populations can therefore be supported by enhancing native forb habitats and by wetland restoration (Begosh et al., 2019).

2.4.2.6 Water purification

Wetlands are at the boundary between terrestrial and aquatic ecosystems and are therefore important for nutrient exchange, removal and transformation. The effectiveness of wetlands at removing pollutant and nutrients is testified by the fact that constructed wetlands have been used to improve water quality for many years (Mitsch and Jørgensen, 1989, 2004). In a meta-analysis of ES of wetlands, Brander et al. (2006) found that water quality improvement was the ecosystem service valued highest.

The ES of water quality improvement arises from several chemico-physical and biological processes, namely: redox transformations, nitrification-denitrification, adsorption, sedimentation, in some of which microorganisms play a role. These processes result in the reduction of pollution from, among the others, heavy metals, nutrients, organic pollutants, and microorganisms.

Heavy metals are adsorbed on clay and organic matter particles, removed by microbes, and also taken up by plants. In a study on uptake of heavy metal by reed (*Phragmites australis*), Du Laing et al. (2009) found that higher water salinity and low soil clay and organic matter content promoted uptake of heavy metals, independently of heavy metal concentrations in the water. The uptake of heavy metals also depends on plant species, independently of ecological and morphological similarities, with marine phanerogams and wetland macrophytes showing similar capacity for accumulation of heavy metals in the root, compartmentalization in different organ and capacity of being indicators for Cu, Mn, and Zn levels in the substratum (Bonanno et al., 2017). Marques et al. (2011) found a higher bioremediation of mercury from *Juncus maritimus* through phytostabilisation and phytoaccumulation compared to *Scirpus maritimus.*

Dissolved inorganic forms of nitrogen (N) and phosphorus (P) are taken up by microorganisms and plants as organic compounds. Nitrates and nitrites in turn are reduced to gaseous forms of nitrogen (N_2O and N_2) by microorganisms and returned to the atmosphere (denitrification). Ammonium ions (NH_4^+), on the other hand, are oxidised to nitrates (nitrification) and taken up by plants. Accumulation of soil organic matter is another mechanism of nitrogen removal (Widney et al., 2018). Nitrogen is also taken up by vegetation in the riparian zone and this route is effective for nitrogen removal if the vegetation is harvested. If the denitrification process is hampered, nitrous oxide can be emitted which is a potent greenhouse gas. It is therefore important to consider this ES tradeoff appropriately (Verhoeven et al., 2006).

Phosphorus in wetlands can be in organic or inorganic form and particulate or dissolved (which can also be distinguished in labile and recalcitrant). Several abiotic and biotic processes regulate the pools of P in the soil column, sediment, water and plants. The main biotic processes are assimilation by plants, periphyton, plankton, and microbes and incorporation into soil organic matter (Widney et al., 2018). The main abiotic processes are sedimentation adsorption by soils, exchange processes between soil and the overlying water column and precipitation (USEPA, 2008).

Flow volumes, retention times and vegetation characteristics are important factors that determine whether a wetland is a source or a sink of nutrients (Fisher & Acreman, 2004). The same authors found that riparian wetlands were more likely to reduce loads of total N and P than marshes or swamps, but the opposite is true for ammonium and soluble phosphorus.

Often the size of a wetland is taken as a proxy for nutrient removal capacity, however the ecological condition is also important as degraded sites will have a diminished capacity for removing pollutants (Burkhard et al., 2018). Research has also shown that in temperate wetlands, the removal capacity of wetlands can reach up to 1000-3000 kg N ha^{-1} y^{-1} and 60 to 100 kg P ha^{-1} y^{-1} (Verhoeven et al., 2006).

Reducing the impact of nutrients has been identified as a priority by Maes et al. (2018) as nutrients from agricultural and industrial processes have an adverse effect on other ES like the provision of clean air and water, recreational activities, fisheries and aesthetic value.

Microorganisms contribute to pollution removal also by assimilation, adsorption and biodegradation. Microbial aggregates with various composition might also show other potential mechanisms. Microbial remediation is in general an inexpensive, flexible and rapid bioremediation method (Wu et al., 2012).

2.4.3 Cultural services

Cultural services including tourism, heritage value, aesthetic and spiritual value should be included as a key component of ES assessment for their importance to the public (Kelly-Quinn et al., 2020).

Wetlands are also important for the so-called non-monetary or existence values it provides. Cultural services have been defined by the MEA as "non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience (MEA, 2005). They are in fact a record of the past, including past climates and habitats (palaeoecology) as well as human history dating back to the very dawn of civilization. As such, they are also important for educational purposes, as students can learn about these habitats first-hand (Mitsch & Gosselink, 2015). Hunting and fishing, tourism, as well as sports and exercise, are also occasions for recreation and appreciation of nature. Natural heritage is also present in wetlands, as some of them store artefacts from all human history. Spiritual value has also been attributed by various cultures to wetlands, especially mires. This might be linked to their remoteness and wildness, which can provide a setting for religious reflection (Bonn et al., 2016).

The aesthetic value of wetlands is testified by the various artists who painted or photographed them, like the American poet Sidney Lanier, the painters John Constable and John Singer Sargent (Mitsch & Gosselink, 2015). Even the Water Lilies painting by Monet can be considered as inspired by an ante-litteram created wetland.

Wetlands have also constituted the subsistence of entire communities that have adapted to living integrally with them. Examples are the Camarguais in France, the Louisiana Cajuns in the United States, and the Marsh Arabs in Iraq (Mitsch & Gosselink, 2015). Sometimes they sustain traditional handicraft work and courses are available to learn these ancient skills (Bonn et al., 2016).

Recreational activities like fishing and hunting are an important service provided by wetlands and this is testified by analyses of fishery harvests. Studies have shown that recreational fishing far outweighs commercial fishing for some species and the value to the economy is far greater, as recreational fishermen spend more money per fish caught than commercial operators (Mitsch & Gosselink, 2015). Hunting of waterfowl is an important activity, as already mentioned. However, hunting has caused the decline or extinction of several species (like the Dorcas gazelle, *Gazella dorcas* or extermination of the Nubian bustard (*Neotis nuba*), but there is evidence that controlled sports hunting actually benefits some species and generates significance revenue (Loveridge et al., 2007). Hunters are usually concerned about their prey species and can also become the drivers for conservation efforts like in the U.S.A. (Fitter & Scott 1978; Adams 2004).

The different cultural ES also pose the problem of competing interest between conservation and restoration of wetlands and their study as archaeological and palaeoecological records. In fact, an unwanted consequence of wetland restoration might be the unintentional damage to archaeological and palaeoecological resources. Specialists should therefore be employed to ensure that these risks are minimised (Gill-Robinson, 2008, Bonn et al., 2016). Zhang et al. (2020) analysing the value of wet meadows in the Chinese Genheyuan region found that the value of cultural services varies with ethnicity, with nomadic people giving more importance to wetlands and water bodies than Han people. Wetlands were also found to be the most valued landscape element in the region.

2.5 Valuation of ecosystem services

As defined by the MEA (2005), value is "the contribution of an action, or object to user-specific goals, objectives, or conditions). More specifically, the value of ES is the contributions of the ecosystem to supporting sustainable human wellbeing (Costanza et al., 2014). Different values can be highlighted depending on the frame of reference and on the stakeholders considered. It is important not to restrict valuation only to economic values but be aware of the other values such as inherent, fundamental, and eudemonistic (Jax et al., 2013).

The valuation can be performed in different phases and using different tools, depending on the ES present and on the scale of the assessment. A biophysical valuation of ES is a prerequisite of carrying out an economic one. It can use direct measurement of the variables of interest, though this can be costly, and therefore indicators or proxy data and models are often used. Indicators can be primary (when they directly refer to the ES quantified, (e.g. number of tourists visiting a natural area) or secondary, when they indirectly help quantify said ES (e.g. accessibility or naturalness as a proxy for touristic value). The most used indicators for mapping ES are land cover, soil, vegetation, and nutrient related indicators. Egoh et al. (2012) found that land cover is an important secondary indicator for all the categories of ES. Nutrient fluxes and soil characteristics are other important secondary indicators. Vegetation maps are useful for carbon sequestration and water regulation.

The spatial and temporal scales of valuations should also be considered. Spatially, the amount of population affected by an impact under investigation must be determined. Direct uses of the wetland concern existing and potential users of the resource. Indirect uses values may not be site-specific, for example, the benefits provided by flood risk reduction further down the catchment. Non-use benefits are valued over a wider geographical area but are also subject to decrease with distance from the site of interest.

The temporal scale entails considering a trade-off between short-term and long-term benefits. Many projects consider a long-term timescale and issues like future demand for a particular service and discount rates must be considered.

Recently, several studies have made a distinction between ES supply and demand (Burkhard et al., 2014; Schröter et al., 2014; Villamagna et al., 2013). Supply can be defined as the capacity of an ecosystem to provide ES within a certain timeframe, while demand can be described as the sum of all ecosystem goods and services currently consumed or used in a particular over a given time period (Burkhard et al., 2012, Ala-Hullko et al., 2019). The analysis of supply and demand of ES is important to assess the sustainability of ES provision.

Several programs at national, European and international levels have focused on mapping ES through indicators. On an international level, the United Nations System of Economic and Environmental Accounting framework (SEEA-EA), is the accepted international standard for ES and natural capital accounting. At a European level, the Mapping and Assessment of Ecosystem Services (MAES, Maes et al., 2018). The MAES project was carried out in Ireland as well and included turloughs.

2.5.1 Ecological valuation methods

These can also be defined as functional methods and the most important are the Habitat Evaluation Procedure (HEP), and the Hydrogeomorphic analysis (HGM).

The HEP assigns a Habitat Suitability Index (HSI) from 0 to 1 (optimal) to each animal or plant species. The HSI is then taken to compare different development options and against the status quo or no-change scenarios. The appropriate scenario is then weighed against the projected economic benefits (U.S. Fish and Wildlife Service. 1980, Mitsch & Gosselink, 2015).

The HGM method consists in comparing the wetland of interest to a reference site that is characteristic of the same HGM class. The steps of the assessment procedure are summarised by Brinson et al. (1994). Wetlands are first grouped in classes with shared properties. The classification is based on three elements: the position of the wetland in the catchment (geomorphic setting), the hydrology of water feeding the wetland and the movement of water in the wetland (hydrodynamics). The properties are then linked to functions and functional profiles are developed for each wetland class. Pressure and threats are then linked to the function to assess the integrity of the wetland. Afterwards, explicit benefits are assigned to functions and the final stage is the economic valuation of benefits. The HGM approach focuses on ecosystem integrity rather than individual ecosystems services. On the valuation side, there is a risk of double counting complementary or substitutable services (Georgiou & Turner, 2012).

A different approach uses the idea of energy flow through the system or the similar concept of embodied energy. Two main concepts exist: embodied energy (Costanza, 1980) and *emergy*, or energy memory (Odum, 2000). In *emergy* analysis ratios are determined to convert a form of energy into another. These ratios are expressed in terms of solar emjoules (sej) per joule of base energy or ecosystem flow. Energy valuations are usually favoured by scientists as they are based on the inherent function of the ecosystem, not on perceived economic value. Buller et al. (2013) used *emergy* calculations to derive the production of water hyacinth in the Pantanal wetland and assess the monthly *emergy* value. This allowed to determine the feasibility of water hyacinth use in phase with floods to ensure its sustainability.

2.5.2 Economic valuation methods

Traditional economic theory postulates that in a free market the benefit of a commodity is the amount that the public is willing to pay for the good or service. This approach is straightforward when considering the so-called "use value" directly linked to the benefit of the individual. Examples are hunting, fishing, or water consumption. The value can then be estimated by the price of the good or service. This approach however has several problems, among which the fact that it fails to account for nontangible and non-marketable services that nature provides, the so-called "non-use values". It also ignores ecosystem- and global-level ES related to clean air and water and other life-support functions.

A common approach is to consider the Total Economic Value (TEV), which includes not only use and non-use value, but also non-direct values (Turner et al., 2003, as seen in Figure 2.5). Non-direct values are the benefits provided by a good or service that are used indirectly by an economic agent (like water purified by a wetland and enjoyed further down in the catchment). The different kinds of value include:

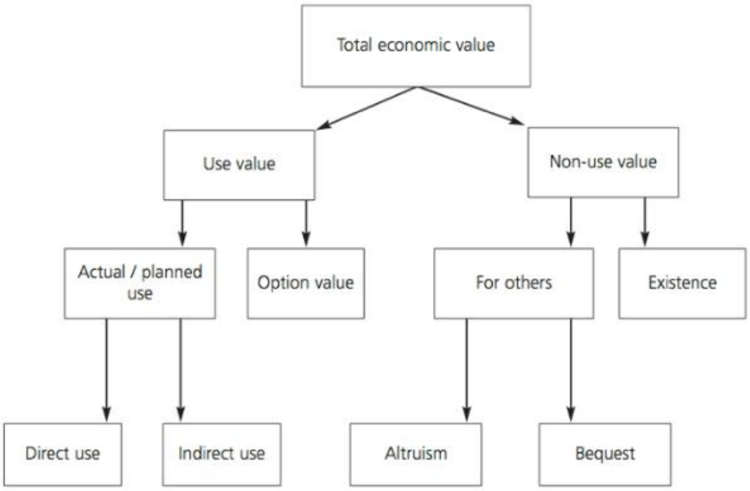


***Figure 2.5**. Total Economic Value framework (DEFRA, 2007).*

- Social value. Benefits are received by a group, not an individual. Examples are improved water quality and flood protection.
- Option value. The value for the conservation of a public asset or service even if it is not likely that it will be used and ensuring future availability.
- Existence value. The value deriving from the simple knowledge that the valued resource exists, even if it will never be used.
- Altruistic value. The value of ecosystems to others.
- Bequest value. The value associated with the satisfaction of preserving natural or cultural heritage for future generations.

Different methods have therefore been used to try to estimate the different components of TEV when a direct market and price are not available, as follows.

2.5.3 *Market prices*

This approach estimates the value of an ecosystem good or service and its price on a market on which it is bought or sold. The value is determined by measuring the change in producer and consumer surplus after applying a change in production or price. Adjustments should be made to correct for market distortions, such as taxes and subsidies (Bateman et al., 2014).

2.5.4 *Cost-based methods*

These methods are not a strict evaluation of the economic value of ecosystem service and assume that these values can be estimated by analysing the costs incurred in substituting them or avoiding damage. Examples are the replacement cost, the avoided damage cost, defensive expenditures, replacement/substitute costs and restoration costs methods (Georgiou & Turner, 2012). The replacement cost method requires the evaluation of the cheapest price that should be paid for the replacement of the function under scrutiny. This method has the advantage of being accepted by traditional economists. It also gives higher valuations than the other methods. Uncertainties remain though as to whether all the services provided at the moment would be replaced.

2.5.5 *Contingent valuation and choice modelling*

Both methods involve using a hypothetical or contingency market in the absence of a free market for non-market goods. For the contingency valuation method, originally proposed by Davis (1963) the value is then the amount that society would be willing to pay to produce and/or use a good beyond the value it already pays.

Choice modelling involves the public in choosing between alternatives, thus having them reveal or state their willingness to pay for a good or service. It can be traced back to consumer studies by Thurston in the 1920s and to random utility theory (Thurstone, 1994). This was then developed by Daniel Mc Fadden in economics (Zarembka, 1987) and by Duncan Luce (1959) and Anthony Marley (1968) in mathematical psychology.

2.5.6 *Revealed preference method*

These methods imply gathering data linked to the preference of the public for a good linked to a specific ecosystem service. The main ones are hedonic pricing and travel cost methods. The hedonic pricing method (HPM) uses a surrogate market (usually the housing market) to quantify the revealed preference of the public in living in a certain area affected by an ecosystem good or service (Vanslembrouck et al., 2005).

2.5.7 Production function

The production function method estimates changed in producer and consumer surplus due to quantity or quality changes in an environmental good or services which is part of a production process. If the price does not change, only the producer surplus is affected (Brander et al., 2006).

2.5.8 Value transfer

This method consists of using estimates from previous studies to value services provided by the studied ecosystems. This method takes two different approaches. In direct value transfer a value for an ecosystem service is directly transferred to the studied site. Ideally the two sites have similar characteristics, otherwise corrections should be applied. The other approach uses transfer functions, the terms of which have ideally been determined through a meta-analysis of valuation literature (Brander, 2013).

The total revenue, opportunity and replacement cost methods are not based on sound economic theory and therefore will tend to under- or overestimate values (Brander et al., 2006). Brander et al. (2006) also found that value transfers tend to have an average transfer error of 74%, which might be justified however, in light of the higher cost of primary valuations.

The TEV does not however represent the whole value of ecosystems, as other sets of values are provided by ecosystems. These represent the role of wetlands in the natural system and are usually presented in terms of biodiversity.

More inclusive estimations of values should be used, as to try to incorporate values such as inherent, contributory, primary, and infrastructure values (Georgiou & Turner, 2012). One of these approaches is the eco-price, which considers both biophysical and economic valuation (Campbell, 2018).

2.6 Valuation methods for the different ecosystem service classes

The valuation methods described above can be applied to the various ES as summarised in Appendix A, Table A.7, with further explanations as follows.

2.6.1 Provisioning services

Provisioning services can be valued by primary data (market prices); however, usually indirect indicators are used (e.g. landscape cover for food production, Appendix A, Table A.6).

2.6.1.1 Water provisioning

This function will also benefit other services like the provision of biomass, though these benefits are calculated in the specific ES, to avoid double counting.

The valuation requires identifying the potential of the wetland to recharge aquifers, the extent to which water levels are influenced, the potential uses of the water and finally the economic valuation of this water.

Examples of valuation methods are hedonic pricing linked to cost variation due for example to the availability of irrigation water, estimation of the costs of installing substitute wells and contingent valuation of the willingness to pay for alternative piped water supplies (Georgiou & Turner, 2012). Similar methods are used for the valuation of the prevention of land subsidence and saline water intrusion. For examples, the costs associated with these phenomena can be estimated and these could exceed the costs of measures that are employed to prevent these negative impacts. Hedonic prices might be used, but the specific component of a house price variation that is due for example to subsidence must be determined (Georgiou & Turner, 2012).

The provision of water in agriculture can be also calculated through the production function method, as the impact of water on the production of a good related to the water, like beef. More specifically, the value is the change in net value of the total output that is due to the used water. The value of this service can be calculated as (Equation 2.1):

$$(A) \times ((B)-(C)) \qquad (2.1)$$

where

A is the total amount of water consumed by cattle in a year (estimate can be calculated like average water requirement for a single animal multiplied by the number of animals);
B is the annual price for water from an alternative source x total amount of water consumed by cattle);
C is any cost associated with the operation.

In the use of water for hydroelectric power production, a market approach can be taken where the adjusted price of electricity is analysed. The value is computed as the fraction of the total value of the electricity generated by a dam which is due to the water generated by the watershed considered, minus the costs of production.

The shadow price method can also be used. It can be calculated as (Equation. 2.2):

$$V = \Sigma W_i \times C \tag{2.2}$$

where

V is the total value;
W_i is the water storage capacity;
C is the capacity cost of unit storage capacity;
i is the wetland type (Lin et al., 2019).

2.6.1.2 Provision of biomass as food and for other uses

The provision of biomass for food (fish, crustaceans, molluscs, rice) or other uses (reed for thatching and construction) is valued through market analyses. For example, the total revenue generated by fish catch can be used as a proxy for the value. This however does not reflect environmental and social damage in the case that the fishing activity is not sustainable. In this case the value can be estimated by replacement costs of shadow projects. These are projects undertaken to offset environmental damage. These estimate the shadow price, or the price attributed to the service to reflect its true societal value (Asher & Mirovitskaya, 2002).

Another use of biomass is in the growing market of energy production. Some wetlands are colonised by invasive plants. An example is in the wetlands associated with the

Great Laurentian Lakes, where invasive cattail, common reed, and reed canary grass compromise their unique habitats and ecosystem services. Harvesting of their biomass therefore would also help with preserving these ecosystems, while diminishing our dependence to fossil fuels (Carson et al., 2018).

Peat can be used commercially as fuel and as a growing medium in horticulture. Though a price could be given based on the market prices of these two uses, it must be highlighted that these uses are not sustainable as peat accretion is very slow (estimates of about 1 mm/year).

2.6.2 Regulating services

Regulating services like carbon sequestration and water quantity regulation are usually valued through models, given their complex nature (Egoh et al., 2012).

2.6.2.1 Water quality improvement

The main benefits that this ES provides are in terms of provision of drinkable water downstream of the wetlands. There are also non-use values like knowing that water quality and biodiversity are maintained for the benefit of others (existence value), of posterity (bequest) and for the mere existence and preservation of quality habitats. Another example are the recreational benefits linked to clean water. For these values non-market benefits that elicit the WTP have to be used. One of widest used methods is the contingent valuation method and an example of its application can be found in Ramajo-Hernández & del Saz-Salazar, 2012.

The most used method of valuation for the use value of wetlands concerning water purification is the replacement or alternative cost method. The value is calculated as the costs that an alternative treatment method would be required to achieve the same water quality of the wetland considered (Grossmann, 2012). The procedure involves identifying all the possible solutions for achieving the required pollution removal, estimating their cost and choosing the cheapest one. The service is then valued as the unit value of the cheapest option.

While this method is less time-consuming than measuring the value of the benefits, it does not consider individual or social preferences for clean water or pollution removal technologies. Also, the replacement cost tends to overestimate the value of the service (Grizzetti et al., 2016).

2.6.2.2 Global climate regulation

Once the amount of carbon sequestered has been determined (see Section 2.4.2.3), the economic value can be calculated. Assessing the value of carbon sequestration for global climate regulation is complicated and only a rough estimate, as the benefits are on a global scale. The damage of carbon on an ecological and social scale is also difficult to establish. Estimates vary between \$31 $t^{-1}$of CO_2 (Nordhaus, 2017) (€ 32 t^{-1}) and 68-83 t^{-1} of CO_2 (€ 69-85 t^{-1}) (Howard & Sterner, 2017) and \$1 more per year from then (Clarkson & Deyes, 2002) for social damage from carbon emissions. A recent proposal by Kaufman et al. (2020) based on the marginal damages of one ton of carbon, suggests a price of \$125 t^{-1} (€ 113 t^{-1}) by 2030.

A value that can also be used is the market price of carbon (e.g. European Union Emission Trading Scheme) for a one-ton emission permit and a discount factor for long-term assessments (Grizzetti et al., 2012). Alternative methods are the avoided damage methods and contingent valuation.

2.6.2.3 Flood risk reduction, sediment retention, erosion prevention, and shoreline stabilization

Wetlands can both alleviate flooding in their basins and soils but also cause it, following exceptional rainfall events. Assessing the value of flood risk reduction of a wetland requires different stages. First of all, determining the assets that are at risk of flooding downstream and the amount of flooding that is influenced by the wetland. This also requires considering how flooding would be affected when the wetland was removed. Then there is the potential for floods to damage assets at risk and finally the value of the ecosystem service can be calculated.

Flood risk reduction can be calculated by the avoided damage costs method. These are the costs that would be incurred if the flood protection provided by the wetland was not there. These costs can be direct, indirect and intangible. The direct costs are the ones incurred by buildings, productive activities (including agriculture) and by the natural environment (though these are usually temporary). The indirect ones act on the physical and economic linkages, while the intangible one are due to factors like stress and disruption on people. These are however difficult to quantify. Defensive expenditures are also used, however these tend to underestimate the real costs, as they may omit costs against which defensive action is not taken. These include replacement of population and assets, rewiring of electrical points and raising of houses.

Replacement costs can also be used and are usually determined by a shadow project. This is usually the creation of a restoration of another wetland which could provide the same flood risk benefits.

The final value of flood risk reduction can be expressed as (Equation 2.3):

Wr =_ _n _i=_1 Wri =_ _n _i=_1 Ai ∗ _Hi (2.3)
Wr =_ _n _i=_1 Vri =_ _n _i=_1 Wri ∗ _Pr

where

W_r is the volume of water retained by the wetland (m^3y^{-1});
V_r is the economic value of water regulation (monetary unity y^{-1});
A_i and H_i are the i^{th} wetland patch mean area and height respectively;
P_r is the unit cost of a reservoir in a particular area (Zhang et al, 2017).

Analysing current flood defense measures in place can also give an indication to the possible extent and possible costs associated with increase flooding. If no measures are in place this might mean that the risk in low or the costs of implementing measure would exceed the benefits of reduced flooding. Hedonic pricing is also used, where all aspects of the price of a property are considered, like location, aspect and age of the property. The analysis might be complicated by the existence of flood defense measures and by price not reflecting the flood risk because the last flooding event is too far in the past (Georgiou & Turner, 2012).

Contingent valuation can be also used, though the method is expensive and time-consuming and therefore usually limited to the valuation of impact on unique ecosystems, for which markets do not exist.

According to Maes et al. (2016), the most useful indicators for flood risk protection are floodplain area (and record of annual floods) and areas of wetlands located in flood risk zones).

Sediment retention is beneficial for several aspects, first of all improving water quality and then supporting biodiversity. A positive effect is also evident on water conveyance (avoidance of siltation) and on maintaining navigation. This service is also calculated and valued in different phases, similarly to flood risk. Some conditions must be met to have sediment retention: there must be sediment in the catchment and the speed must be low enough for it to be deposited. The most common approach is by considering the value of the avoided damage to the functions mentioned above (Georgiou & Turner, 2012).

2.6.2.4 Habitat preservation

Biodiversity provides both use and no-use values, so it is necessary to consider the Total Economic Value (TEV). The various economic techniques used can be found in Figure 2.6.

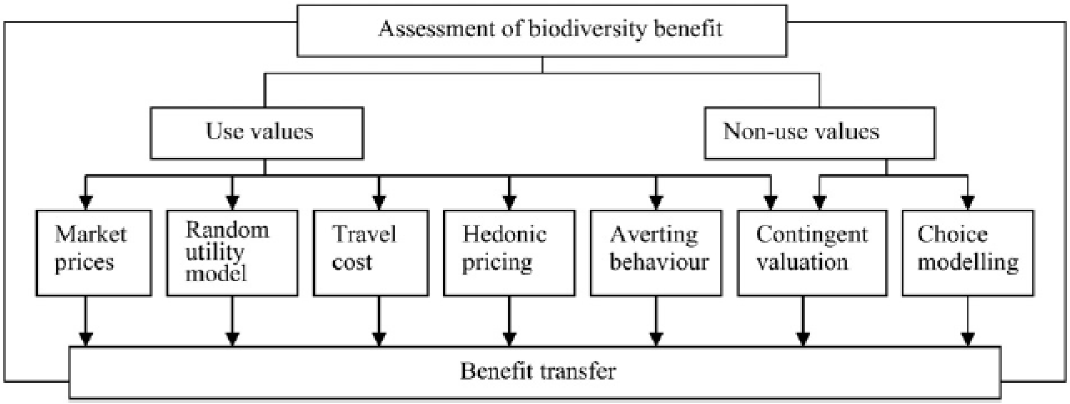


***Figure 2.6**. Methodologies for the economic valuation of biodiversity (from Nijkamp et al., 2008).*

Different indicators can be taken to quantify this service. La Notte et al. (2012) distinguish three main categories of indicators: ecological value, ecological sensitivity, and human pressure. The first category describes the biological importance of the habitat, the second the tendency to suffer alterations, and the third the disturbances due to human activities. Values can then be quantified by the contingent valuation methods by interviewing members of the public around the areas. The use of these indicators makes it also possible to use the benefit transfer method from areas with similar habitat characteristics, as described by these indicators.

Other common methods are getting the public to choose between different scenarios (choice experiment), using market analyses of species of commercial value and using replacement/restoration costs. Another method is through the estimation of expenditures for the conservation of biodiversity by governmental and non-governmental bodies (Baral et al., 2016).

2.6.3 Cultural services

2.6.3.1 Nature-based recreation

Some wetlands are important tourist destinations, or are used for recreational hunting, fishing and bird watching. The travel cost method can be used to establish the value of these services. For example, nature-based recreation can be estimated from the direct expenditure of tourists at the site as shown in Equation 2.4.

$$\text{Economic value} = (A) \times (B) \tag{2.4}$$

where

A is the total number of visitors at the site, and

B is the expenditure per visitor.

The relevant authorities can be contacted to have figures about tourist visits. Alternatively, interviews can be performed with tourists asking about their expenses to enjoy the site or for a change in the activities at the site. Property prices at different distances from the site studied can also be used as a proxy value (hedonic pricing).

2.6.3.2 Cultural, historic, and aesthetic value

Similar to recreation services, these values are estimated by surveys given to residents and tourists on their willingness to pay to conserve the area (contingent valuation) or on alternative choices for the sites (choice experiment). Hedonic prices are also used. Though the contingent valuation is also able to capture non-use values, these are not consistent with the ones obtained by the other methods. The hedonic prices might be influenced by factors that can bias the results (like taxes and interest rates). Another possible source of error is that environmental benefits should be known to the public to be reflected in house prices (Grizzetti et al., 2012).

2.6.4 *Valuation and mapping tools*

Several tools have been developed over the years to value ES in qualitative and/or quantitative ways. A summary of these tools and their applicability in the valuation of ES can be found in Appendix A, Table A.6.

2.7 Wetland ecosystem service monetary valuations

All the valuations present in this Section and the following ones have been adjusted to 2022 values (given in parentheses after the original valuation) considering inflation by using the Consumer Price Index (CPI) inflation calculator (https://visual.cso.ie).

Costanza et al. (1997) estimate the value of the world's ecosystems using upscaling and transfer functions at US$33 trillion (equivalent to US$51 trillion in 2022). The revised value in 2014 (Costanza et al., 2014) was US$125-145 trillion (US$131 to 151 trillion), with wetlands worth US$26.4 trillion (US$27.7 trillion) and US$140,174 $ha^{-1}yr^{-1}$ (US$147,086 $ha^{-1}yr^{-1}$). The inland swamp/floodplain number stayed approximately the same, while the tidal marsh/mangrove unit value increased 14-fold, due to new studies on storm protection, erosion protection, and waste treatment values of these tidal wetlands.

The valuation was based on a simple benefit transfer function. This valuation was controversial, yet it received significant attention from the media and highlighted the number of benefits that humans derive from wetlands and made the public aware of it. It also highlighted the growing awareness worldwide of these benefits since the declaration of the Ramsar convention in 1971 (Matthews, 1993). Balmford et al. (2002) argued that rather than considering the total value of the ecosystem we should rather focus on net marginal benefits.

This study also showed that inland swamps and flood plains were significantly more valuable than lakes, rivers, forests and grasslands. Only coastal estuaries had higher unit values.

A milestone for the definition of the ES concept has been the already mentioned MEA, with other important initiatives being the Economics of Ecosystems and Biodiversity (TEEB, Russi et al., 2013) and the MAES. The TEEB analysed the literature on valuation studies and found a total of 364 studies (also comprising tropical areas). They show that values of both coastal and inland wetland ES are typically higher than for other ecosystem types and generally higher than those of terrestrial ecosystems.

Several reviews of the ES of wetlands have already been published, testifying the already established awareness on these ecosystems. The most relevant worldwide are Brouwer et al. (1999), Woodward and Wui (2006) and Brander et al. (2006). Brouwer et al. (1999) focussed on temperate wetlands in developed countries, reviewing 30 studies that used the contingent valuation method. They found that the highest WTP was for flood prevention, probably for the risk to life and assets, followed by water provision and water quality improvement. Woodward & Wui (2001) reviewing 46 studies on temperate wetland valuations, found some evidence that the method used affected the resulting value, with contingent valuation giving lower estimates. Zedler & Kercher (2005) found that among the ES which have a global relevance are flood abatement, carbon sequestration, biodiversity conservation and water quality improvement. Brander et al. (2006) identified 190 valuation studies providing 215 value observations. They found that socio-economic variables like income which are often neglected are important in explaining wetland value. They also found that benefit transfer is associated with 74% average error and that contingent valuation and revealed preference give roughly similar value estimates. They also interestingly found an inverse correlation between value and size of wetlands.

In a meta-analysis of US wetland valuation studies, Borisova-Kidder (2006) found a mean value per acre for wetland services of \$262.43 (€315 acre^{-1}). The ES of coastal wetlands (intertidal marshes) have been valued to \$10,603 ha^{-1} (€11,042 ha^{-1} yr $^{-1}$) by Barbier (2011) and the JRC valued European wetland ES at €125 billion yr $^{-1}$ (€145 billion yr^{-1}, Maes et al., 2011).

Okrusko et al. (2011) reviewed the ES of European wetlands, used local studies and existing land use and vegetation classification maps, and gave a classification to each ES, depending on whether it was present, present and well developed, or absent. They considered 5 ES as being the most important: biodiversity conservation, biomass production, nutrient removal, carbon storage and fish production. Brander et al. (2013) estimates the total world value of the regulating services of wetlands within agricultural areas at US\$26 billion yr $^{-1}$ (€26 billion yr $^{-1}$). For European wetlands they find an average value per hectare of US\$15,339 (€15,648 ha $^{-1}$ yr $^{-1}$) and a median value of US\$ 3,706 per hectare (US\$ 3,781 ha $^{-1}$ yr $^{-1}$). The TEEB (Russi et al., 2013) estimates the value of inland wetlands as up to US\$ 44,000 per hectare per year (€ 44,887 ha $^{-1}$ yr $^{-1}$), ranking as one of the highest values among all biomes. This study also recognises the mapping of ES of wetlands as a knowledge gap that must be filled. Campbell et al. (2018) calculate a value of US\$ 9,693 ha $^{-1}$ yr $^{-1}$ (€9,825 ha $^{-1}$ yr $^{-1}$) for palustrine wetlands of Maryland, with wildlife habitat, nutrient retention and stormwater runoff mitigation the biggest contributors. In Europe, freshwater wetlands in Finland, Sweden and Ireland show low per hectare value but high aggregate ES values, due to the large number of wetlands in these countries (Kuik, 2010). Bulgaria and Croatia on the other hand, show high per hectare values for inland wetlands, due in part to the low GDP's in these countries (Ghermandi et al., 2013).

Among the ES identified by De Groot et al. (2012) the highest monetary valuation per hectare is waste treatment by coastal wetlands with a value of US\$ 162,125 ha $^{-1}$ (US\$ 184,393 ha $^{-1}$). Following are the nursery services, with a value of US\$ 10,678 ha $^{-1}$ (US\$ 12,145 ha $^{-1}$) and the habitat preservation, with a value of US\$ 6,490 ha^{-1} (7,381 US\$ ha $^{-1}$), both for coastal wetlands. They also found that for inland wetlands, the single most valuable ES per hectare is the regulation of water flows, with a value of US\$ 5,606 ha $^{-1}$ (US\$ 6,376 ha $^{-1}$).

Davidson et al. (2019) studying wetlands and using values from Costanza et al. (2014) but with updated areas of the different classes of wetlands, arrive at a minimum value of US\$47 trillion annually (US\$52 trillion, 43.5% of the value of all natural biomes), with 57% coming from inland wetlands and 43% from coastal wetlands. 80-95% of the values of different wetlands is linked to water: water recharge nutrient retention, flood prevention, storm abatement (Davidson et al., 2019).

Unfortunately, the cumulative ES value of wetlands is declining, due mainly to land use change disrupting wetlands biophysical processes. Sannigrahi et al. (2018) found that wetlands' ES value per year decreased between 1995 and 2015 from US\$22.19 to 21.11 trillion year^{-1} (US\$24.9 to 23.69 trillion year^{-1}). Coastal wetlands have been particularly affected by reclamation. It has been found (Yim et al., 2018) that in the

Yellow Sea there was a loss of US$8 billion year^{-1} (US$9 billion year^{-1}) in ES value, with a high proportion of climate regulating ones (carbon sequestration).

There has been a relevant growth in studies made in China, which for the majority are based on land-use maps and associated ecosystem values per unit area modified from Costanza et al. (1997), though adapted to the Chinese peculiarities. They are also geared toward the application to wetland conservation policies (Zhou et al., 2020). Zhou et al. (2020) through a meta-analysis of 134 Chinese articles using benefit transfer as valuation technique, highlighted how it is necessary to expand wetland ES studies to include more types of wetlands, valuation methods and a wider geographic range.

Similarly, Russi et al., (2013) show that values of both coastal and inland wetland ES are typically higher than for other ecosystem types and generally higher than those of terrestrial ecosystems (Ramsar Convention on Wetlands, 2018). For example, the study showed that the total value of a freshwater marsh in Canada was $8,800 ha^{-1} yr^{-1} ($9,940 ha^{-1}yr^{-1}), about 2.4 times the value of the marsh converted to intensive agriculture. These values were used by the Millennium Ecosystem Assessment (2005).

There is a wide discrepancy on the value of flood prevention, especially for coastal wetlands, depending on the method of valuation used. As already mentioned, the defensive expenditure method tends to give values which are much lower than those obtained by the avoided damage cost. For example, Ming et al. (2007) calculated a value of US$5,700 ha^{-1}yr^{-1} (US$6,664.79 ha^{-1}yr^{-1}) for coastal wetlands in China, while Vazquez-Gonzales et al. (2019) calculated values between US$148,277 ha^{-1}yr^{-1} and 193,674 ha^{-1}yr^{-1} (US$164,623.74 ha^{-1}yr^{-1} to 215,025 ha^{-1}yr^{-1}) for freshwater marshes and mangroves respectively for coastal plains in the Gulf of Mexico. Costanza et al. (2008) calculated a value for coastal protection of US$250 ha^{-1}y^{-1}(US$278.50 ha^{-1}y^{-1}) to US$51,000 ha^{-1}y^{-1} (US$56,814 ha^{-1}y^{-1}), with a mean of 8,240 US$ ha^{-1}y^{-1} (US$9,179 ha^{-1}y^{-1}) and US$23.2 billion y^{-1} (US$25.8 billion y^{-1}) for total storm protection services. As for the valuation method used, Mehvar et al. (2018) found that avoided damage, replacement and substitute cost method as well as the stated preference method are the most used valuation methods for coastal ES.

Okrusko et al. (2011), in a review of the ES of European wetlands, used local studies and existing land use and vegetation classification maps and gave a classification to each ES, depending on whether it was present, present and well developed, or absent. They consider five ES as being the most important: biodiversity conservation, biomass production, nutrient removal, carbon storage and fish production.

2.8 Ecosystem services of intermittent karst wetlands

Poljes and turloughs offer provisioning, regulating and cultural ES which might be very important at the local and regional scales, yet their ES are not well studied. In general, turloughs have a combination of wetland and grassland (with some forest patches) habitats, therefore the quantification and valuation of their ES should be based on existing methods for those habitats, adapted to their peculiar ecohydrology.

Most turloughs are grazed and their central area is used as commonage. They can be an important source of water for grazing animals in the meat and dairy industries and therefore linked to food provision too. Poljes may constitute the only arable fields in their area and therefore be very important for food provision. The provision of food for humans during the flooded time of the year is limited to forage of berries, as there are generally no fish present in them. Hunting of wildfowl in turloughs is allowed outside Special Areas of Conservation (SAC) and Wildfowl Sanctuaries (www.npws.ie).

Both poljes and turloughs are groundwater-dependent and are therefore affected and affect water quantity and quality (the ES of water provision and water purification). The changing of rain patterns with climate change might therefore affect them, by changing water levels and in turn habitats as it has already been established with some poljes (Dolinar et al., 2010); this is another reason for them being better studied. Land abandonment is also expected to have a negative effect on mesotrophic and eutrophic turloughs by favouring taller and ranker vegetation, while the more oligotrophic ones should be not affected as they already have low levels of grazing. Land abandonment might also lead to degradation of stonewalls also bringing unrestricted animal grazing. On the other hand, the concentration of grazing on fewer agricultural sites might have a simultaneous negative effect (Irish Ramsar Wetlands Committee, 2018).

According to de Groot (2012), as inland wetlands, their most valuable ES should be the regulation of water flows and water purification. Regarding the latter, Blackwell &

Maltby (2003) estimated that the nutrient removal of small wetlands is worth £58 ha^{-1} yr^{-1}, (€91 $ha^{-1}yr^{-1}$ in 2022) a value that could be of relevance for the smaller turloughs. The question still remains on whether they are a source or sink of water nutrients, or their water purification service. Mc Cormack et al. (2016) found that nutrient loss processes were occurring within turloughs. For nitrogen, denitrification happens mainly during flooded periods, while for phosphorous sedimentation and subsequent soil deposition is the main process. According to this study, turloughs can therefore be a sink of nutrients.

Flooding regulation is expected to increase in importance as flooding frequency is increasing both for poljes (Dašić & Vasić, 2020) and turloughs (Morrissey et al., 2020) due to climate change. It is therefore crucial to understand the hydrology linked to these karst forms in order to reduce the impact of floods on habitats and on people and the local economy and the ES methodology can aid in such a task. Flood risk attenuation is expected to be significant for turloughs, as it tends to be greater in wetlands with substantial water level fluctuations and in wetlands with intermittent, temporary, semi-temporary hydrologic regimes (See Section 4). It will also depend on the specific position of the turlough in the catchment and on its hydrological regime. In very extreme weather conditions, they can cause flooding for nearby houses, but equally more normally provide a flood attenuation function. This will depend on local hydrological processes and landscape characteristics. Modelling a network of 15 turloughs in the Gort lowlands, Morrissey et al. (2020) found that should the optimal flood alleviation schemes be implemented, there would be an impact on turlough ecosystems, though the further elevated areas might actually benefit from the flooding reduction that killed trees in past flooding events, thereby underscoring the complexity of flooding in such areas. According to recent modelling, climate change is expected to exacerbate flood risk through increased winter rainfall.

Many of the turloughs are important for habitat preservation, being important sites for birds, insects, and amphibians and also hosting important plant species. Rahasane turlough in County Galway for example, has been defined the most important turlough for birds in Ireland (BirdLife International, 2020). Common visitors are great white-fronted geese (*Anser albifrons flavirostris*), whooper swans (*Cygnus cygnus*), wigeon (*Mareca penelope*), teal (*Anas crecca*), and waders (order *Charadriiformes*) in winter

Coole Park is also an important turlough complex located in county Galway and important as a habitat for birds.

Some of the turloughs have peaty soils and peat accumulating mainly in fen habitats, therefore providing climate regulation through carbon sequestration (which can also be provided by grasslands and water basins). Grassland soils in Europe are also estimated to sequester carbon, though these estimates (between 1 and 45 Tg y^{-1}, Smith et al., 2005, 101 Tg y^{-1}, Janssens et al., 2003) are associated with large standard deviations, which could potentially mean that some of them are carbon emitters. Improved grazing practices also lead to carbon sequestration of about 0.3 Mg C ha^{-1} yr^{-1} (Conant et al., 2001). Improved management practices could lead to the sequestration of additional 0.2-0.8 GT CO_2 yr^{-1} in grassland soils globally by 2030 (IPCC, 2007a).

Turloughs are also culturally important for local people; since they represent a feature virtually unique to Ireland, they are important for education. This can be seen for example at Moate turlough (www.dunnasi.ie), where a heritage park is present, at lough Gealain, part of the Burren National Park and at Coole/Garryland, home to Lady Gregory, dramatist and folklorist and visited by notable people, such as William Butler Yeats, George Bernard Shaw, John Millington Synge and Sean O' Casey (www.coolepark.ie). Also, the fact that they are strongly tied to the productive social and cultural life of the surrounding communities presents an additional challenge in their conservation and the fruition of their ES.

The European MAES project has been carried out in Ireland and included turloughs (habitat class 3180). However, it only includes approximate locations and areas for the turloughs, therefore the only turloughs that have been studied in depth in recent years are the 22 included in Waldren et al. (2015).

The NPWS, which was involved in the MAES exercise in Ireland, also published reports on the achievement of conservation targets for the turloughs (O'Connor, 2017). These targets were used to derive indices of habitat quality and therefore potential for ES provision.

2.9 Summary of Literature Review Findings

The total benefits of wetlands go beyond the mere short-term monetary value of services that can be traded in a market. Some researchers have highlighted the risk of the commodification of ES, which reproduces the market logic and structures and applies them to ecosystems (Gómez-Baggethun et al., 2010). Nonetheless, such studies have surely contributed to raising the attention of the important of such services. Several specific problems with the monetisation of ES can be highlighted:

- Attaching values to different biophysical processes is linked to an anthropocentric concept;
- Valuable wetland ES have no commercial value;
- The ecological value of a wetland depends on its location and linked to population density and income;
- The relationships between wetlands, surrounding population and marginal areas are complex;
- Market prices are limited in time, while wetlands provide ES for much longer timeframes therefore a comparison of economic short-term gains with long-term value is often not appropriate.

These problems with monetisation were considered in this thesis by also quantifying the cultural ES and not giving a monetary value to the habitat preservation ES.

Brooks et al. (2014) advise that including several stakeholders when performing valuations, maximises the benefits of the ES approach. Ghermandi et al. (2010) found that relatively little information is available in the literature on the valuation of regulating services and supporting services and they found no valuations for provision of genetic materials, climate regulation, erosion protection, spiritual and educational values, and support of pollinators. Similarly, Barbier (2011), found that, for a number of important ES, no or few studies exist.

Though several studies were published in the last decade on wetland ES, gaps still need to be filled. Barbier (2019) reviewing 80 valuations of coastal wetland ES recognises that there must be more attention to a wider range of goods and services, that geographical coverage has to be improved and that spatial considerations must be made in ES studies. Xu et al. (2020) similarly highlighted that provisioning and cultural services received less attention. While spatial patterns of ES are an aspect that has been investigated recently, few studies have investigated how land use change affects ecological changes and in turn ES (Li et al., 2017). As for the ES lacking valuations, Harrison et al. (2010) highlight that evidence should be gathered for the provisioning of biochemical/natural medicines and ornamental resources and the regulating services of seed dispersal, pest/disease regulation an invasion resistance in all ecosystems. Climate regulation studies were found lacking for forests and peatland, and pollination in agro-ecosystems, mountains, and forests.

At a European level, several ES (like nutrient retention, water provision, cultural services) are not accounted in the relevant EU programs (MAES, KIP INCA, Vallecillo et al., 2019). There is also a need for more primary valuation studies of regulating ES of wetlands and for filling gaps in the geographic distribution of such studies (Brander et al., 2013).

Some of the wetlands at northern latitudes were estimated as having some of the highest values in ES among wetlands. After centuries of development and exploitation their true value is finally beginning to be recognised. The ES framework can provide a useful contribution to such considerations and policy formation, for example, when assessing the potential consequences of climate change.

The number of articles on the ES of wetlands has increased exponentially (Delle Grazie & Gill, 2022), though several ES have been studied less than others and for some classes of wetlands or not studied at all (including intermittent karst lakes), therefore much research is left to ensure that these research gaps are filled, with this thesis being a contribution. Interaction among ES should also be analysed. These include trade-offs, synergies and compatibilities (Willemen et al., 2010). Liu et al. (2020) found for example for a lake in China, that food provision caused a negative impact over other ES over a certain threshold. In general also, provisioning services have a negative impact on regulating ones, though the latter have a higher value, as highlighted in previous paragraphs. Spatial patterns of ES are an aspect that has been investigated recently, though few studies have investigated how land use change affects ecological changes and in turn ES (Li et al., 2017).

Hence, the valuation techniques reviewed in this thesis can be used for wetland types that did not receive much attention so far, such as intermittent karst lakes (poljes/turloughs) and to cover gaps in the ES considered, like the regulating ones. The mentioned spatial element is also considered here, using Geographic Information Systems (GIS). GIS and other software tools could also bring forth a much-needed geographic and methodological homogenisation in the quantification and valuation of the ES of wetlands.

Turloughs offer provisioning, regulating and cultural ES which might be very important at the local and regional scales, yet their ES are not well studied. In general, turloughs have a combination of wetland and grassland (with some forest patches) habitats, therefore the quantification and valuation of their ES can be based on existing methods for those habitats, though adapted to their peculiar ecohydrology.

Some of the approaches for the quantification and valuation of ES revised here were tested in this thesis, considering the peculiarity of turloughs in the wider picture of temperate wetlands. Though mapping of ES exercises have taken place in Ireland, this thesis constitutes the first example of in depth quantification of the ES of 7 turloughs, as well as giving an overlook of the provision of ES for further 48 turloughs based on water quality and existing information.

3 RESEARCH METHODOLOGY

3.1 Site selection

3.1.1 Preliminary assessment

This research project started with a preliminary general assessment of once-off water quality of 55 turloughs (the 55 turloughs from now on) whose water level has been monitored by the GSI (Table 3.1 for names and Figure 3.1 for locations). This set included almost all of the 22 turloughs studied in Waldren et al. (2015) and 7 turloughs studied in depth in this study (the 7 turloughs from now on). Field measurements of chemico-physical parameters and water samples for laboratory analyses were taken. This aims to provide a broad overview of the quality of turlough waters.

Table 3.1. *The 55 sites where water was sampled (showing those highlight in green included in Waldren et al. (2015), and the 7 sites invetigated in this study in bold red text).*

Site Name	Site code	Site Name	Site code	Site Name	Site code
BreanDrum	BRDR	Drumadoon	DRUM	Glenamaddy	GMAD
Castleplunket	CPLK	Kilglassaun	KILG	Managh	MANA
Brierfield	BRFD	Rathbaun	RATB	Termon North	TERN
Coolcam	**COOL**	Ardacong South	ACGS	Termon South	TERS
Rathnaulleagh	RATN	Belclare	BCLR	Tullynafrankagh	TULL
Carrowkeel	CRKL	**Caranavoodaun**	**CARA**	Labane	LABN
Correal Cross	CORC	Ballinderreen	BALL	Croaghill	CROA
Ballinturley	BTUR	Ballyboy	BBOY	Lough Loum	LOUM
Lisduff	LISD	Cockstown	CKTO	Carran North	CRNN
Four Roads	FRDS	**Blackrock**	**BLA**	Carran South	CRNS
L. Funshinagh	FUNS	Cahermore	CMOR	**Lough Aleenaun**	**ALE**
Ardmullan	ARDM	**Lough Coy**	**COY**	**Lough Gealain**	**GEA**
Ardkill	ARDK	Caherglassaun	CGLS	Knockaunroe	KNOC
Balla	BALA	Coole	COLE	Turloughnagullaum	TURL
Cuillaun South	CULS	Garryland West	GLDW	Fortwilliam	FTWM
Skealoghan	**SKE**	Rahasane	RAHA	Moate	MOTE
Turloughmore	TMOR	Newtown (Coole)	NEWC	Ballinduff	BLDF
Polldowagh	PDOW	Hawkhill	HAWK		
Shrule	SHRU	Roo West	ROOW		

The 55 turloughs were monitored in February to April 2018 and in February 2020 (the water chemistry near the highest hydrographic level was shown to be representative of the turlough hydrochemistry and to vary little in different years (Cunha Pereira, 2011).

The 7 turloughs were selected according to the unique attributes including different hydrological regimes, water, soil quality and biodiversity value. Location and accessibility were also taken into consideration. The turloughs are located in the west of Ireland, in counties Clare, Roscommon, Galway and Mayo (Figure 3.2). Their extensions and depths are presented in Table 3.2.

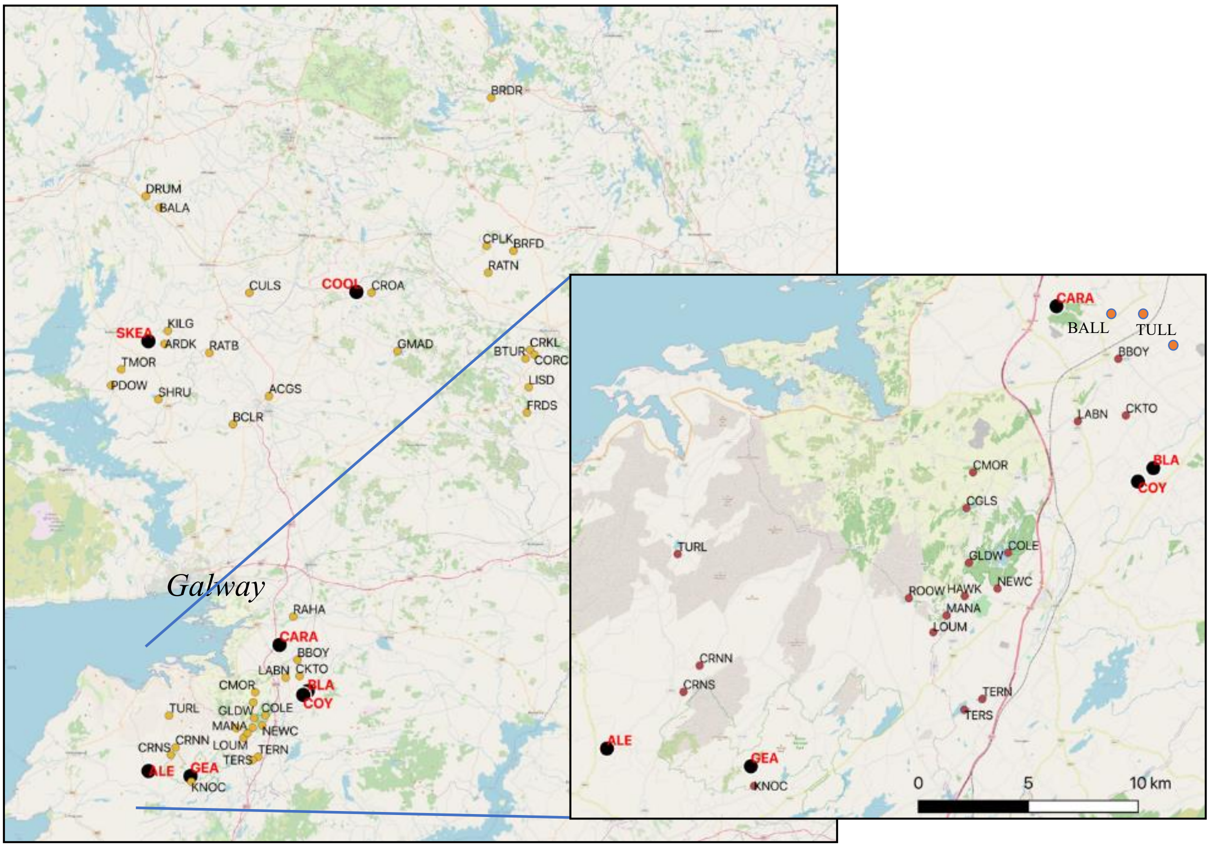


Figure 3.1. *Location of the turloughs sampled. For the correspondence of the acronyms with turlough names, see Table 3.1. In red the 7 turloughs studied in more detail.*

In the spectrum from flashy hydrological regime to long and steady one, Lough Aleenaun was chosen as the quintessential example of the first, while Coolcam at the other end, showed a single flooding event and a long duration of flooding. Blackrock and Lough Coy were chosen as part of the Gort-Kinvarra chain of turloughs, showing characteristic dark brown water and having mineral soils. They also show two different hydrological models, with Blackrock functioning according to the follow-through model was Lough Coy is an example of the surcharge tank model (Gill, 2010). Lough Gealain was chosen as an example of a turlough in pristine conditions, not being subject to grazing, or having other anthropic pressures. Caranavooudaun was chosen as a turlough with calcareous substrate, in good condition and with high variety of habitats, but subject to some agricultural pressure. Skealoghan was chosen as a turlough with an intermediate duration of flooding, peaty deposits and some interesting plant (*Stellaria palustris*) and animal species (the invertebrates *Alonella excisa* and *Eurycercus glacialis* and beetles like *Panagaeus crux-major,* Moran et al., 2012). The seven turloughs were also chosen as significant information was already available from Waldren et al. (2015) and also these sites, being all protected areas, host some of the best conserved and valuable habitats between turloughs.

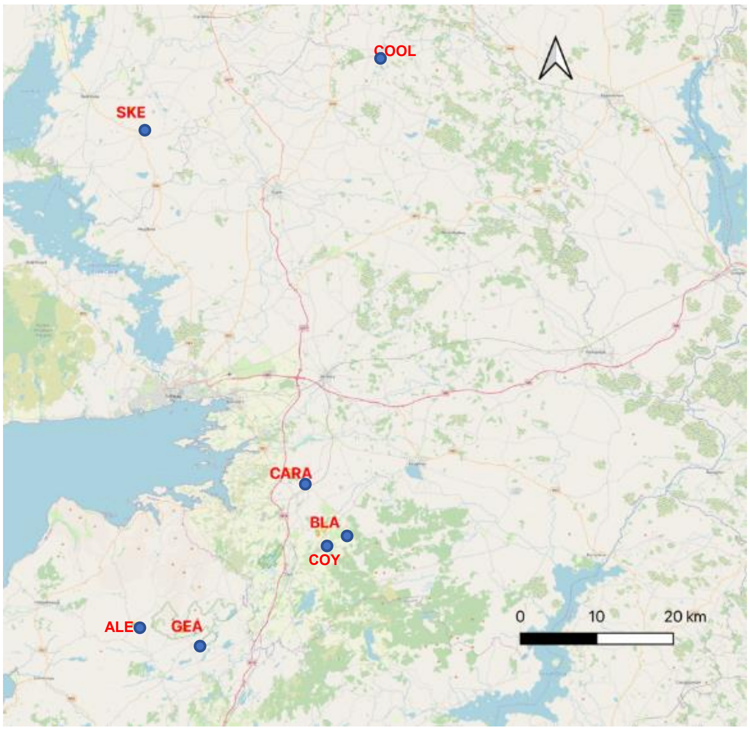


Figure 3.2. *Location of the 7 turloughs in the west of Ireland.*

Table 3.2. *Location of the turloughs, and their specific characterstics including extensions, depths and water volume (from Waldren et al., 2015).*

Turlough	**Easting**	**Northing**	**Max depth (m)**	**Max volume (m^3)**	**Max area (ha)**	**Average depth (m)**
ALE	124917	195456	5.9	355.6	14.3	2.59
BLA	149863	208159	15.4	4008.1	60.2	6.76
CARA	145277	215558	3.8	498.5	34.0	1.44
COOL	157750	270796	4.5	1570.2	55.4	2.01
COY	148986	207413	10.6	1479.1	25.3	5.86
GEA	131458	194781	4.9	919.9	37.0	2.57
SKE	124562	262765	3.2	382.2	33.0	1.17

The parameters analysed are the ones routinely considered for the characterization of natural waters, with most of them also being indicative of habitat quality, therefore useful for ES quantification. The rationale for their consideration can be found in Table 3.3.

Table 3.3. *Rationale for the surveying of water quality parameters.*

Chemico-physical or chemical parameter	**Rationale for surveying**
TN, TON, TP, SRP	Productivity; potential eutrophication
Chlorophyll α	Proxy for productivity (La Pierre et al., 2017)
DOC	Organic carbon in waters; potential pollution at high levels; useful to calculate the carbon balance
Turbidity	Proxy for primary productivity, habitat quality, potential microbial contamination (Huey & Meyer, 2010)
Electrical conductivity and Total Dissolved Solids	Potential pollution (Das et al., 2006)
pH	Alkalinity or acidity of waters; potential release of metals (Atkinson et al., 2007); extremely high or low values also indicative of pollution
ORP	Reduction-oxidation potential of waters. Low values point to pollution, high values to healthy ecosystems (Horne & Goldman, 1994)
Colour	Presence of organic compounds or algae
Dissolved Oxygen (DO)	Ecosystem quality (higher values are better); low values indicate eutrophication
Alkalinity	Acid buffering capacity; geological substrate
Major cations	Water quality and origin; ion composition imbalances can be indicative of pollution (Hem, 1985)
Major anions	Water quality and origin; ion composition imbalances can be indicative of pollution (Hem, 1985)
Trace elements	Potential pollution; water origin

ArcGIS ArcMap 10.1 and QGIS Geographic Information Systems (GIS) were used to map the different environmental characteristics of the turloughs. Shape files for the habitat extensions and the soil types were obtained from the EPA website and from Waldren et al. (2015). Habitat extensions were assumed still valid and further assessment was not carried out for this thesis. Several turloughs visited by Prof. Stephen Waldren (personal communication) did not show any major shift in vegetation through these years. Also, a study of the ecohydrology of some turloughs and among these Blackrock and Lough Coy (Bathnagar et al., 2021) compared the habitat survey with maps produced using Sentinel-2 satellite images up to 2018 and concluded that *"the majority of the communities appear to stay intact"*. Soil data from Waldren et al. (2015) were compared to the data gathered in this thesis (see Section 4) to check whether they could be used (in the case that they were not statistically significantly different). The results from the statistical tests comparing the soil samples taken during the Waldren et al. (2015) study and during this thesis can be found in Appendix F.

3.2 Hydrology of the selected sites

Two of the turloughs, Blackrock and Lough Coy belong to the Gort-Kinvarra chain of turloughs which are hydraulically connected, drain the Slieve Aughty mountains and end up at Kinvarra bay (Figure 3.3). Table 3.4 presents the highest depths and water volumes. Lough Gealain and Lough Aleenaun are located in the Burren, and unlike the previous two they are characterised by a shallow karst system. Lough Aleenaun in particular shows frequent filling/emptying cycles during the hydrological year.

The hydrological characteristics of the turloughs can be found in Table 3.4. In the turloughs where deep conduits are present, contaminants have the capacity to travel faster than in turloughs where a shallow system is present. For example, in the Gort lowlands velocities between 60 and 1,000 m hr^{-1} can be reached (Coxon & Drew, 2000). Therefore, these turloughs can be affected by activities which are present in the Zone of Contribution (ZOC), but far from the turlough (Waldren et al., 2015).

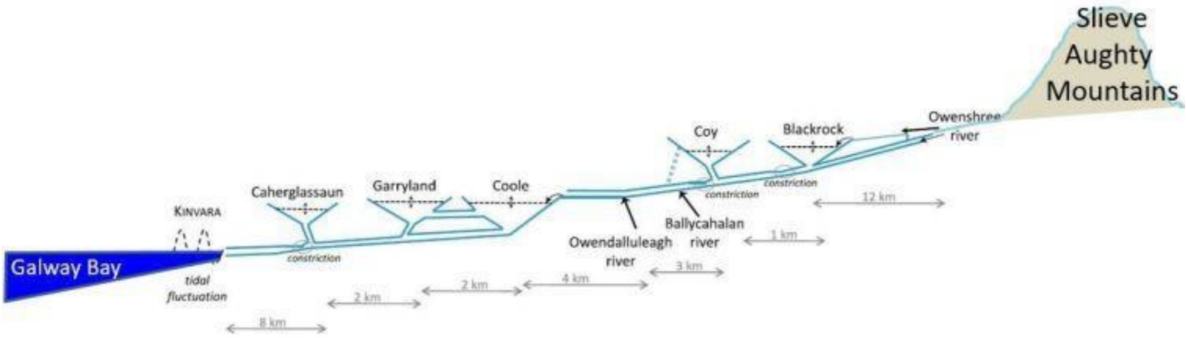


Figure 3.3. *Schematic representation of the hydrological connections from the Slieve Aughty mountains to Kinvarra bay (from Gill et al., 2013).*

Water levels and temperatures have been monitored at these sites by the GSI. Hydrological characteristics of the turloughs can be found in Table 3.4. The hydrographs were computed with data surveyed by the GSI and Naughton et al. (2011) and were used to calculate water volumes and then carbon and nutrient budgets (see Section 5.3.1 for water volumes, Section 5.4.2 for carbon budgets and Section. 5.4.3 for nutrient budgets).

Lough Aleenaun and Blackrock have the highest daily inflow and outflow percentages (Table 3.4), showing their speed in filling/emptying, which can translate for example, in flooding of nearby structures when basins are filled quickly and by particularly large water volumes.

Table 3.4. *Hydrological characteristics of the turloughs (from Waldren et al., 2015).*

Turlough	Average daily inflow ($m^3 s^{-1}$)	Average daily outflow ($m^3 s^{-1}$)	Inflow/ outflow ratio	Daily inflow/ volume (%)	Daily outflow/ volume (%)
ALE	1.548	-0.555	2.8	37.6	13.5
BLA	10.253	-2.018	5.1	22.1	4.4
CARA	0.309	-0.162	1.9	5.4	2.8
COOL	0.684	-0.193	3.6	3.7	1.1
COY	1.331	-0.842	1.6	7.8	4.9
GEA	0.844	-0.222	3.8	7.9	2.1
SKE	0.500	-0.166	3.0	11.3	3.7

3.2.1 Blackrock

Blackrock turlough is located in south Galway, between the towns of Knockauncora and Peterswell and west of R380. It extends for 143 hectares, is characterised by a conduit karst flow system and is included in the Peterswell SAC. It receives surface waters from the Owenshree River (Figure 3.3), has a drainage channel visible in summer (Figure 3.4) ending in a swallow hole where the GSI diver for the monitoring of depth is located (Figure 3.5).

***Figure 3.4**. Drainage stream in the centre of Blackrock, July 2018.*

Figure 3.5. *Lowest point at Blackrock, where the GSI's diver is located.*

Blackrock caused floods to surrounding properties in past years and its hydrological regime is an example of a part river flow-through, part surcharge tank functioning. It shows a short duration of flooding (Figure 3.6); the turlough is deep (average depth of 6.6 m and a maximum depth of more than 15 m). It has the largest volume of water of the 7 studied, and, due to the steep sides of its basin, the fastest daily inflow (Table 3.4).

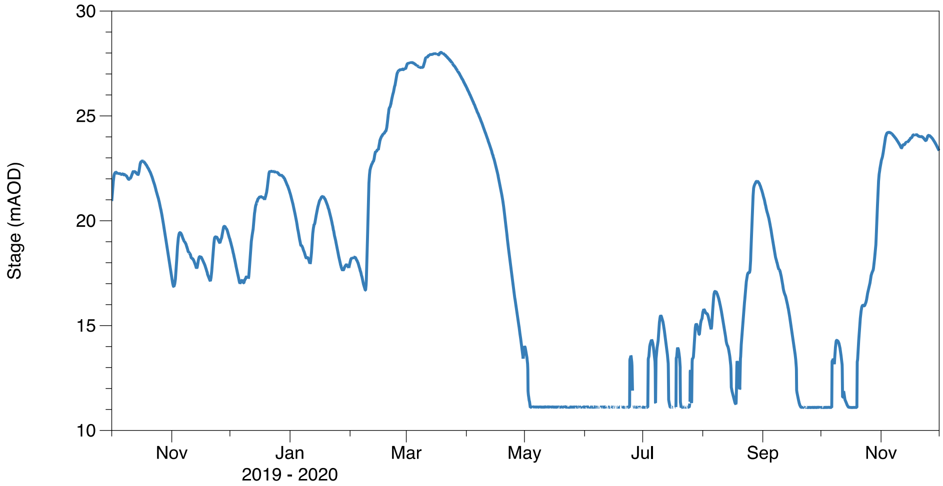


Figure 3.6. *Hydrograph of Blackrock from October 2019 to December 2020.*

Water in the turlough has a characteristic deep brown colour, due to the drainage of the Slieve Aughty mountains, covered in forestry and peatland. The depth of the turlough makes it possible to have anaerobic conditions necessary for denitrification

(Mc Cormack et al., 2016). Previous research showed nutrient concentrations dropping while the turlough is still filling which may indicate a constant influx of water, whether the turlough is flooding or emptying (McCormack et al., 2016). This could also be due to denitrification as waters in this turlough are deep, therefore making it possible to have anaerobic conditions necessary for denitrification (Mc Cormack et al., 2016).

The deposits present in the area are very shallow, well drained, moderately acidic unsorted glacial deposits, with low amounts of calcium carbonate. Ten vegetation types were recorded by Waldren et al. (2015), with the *Potentilla anserina/Potentilla reptans* community the dominant one, with abundant Lolium grassland. It hosts the important plant *Viola persicifolia*.

Several farming businesses insist on the turlough, including an abattoir. The turlough is grazed by cattle in all its extension. Another pressure source is forestry, while habitation in the ZOC is relatively low.

3.2.2 Lough Coy

Lough Coy is a 26 hectare turlough located in south county Galway and 1 km south of Blackrock turlough. It is connected to the same conduit system and its hydrological regime (Figure 3.7) shows a peak in February with several minor filling and emptying events during recharge.

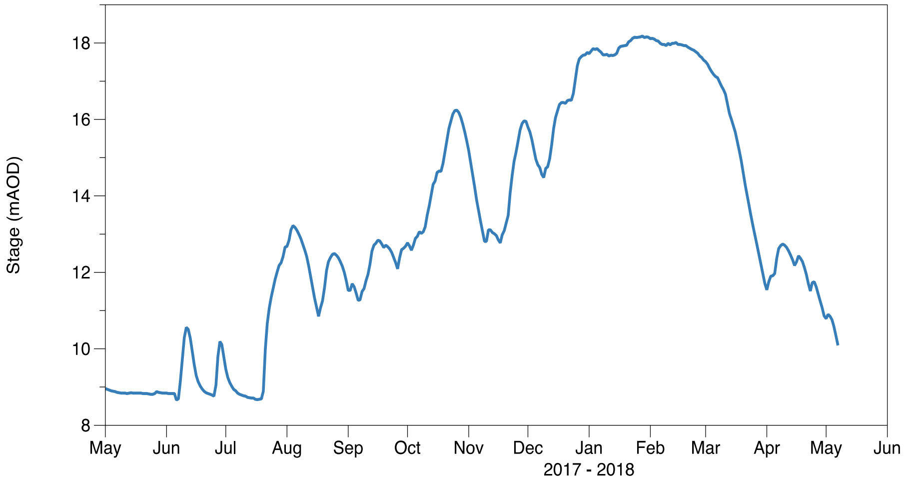


Figure 3.7. *Hydrograph of Lough Coy from May 2017 to June 2018.*

It is an example of surcharge tank turlough filling and emptying through an estavelle (Figure 3.8) and it divides in three basins during recession (Figure 3.9), while it has a single one in the flooded phase (Figure 3.10).

Figure 3.8*. Estavelle at Lough Coy.*

Figure 3.9*. Lough Coy divided in different basins, June 2018.*

Figure 3.10*. Lough Coy in the flooded phase, September 2017.*

Water nutrients show a pattern of reducing concentrations during the hydrological year similar to the one observed for Blackrock. Eight vegetation types were mapped within the site; the dominant vegetation types were *Filipendula ulmaria-Potentilla erecta-Viola sp.* and *Agrostis stolonifera-Potentilla anserina-Festuca rubra*. It contains the important plant *Viola persicifolia* and the aquatic invertebrate *Alonella excisa*. Bivalve molluscs (*Anodonta anantina*) are also present, as found during surveys in the drained phase (Figure 3.11). Lough Coy has also hosted nationally and internationally important numbers of Bewick's swans (Madden & Heery, 1997). It is therefore an SAC.

Figure 3.11. *Bivalves at Lough Coy during drainage (June 2019).*

Lough Coy soils are moderately acidic and mineral, with low amounts of calcium carbonate. The dominant soil types were 'Very shallow poorly-drained mineral' and 'Alluvial mineral'. The site is under rotational grazing and is at risk. Other impacts come from forestry and agricultural runoff (some land parcels have high stocking levels).

3.2.3 Caranavoodaun

Caranavoodaun is located in south Galway, near Castletaylor and 1 km east of the M18 and it is part of the Castletaylor complex SAC. It has a basin extending approximately for 34.6 ha, with most of the turlough staying wet all year round. Hydrologically it has one main flooding event with minor flooding events (Figure 3.12).

The flow system is shallow epikarst and the flow happens in the uppermost 2 to 5 m of the karst limestone. The duration of flooding is intermediate. Water quality is good (average of 13 μg TP l^{-1} and 9 μg SRP l^{-1}). The soil deposits present are peat-marl and sand-silt. It is at significant risk. The interest of the site lies in the variety of habitats within a small area. Twelve different communities were mapped by Waldren et al.

(2015), with *Eleocharis palustris-Ranunculus flammula* the dominant one. Soils are alkaline and highly organic, with high calcium carbonate. The important plants *Frangula alnus* and *Plantago maritima* are present as well as the small crustaceans *Alona rustica* and *Alonella excisa* which are indicative of acidic lakes.

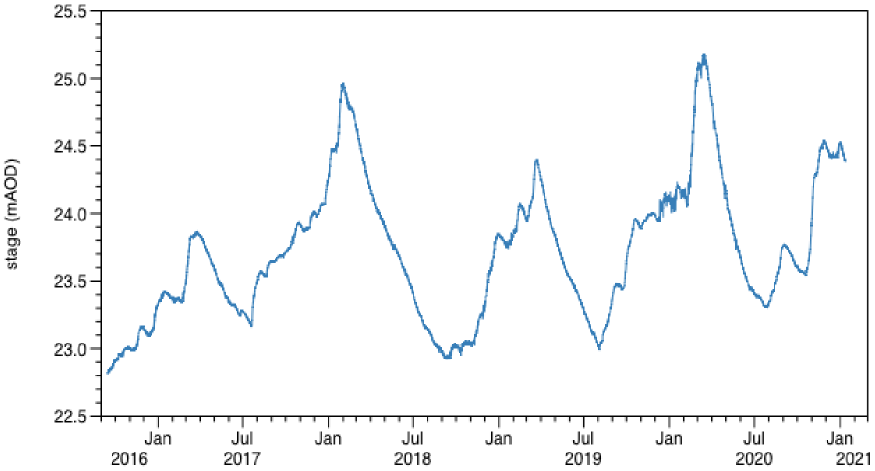


Figure 3.12. *Caranavoodaun hydrograph from January 2016 to January 2021.*

This turlough is a good example of a calcareous turlough in a very good condition (EPA, 2004), though algal growth has been noted during fieldwork (Figure 3.13). All of the site is rotationally grazed and localised damage from heavy cattle grazing and poaching can be seen. Further impacts come from the reasonably high number of dwellings within the ZOC. These threats are likely to increase and potential compromise the present good ecological condition. Threats should be mitigated since the turlough is of probable international significance.

Figure 3.13. *Caranavoodaun in September 2017.*

3.2.4 Lough Aleenaun

Lough Aleenaun is a 13.7 ha turlough in county Clare, near the town of Sheshymore and is part of the East Burren complex SAC. It is characterised by a shallow epikarst system and it has a deep basin, with short duration of flooding (Figure 3.14). It is the quintessential example of a turlough with a flashy hydrological regime, as it shows the highest flood frequency of any monitored site. Figure 3.15 shows many peaks and drops for Lough Aleenaun, as opposed to Coolcam which presents a single filling and emptying event.

The water quality can be classed as intermediate (average of 30 μg l^{-1} of TP and 15 μg l^{-1} of SRP). Six vegetation communities were surveyed in Waldren et al. (2015). *Agrostis stolonifera-Glyceria fluitans* is the most abundant community.

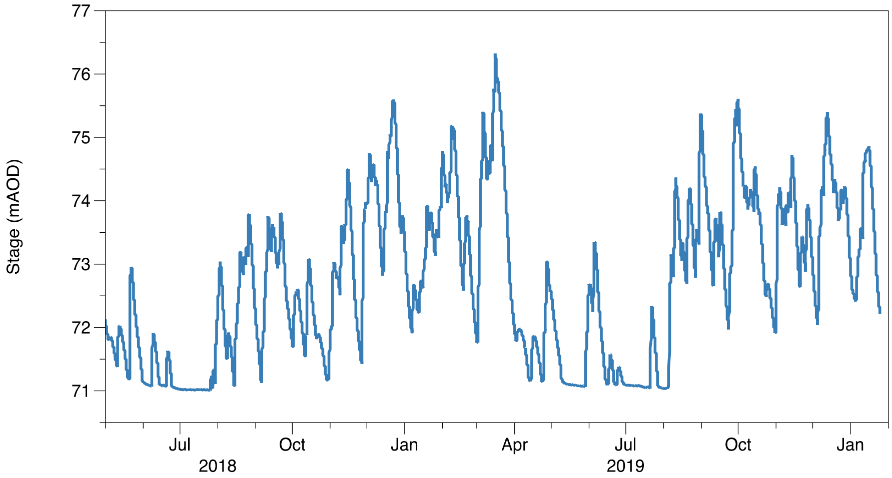


Figure 3.14. *Lough Aleenaun hydrograph.*

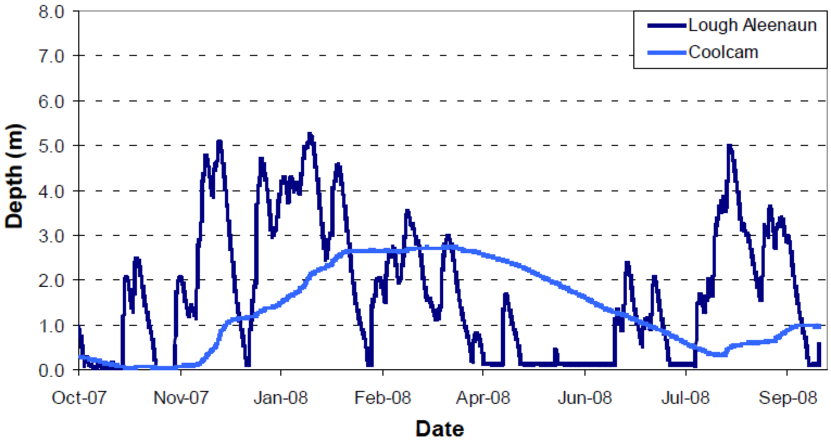


Figure 3.15. *Comparison of the hydrographs of Lough Aleenaun and Coolcam (from Waldren et al., 2015). The two turloughs represent examples of a turlough with a "flashy" regime (Lough Aleenaun) and a turlough with a unimodal flooding regime (cyclic filling and emptying event).*

The deposits present are marl and peat-marl. Eight communities have been identified, with the *Agrostis stolonifera-Glyceria fluitans* community being the most abundant. There is a high number of negative indicator communities and algal mats have been regularly reported; however it also hosts the important species *Rorippa islandica*. The soils are moderately alkaline and organic (mainly fen peat), with high amounts of calcium carbonate. There is rotational grazing throughout the turlough. It has been bulldozed in the past therefore its condition is degraded and it is at significant risk. During the drained stage (see Figure 3.16, b), areas of unvegetated soil can be prone to erosion.

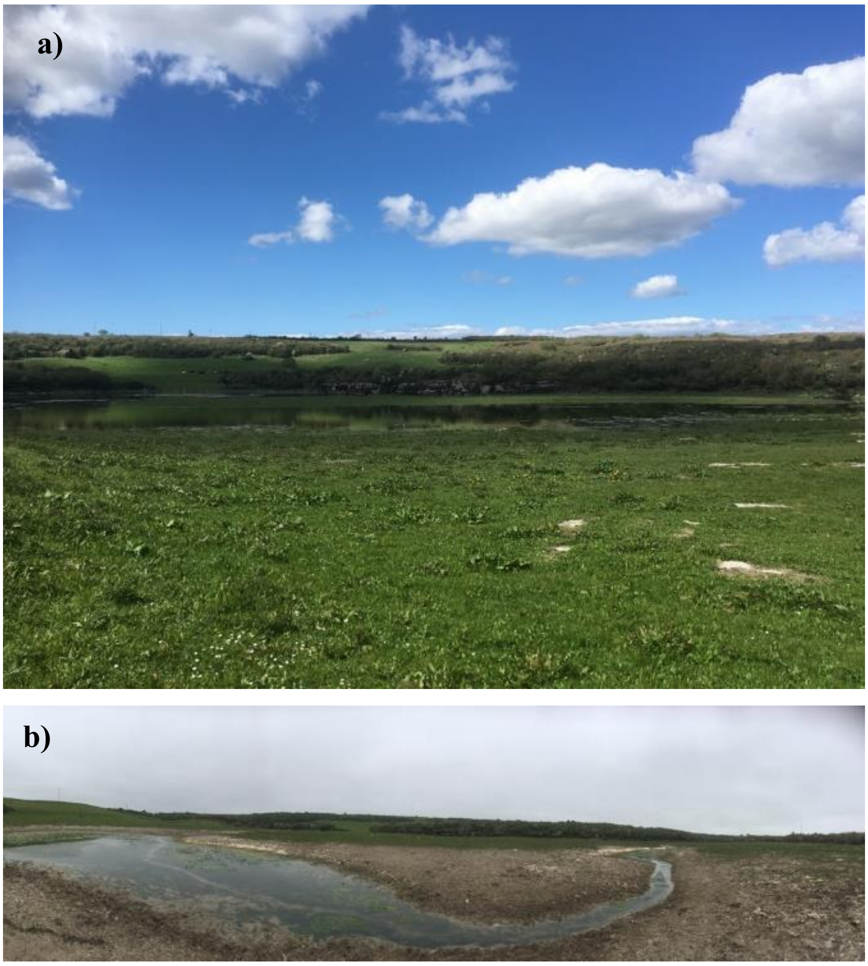


Figure 3.16. *Lough Aleenaun during (a) the filled and (b) the drained stages.*

It is an example of a turlough with a flow-through regime and groundwater in it has been observed simultaneously rising and sinking at separate points within the basin (Naughton et al., 2012, drainage channel in Figure 3.17).

Figure 3.17. *Lough Aleenaun during recession, with drainage channel in the east portion.*

Algal growth has also been noticed, pointing to eutrophication (Figure 3.18).

Figure 3.18*. Lough Aleenaun in summer with algal growth.*

3.2.5 Lough Gealain

Lough Gealain is a 37 hectare turlough located in county Clare, close to the base of Mullach Mor. It has a shallow epikarst flow system and shows one main flooding event, but with some occasional smaller peaks through the year. It is the only turlough which is not reported as grazed (though informal notification about grazing has been received), therefore representing pristine conditions. It has a main flooding event, but also minor ones during the year (Figure 3.19).

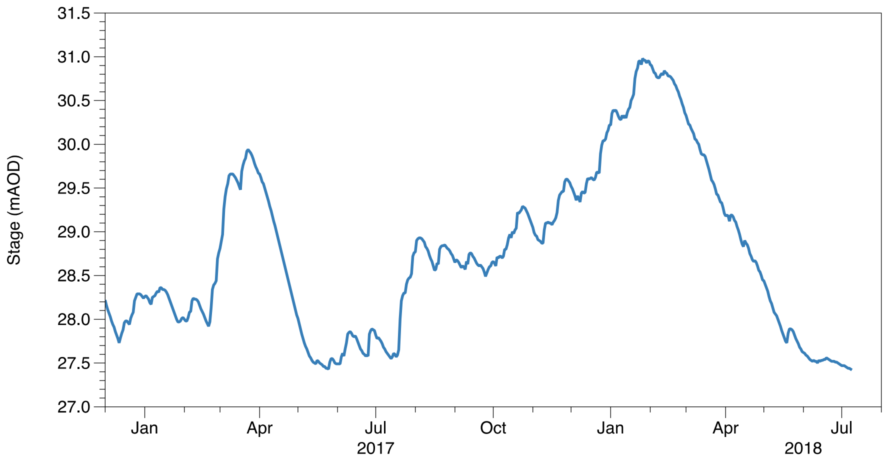


Figure 3.19*. Hydrograph of Lough Gealain from Jan 2017 to July 2018.*

Nine plant communities were mapped, with the flooded pavement one prevalent. They are dominated by *Phragmites australis* stands with a ground cover of *Littorella uniflora*. *Cladium mariscus* is also frequent (Figure 3.20). Lough Gealain soils are moderately alkaline and highly organic, with significant amounts of calcium carbonate. There are also extensive areas of alluvial marl (Figure 3.21) and very shallow poorly-drained organic soils.

Figure 3.20*. Lough Gealain in October 2017.*

Figure 3.21. *Marl deposits at L. Gealain during the drained stage (from Waldren et al., 2015).*

Being nearly pristine, any increase in groundwater nutrient would affect its ecological and it should be therefore monitored regularly.

3.2.6 Skealoghan

Skealoghan is a 33 hectare turlough located in county Mayo, near Ballinrobe. It has a flat topography and is of medium depth and intermediate duration of flooding, with one major flooding event per year, however water levels can vary extensively during the year (Figure 3.22).

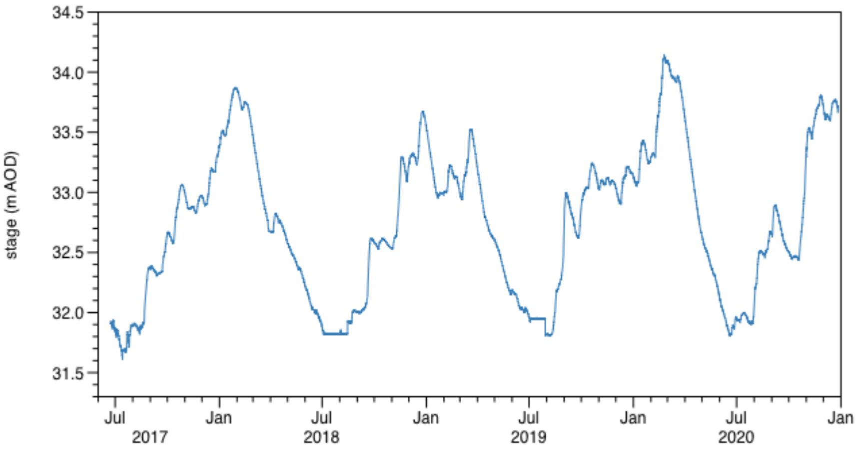


Figure 3.22*. Hydrograph of Skealoghan.*

Its soils are comprised of sand/silt but there are also extensive areas of fen peat. It is ecologically interesting as it hosts almost half of the plant communities identified in turloughs (Moran et al., 2008). Waldren et al. (2015) surveyed 15 communities and 69 plant species all around. *Cirsio-Molinietum* and *Ranunculo-Potentilletum anserinae* are the dominant phytosociological associations among the communities surveyed by Waldren et al. (2015).

Skealoghan (Figure 3.23) also contains important algal species and has extensive algal mats. Important plant species at the site are *Plantago maritima*, while among the invertebrates, *Alonella excisa* and *Eurycercus glacialis* are species of interest (Figure 3.24).

***Figure 3.23**. Skealoghan turlough in November 2019.*

***Figure 3.24**. Skealoghan in July 2018, residual wet areas with fen vegetation and peaty soils.*

Skealoghan is subject to large temporal and spatial variation in its hydrological regime and fluctuations in water level are intrinsically linked to rainfall. The spatial variation in flooding can be linked to the vegetation zones while microtopography, grazing, and soil organic carbon content are also important (Moran et al., 2007). It is subject to moderate rotational grazing and there is some evidence of fertiliser inputs directly into the turlough. It is therefore at significant risk, but despite the threats it retains considerable scientific interest.

3.2.7 Coolcam

Coolcam is a 55.4 ha turlough and is located on the borders of county Roscommon and county Galway. It consists of two basins separated by an esker (Figure 3.25 a and b).

***Figure 3.25**. Coolcam (a) main basin and (b) esker separating the basins in March 2020.*

The larger one stays wet all year long while the smaller one seems to dry out much less frequently than ten years ago. It is of medium depth and has a long flooding duration. It has peat and marl deposits, with the most common deposits being alluvial. Almost half of it is rotationally grazed and the grazing impact is low. A quarry adjacent to the site is likely to have some local impacts and there is some evidence of fertiliser inputs to the site. The number of dwellings in the ZOC is relatively low.

It has a unimodal flooding pattern (Figure 3.26) and the recession duration is the longest among the studied turloughs (140.9 days, Waldren et al., 2015).

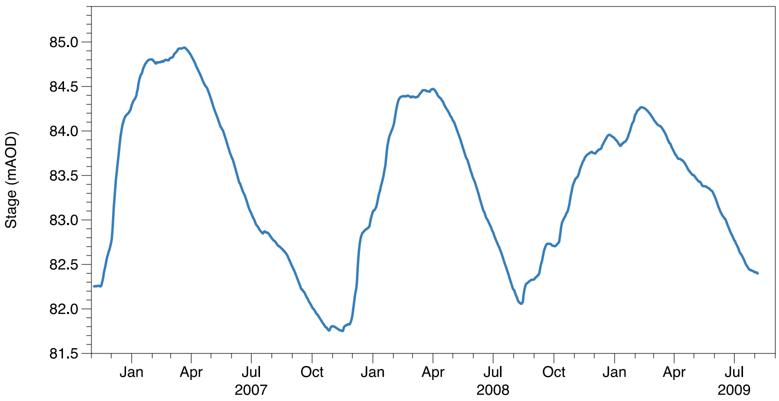
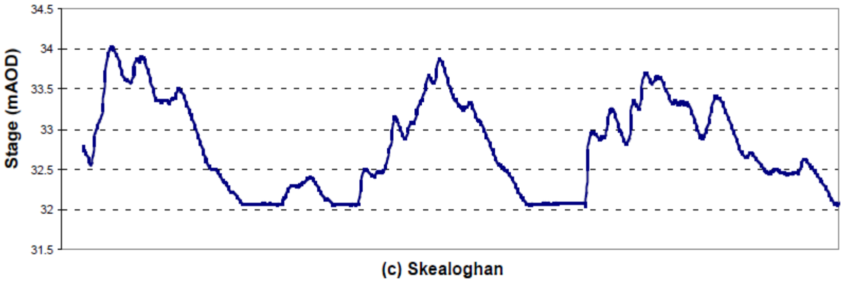


***Figure 3.26**. Hydrograph of Coolcam.*

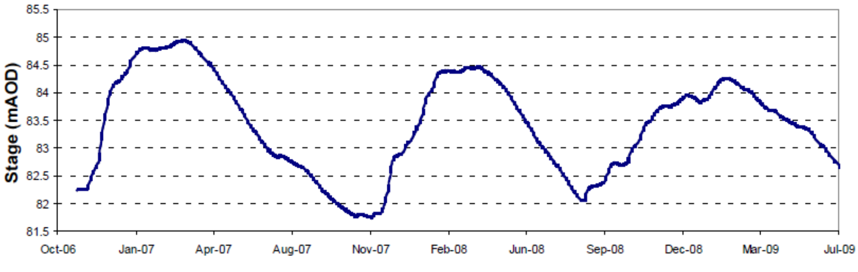
Though having the main filling and emptying cycles as those of Skealoghan, its hydrograph is smoother, as it can be seen from Figure 3.27. Fifteen vegetation communities were mapped in Waldren (2005), the most common being the *Polygonum amphibium* community, the Open water community and the *Eleocharis palustris-Ranunculus flammula* community. It is probably at significant risk and it shows some positive aspects to the vegetation, despite an overall inadequate status for conservation. It is grazed by cattle and horses (Figure 3.28).

a)



(c) Skealoghan

b)



(d) Coolcam

***Figure 3.27**. Comparison of the hydrographs of a) Skealoghan and b) Coolcam (from Waldren et al., 2015) showing a much smoother behaviour for Coolcam, with fewer minor peaks, but major peaks at similar times of the year.*

Figure 3.28. *Coolcam in April 2017 with horses and cattle grazing.*

3.3 Environmental sampling

3.3.1 Water quality

3.3.1.1 Preliminary assessment of the 55 turloughs

Samples of water were then taken once, near the highest water levels. Some of the sampling was repeated in February 2020. The sampling was performed by throwing a tethered and weighted 5 litre bottle from the turlough shores. The location of the samples varied depending on the water levels. Dates and location of sampling can be found in Appendix B. One-litre plastic bottles were then filled for the various laboratory analyses. Sub-samples were taken with a syringe via a 0.45 µm filter and added of 1M HNO_3 to be then analysed for major and minor elements via ICP-OES. For Soluble Reactive Phosphorus (SRP) samples were also passed through a 45 µm filter. The samples were then taken to the laboratory and analysed within 48 hours. The methods for the analyses of the various parameters can be found in Section 3.6.1.

3.3.1.2 Main sampling at the 7 turloughs

Samples of water were then taken monthly in the 7 turloughs selected for in-depth study and for a hydrological year (from December 2018 to November 2019) by throwing a tethered and weighted 5 litre bottle from the turlough shores (using a smaller container when water levels were lower). The location of the samples varied depending on the water levels. Samples were taken from a kayak in some winter months (when also taking measurements of GHG from waters). One-litre plastic bottles were then filled for the various laboratory analyses. Sub-samples were taken with a syringe via a 0.45 µm filter and added of 1M HNO_3 to be then analysed for major and minor elements via ICP-OES. For Soluble Reactive Phosphorus (SRP) samples were also passed through a 45 µm filter. The samples were then taken to the laboratory and analysed within 48 hours. The various parameters analysed can be found in Section 3.4.

The one-month interval was chosen as a previous study of some of the turloughs in the present thesis (Gill, 2010), showed it to be appropriate to model the spatial and temporal variation of nutrients within the turloughs. Other studies (McCormack et al., 2016, Cunha Pereira, 2011; Cunha Pereira et al., 2010; Porst et al., 2012; Waldren et al., 2015) also showed it to be an appropriate sampling methodology for ecohydrological studies on such intermittent lakes.

The date and location of the water samples taken at the turloughs can be found in Appendix B.

3.3.2 Soil characteristics

The 7 turloughs were sampled to determine the organic carbon and nutrient content of the soils and then estimate the carbon and nutrient stocks.

An overview of the number of samples taken can be found in Table 3.5, while the full list of samples, with their location and date of sampling, can be found in Appendix D. It should be noted that fewer samples were taken in some turloughs because water levels were always high.

Table 3.5. *Overview of the number of samples taken at each turlough. Raw data can be found in Appendix D, Table D.1. for a description of the soil types see Appendix A.*

Turlough	**Number of locations sampled**	**Average Soil depth (m)**	**Soil type**
L. Aleenaun	20	0.11	BorgVSP/BorgVSW
Blackrock	26	0.22	BMinSP/BminSW/BMinVSW
Caranavoodaun	5	0.19	BOrgVSW
Coolcam	16	0.16	AlluvMIN
L. Coy	10	0.1	BMinVSP
L. Gealain	23	0.15	BOrgVSP/AlluvMRL
Skealoghan	20	0.3	BOrgVSW/FenPt

Samples were taken with an auger from the uppermost 30 cm of soil if mineral (when possible, or to the soil base when shallower) with an auger (Figure 3.29, a) or to 1 m (when possible) and with a peat corer if peat was present (Figure 3.29, b). Five samples were collected from a surface of 1 m^2 and then mixed to give a composite sample. The samples were then bagged and labelled and split in two fractions: one was used for pH determination and the other was oven dried and sieved to 2 mm for the other chemical determinations (Figure 3.30, see Section 3.4.2). The sample location was recorded via a Garmin Omega 600 handheld GPS device, with an accuracy of about 3 m.

The soil sampling campaign was carried out in the summers of 2017 and 2018, when most turloughs were dry (see results in Appendix D, dates of sampling in Appendix B).

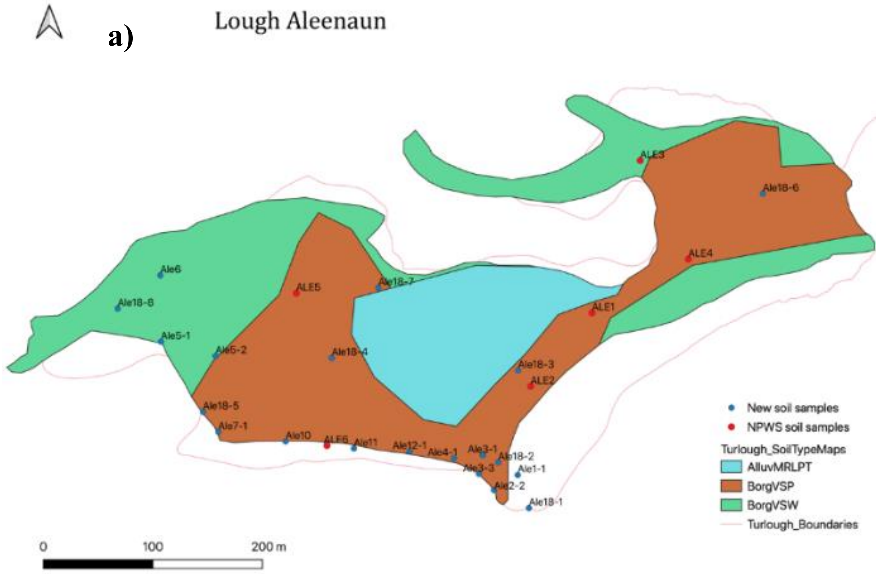
The soils and the subsoil types present at the site, as surveyed in the Waldren et al. (2015) study can be found in Appendix A, Tables A2, A.3 and A.4.

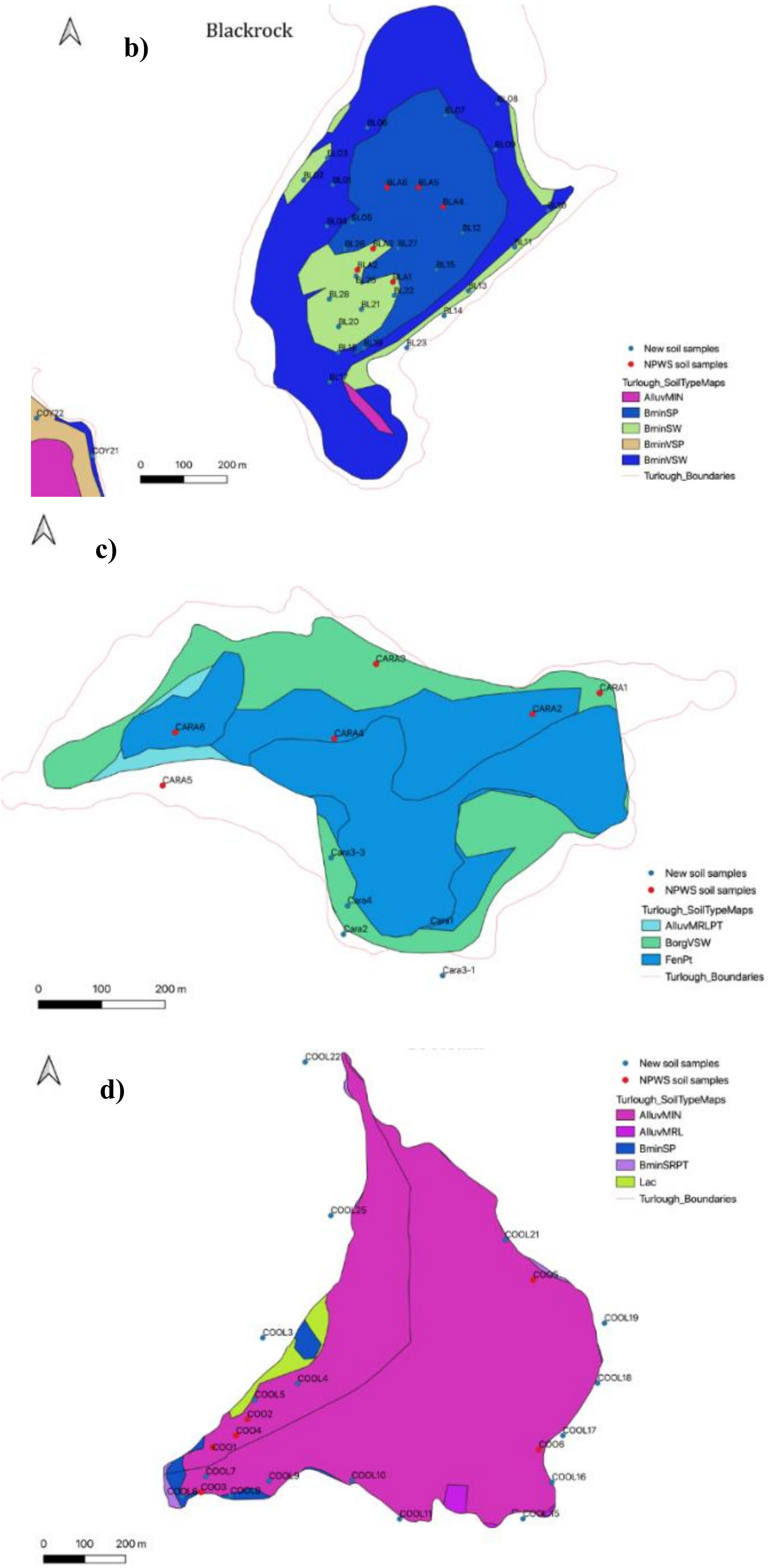
Figure 3.29*. Soil sampling campaign at Skealoghan, (a) auger and (b) peat corer.*

Figure 3.30*. Bagged soil samples after sieving.*

A total of 110 samples were taken between August and October 2017 and 78 further samples were taken in June/July 2018 (Appendix B, Table B.3 for the exact dates). The sampling strategy was to do a random sampling according to soil types and considering the soil samples taken during the Waldren et al. (2015) study. It has been shown in fact, that most soil characteristics change slowly with time, and this was in fact verified by statistical tests (results can be found in Appendix C). As soil maps had been carried out in Waldren et al. (2015) based on Teagasc maps and site surveys, the number of samples taken in each turlough were meant to verify and expand the information already available, considered again that soil characteristics change slowly (on a multi-decadal scale), in the absence of significant land-use change.

The depth of soil was recorded during sampling and in cases where the subsoil was not reached, the depth was assigned using values and estimates from the Waldren et al. (2015) study. Peatland, which is reported as having a depth greater than 30 cm in that study, was assigned a value of 1 m, as per EPA guidelines. Some soil units (like AlluvMRLPT at Lough Aleenaun and FenPt at Caranavoodaun were not sampled for accessibility reasons. The samples taken which were outside of the soil maps (e.g. samples Ale 18-1, Ale 1-1 in Figure 3.31 (a)) were not considered in the calculation of soil organic carbon and nutrient stocks. Soil type maps were not surveyed by Waldren et al. (2015) for the whole boundary of the turloughs, therefore an average of the parameters for the specific turlough was used for the missing areas.



b)
Blackrock
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NPWS soil samples
Turlough_SoilTypeMaps
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BminSW
BminVSP
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COOL9
COOL10
COOL16
COOL8
COO3
COOL6
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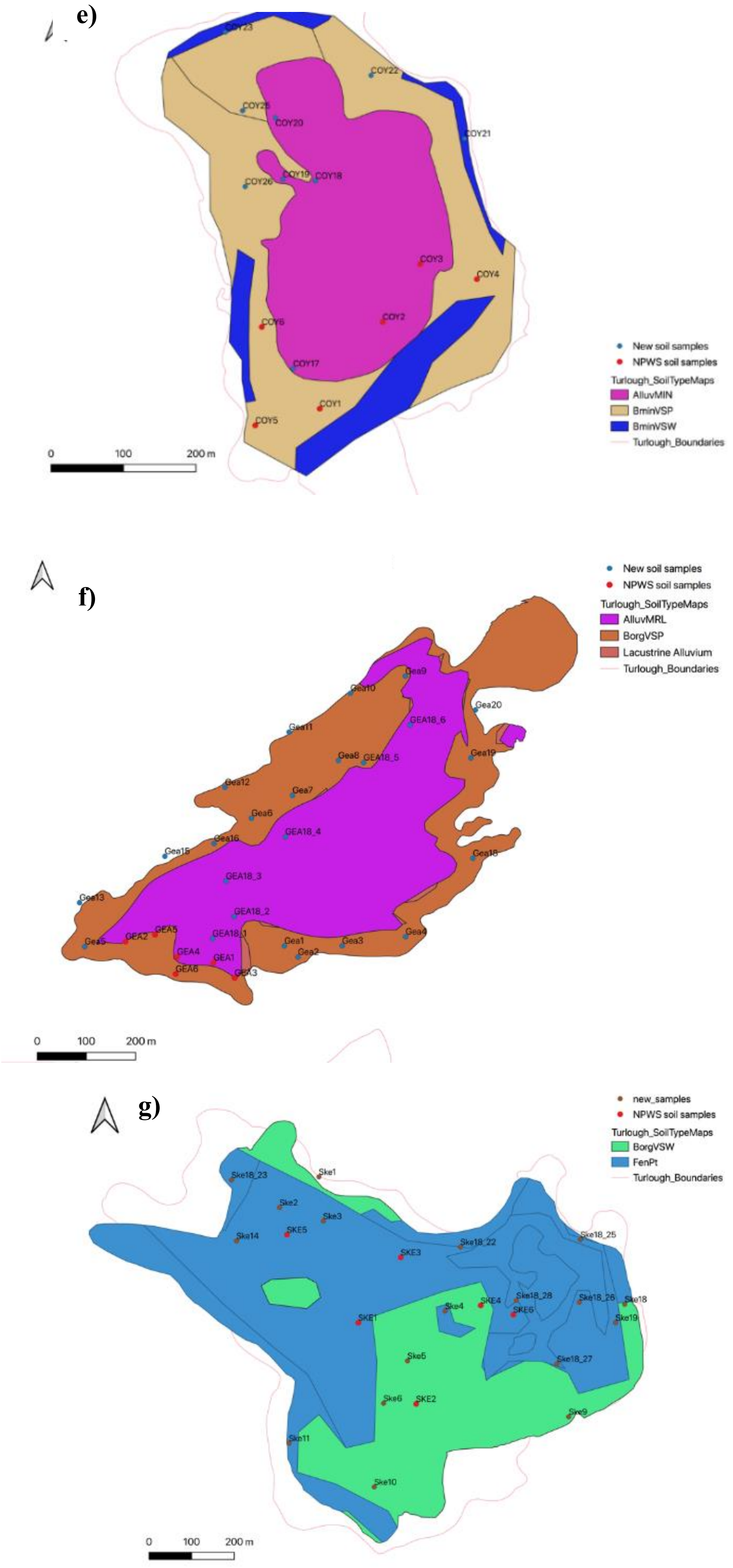

Figure 3.31. *Location of sampling points from the present study (blue dots) and from Waldren et al. (2015) (red dots). a) Lough Aleenaun; b) Blackrock; c) Caranavoodaun; d) Coolcam; e) Lough Coy; f) Lough Gealain; g) Skealoghan. NPWS samples: samples taken in Waldren et al. (2015).*

3.3.3 Measuring greenhouse gas emissions

The closed chamber method was used to determine the emissions of greenhouse gases (CO_2 CH_4 and N_2O). Measurements were taken seasonally (one measurement every three months) in 4 collars per turlough from July 2018 to September 2020 both on land and on water surfaces to capture the wet phase (autumn/winter) and the dry one (spring/summer). Being the measurements time consuming and logistically complicated, the aim was to sample at least each different habitat (grass, wetland) and extrapolate to other sites where direct measurements were missing. Also, there were problems due to the Covid 19 pandemic from February 2020 on. A table with the dates and kind of measurements (on land or on water) can be found in Appendix E (Table E.1). Literature values and emission factors were also used to integrate and validate the measurements taken.

3.3.3.1 Measurements on land

The method consisted in the insertion of 0.36 m^2 metal frames in the soil covered by a transparent Plexiglas chamber (60 x 60 x 30 cm) aiming to create a closed system (Figure 3.32, a) and the measurement was performed by an EGM-4 (PP Systems, Amesbury, USA, Figure 3.32, b).

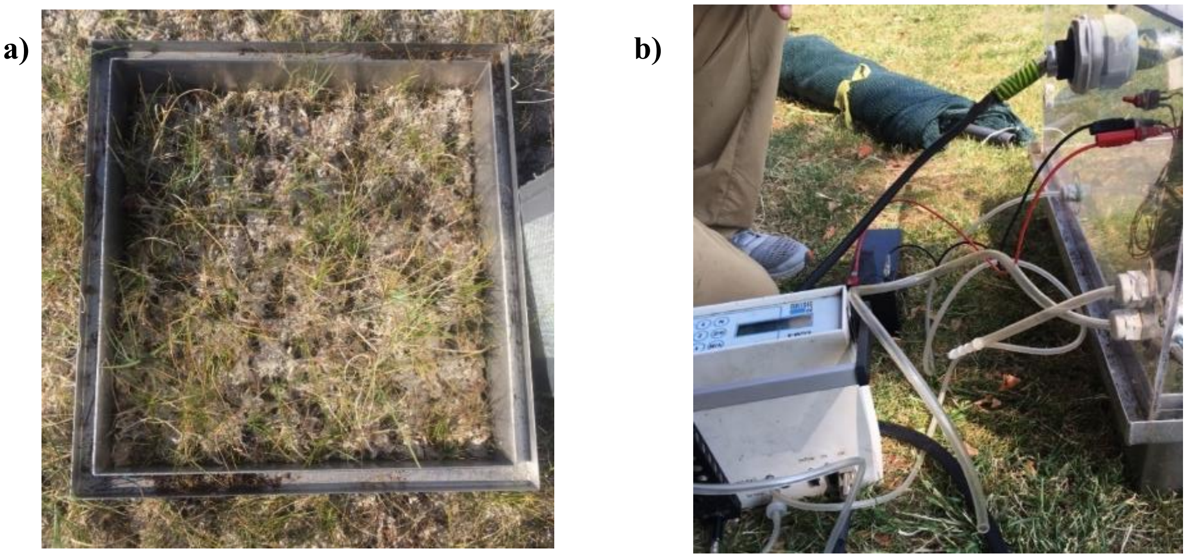

***Figure 3.32**. a) Metal frame and b) transparent chamber with infrared sensor for CO_2 field measurement.*

The EGM-4 (PP Systems, Amesbury, USA) is infra-red gas analyser with an integrated sampling pump and also containing a humidity filter. It measures CO_2 concentrations, as well as air temperature and luminosity. It was optimised for measurement in the 0 to 1000 ppm of CO_2. The luminosity was measured as Photosynthetically Active Radiation (PAR) in µmol m^{-2} s^{-1} by a TRP-2 sensor (PP Systems, Amesbury, USA). The chamber was sealed and the CO_2 concentration was recorded every 15 seconds for a period of 105 seconds. CO_2 was calculated from the slope of the linear increase in CO_2 flux over time. In order to maintain a constant temperature in conditions of high irradiance, a cooling system was installed in the chamber which pumped water from an ice bath through a small radiator located behind the fan. The measurements were performed from late morning to early afternoon, to ensure that the maximum daily irradiances were captured. Air temperatures at the time of sampling were also recorded.

The collar had a water seal at the base to ensure an air-tight closure. The chambers were made of transparent polycarbonate for CO_2 measurement. Dark clothes were used for partial and total shading of the chambers (Figure 3.33)and CO_2 concentrations were measured at each light condition.

Figure 3.33. *Chamber with covering to simulate shading.*

The chambers were fitted with fans to ensure homogenisation of the gases. The chambers were inserted in the soil to a depth of about 4 cm and then removed after the measure where they were interfering with farming operations.

Flux rates were calculated using the gas concentration, the molecular mass of carbon, chamber area, chamber volume, air temperature at the time of sampling and atmospheric pressure using the Ideal Gas Law ($pV=nRT$) (see Section 3.5 for a calculation). The mass of gas in the chamber's atmosphere (g gas-element) is determined and converted to mass of gas chamber area (g gas-element ha $^{-1}$). The flux rate of the gas-element (g gas-element ha $^{-1}$) was then determined using the slope of a linear regression plot of g gas-element ha $^{-1}$ versus time (Badiou et al., 2011).

In this thesis emissions of GHG to the atmosphere are indicated with a positive sign, while carbon sequestration has a negative sign (following for example the convention of the European Union Copernicus Programme, www.climate.copernicus.eu).

A CPY-4 closed soil chamber (PP Systems, Amesbury) was used for bare soil. Several measurements were taken at a single plot (when possible) and then averaged.

CH_4 and N_2O emissions were measured with separate opaque closed plastic chambers fitted with a fan to facilitate air mixing (Figure 3.34). Gas samples were collected from a septum in the opaque chambers in 20 ml glass vials. The vials were evacuated twice the vial volume and additionally flushed with sampling air. To avoid dilution with ambient air the vials were overpressurised by once the sample volume. Four samples were taken every 10 min starting 5 minutes from closure. The analysis was performed by Gas Chromatography with an ECD detector (see Section 3.4.3).

Figure 3.34. *Opaque chamber for the measurement of CH_4 and N_2O.*

3.3.3.2 Floating chamber method

The instantaneous CO_2 evasion from water is a component of the Net Ecosystem Carbon Balance (NECB) which is often ignored (Lawless, 2018). This was estimated by using floating chambers during the flooded phase of turloughs (Figure 3.35). A CPY-4 Canopy Assimilation Chamber from PP Systems was used. A floating platform was constructed using a buoyant material and fitted with a plastic tube insert to ensure a fixed volume and no gas escape. The CPY-4 chamber was connected to the EGM-4 NDIR sensor Environmental Gas Monitor through a power cord and gas in and gas out tubing to form a closed system. Before and in between each test, the CPY-4 chamber was flushed twice and the platform was lifted from the water surface to allow any build-up of gas to escape. Some of the metal collars left in the field were also measured during the flooded phase (Figure 3.36).

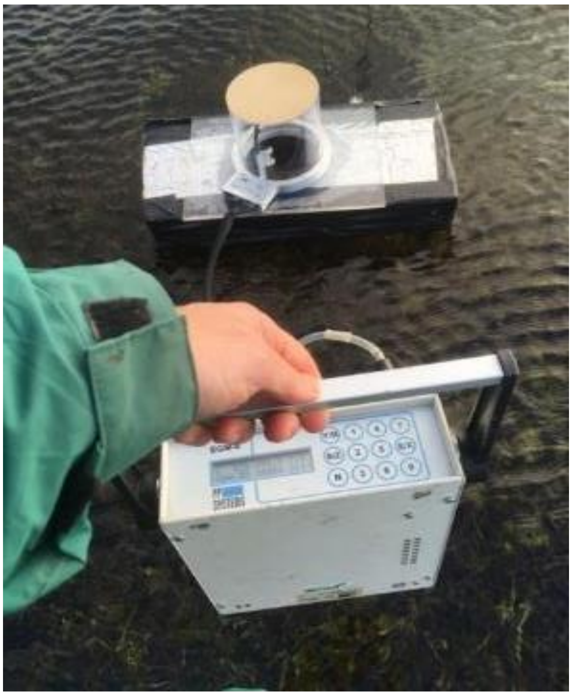

***Figure 3.35**. CPY-4 chamber connected to EGM-4 analyzer.*

At each site, trials were conducted for a total of 4 minutes for each point and CO_2 concentrations and air temperatures were recorded at regular intervals (every 5 seconds) using the EGM-4.

Figure 3.36*. Metallic frame on flooded water (Measurements with transparent chamber and EGM4 infra-red device).*

Measurement points were chosen above the points where gas measurements had been taken during the drained phase, or close to them. Samples were also taken from a plastic modified flower pot with annexed foam for buoyance (Figure 3.37) every 4 minutes for twenty minutes to determine CH_4 and N_2O emissions from water.

Figure 3.37*. Modified flower pot for taking samples of air through the septum on the top of the pot.*

Four collars were deployed in the field for each turlough. The location of the collars can be found in Figure 3.38. An overview of the GHG measurements taken can be found in Appendix E.

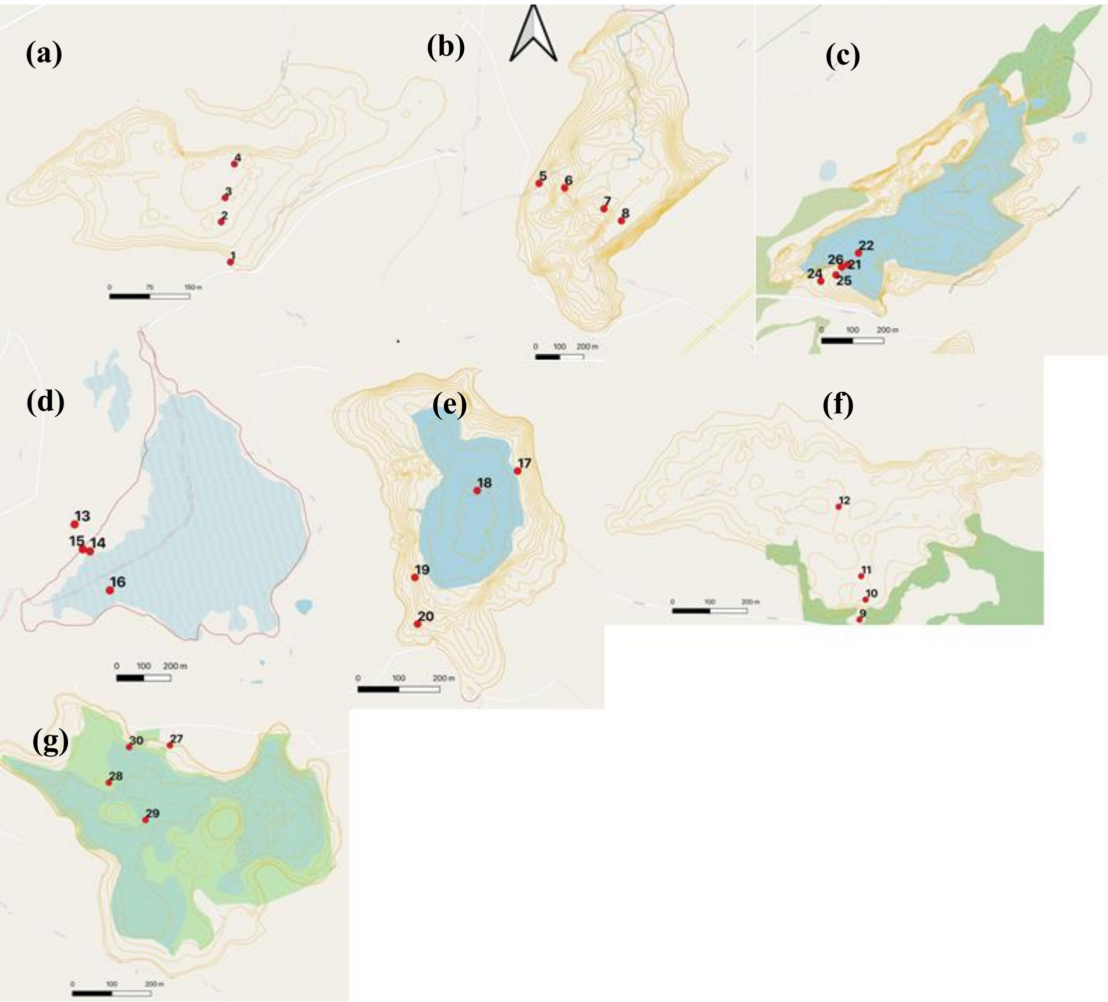

Figure 3.38. *Location of the collars for greenhouse gas measurements. (a) Lough Aleenaun; (b) Blackrock; (c) Lough Gealain; (d) Coolcam; (e) Lough Coy; (f) Caranavoodaun; (g) Skealoghan.*

3.4 Laboratory Analyses

3.4.1 Water samples

3.4.1.1 pH

pH was determined with a Jenway 3510 bench pH meter. This was used with a three point pH calibration and a resolution to the second decimal of pH. The electrode was calibrated using three standards (Varian pH 4, 7 and 10). The electrode was rinsed with milliQ water and allowed to equilibrate in a sample for several minutes.

3.4.1.2 Alkalinity

Alkalinity was determined by automated colorimetry titration at pH 4.5 with 0.01 M H_2SO_4 (Eaton et al., 2005). The pH was determined with the pH meter described in the Section above. The samples were analysed by acidimetric titration (Gran procedure) (Olin Neal, 2001) and titrated to pH 4.5 in less than 2 minutes using 0.01M sulphuric acid.

3.4.1.3 Dissolved Organic Carbon

Dissolved organic carbon (DOC) was measured on water samples using a Vario Total Organic Carbon (TOC) Select Analyzer (Elementar, Langenselbold, Germany). Samples were filtered in the field using a 0.45 µm cellulose syringe filter after rinsing the syringe and filter with 20 mL of sample. Standards containing 1 and 10 mg l^{-1} of carbon were used for quality control.

3.4.1.4 Total Nitrogen and Total Oxidised Nitrogen

Total nitrogen was determined with a Elementar varioEL cube following alkaline persulfate digestion) (Grasshoff et al., 1999). Total oxidised nitrogen (TON) was determined by automated colorimetry (Konelab, Fisher instruments). This is an automated photometer using multiple cuvettes and reagents to quantify different analytes. A scheme of its functioning can be found in Figure 3.39.

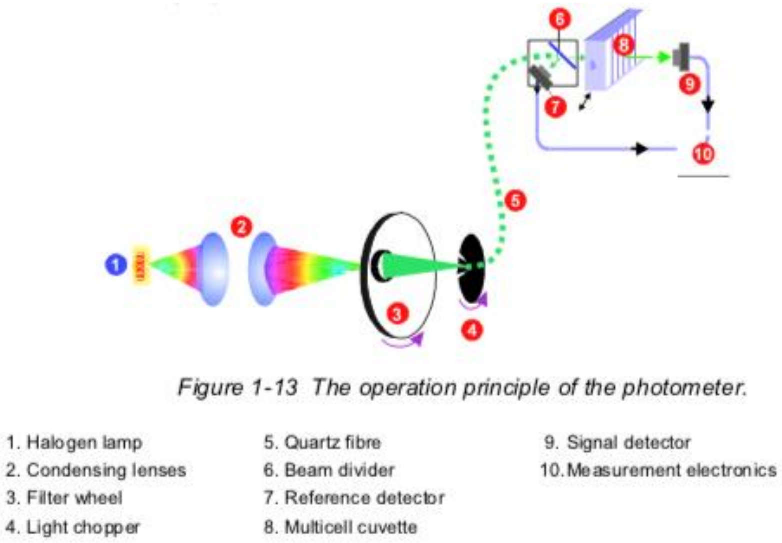

***Figure 3.39**. Scheme of the functioning of a photometer used for the determination of TON.*

Results could be obtained only from December 2018 to August 2019 for TN and TON for issues with availability of the measuring apparatus. Nitrates were however analysed from June 2019 to November 2019 to integrate the missing months for TON (nitrate is the main nitrogen species present in TON).

3.4.1.5 Total and Soluble Reactive Phosphorus

Total phosphorus (TP) was measured by acidic persulphate digestion followed by colorimetry (Eisenreich et al., 1975) with a Hach DR5000 spectrophotometer at 665 nm (single wavelength). 25 ml of water samples were pipetted in glass jars in triplicates and 5 ml of persulfate solution (containing $K_2S_2O_8$ in H_2SO_4). The samples were autoclaved for 2 hours at 120 °C. Five ml of the samples were then pipetted to tubes and 1 ml of the colorimetric solution (containing ammonium molybdate-antimony potassium tartrate solution) was added.

Soluble Reactive Phosphorus (SRP) was also determined by colorimetry similarly to TP, but on filtered samples (0.45 μm Whatman GF/C filters) and without persulfate digestion.

3.4.1.6 Anions

Nitrates, sulphates and chlorides were analysed with a Dionex ICS-1500 Ion Chromatography system which uses conductivity detection. Filtered samples (0.45 μm Whatman G/C filters) were introduced in the machine and before running a sample, the ion chromatography system was calibrated using a standard solution. By comparing the data obtained from a sample to that obtained from the known standard, sample ions can be identified and quantified. Ions were identified based on retention time, and quantified by integrating peak area or peak height and comparing them to those produced from a standard solution.

3.4.1.7 Major and trace elements

Major and minor elements present in the samples (see Appendix C), were analysed by ICP-AES and ICP-OES with two different spectrometers, at the Department of Civil, Structural and Environmental Engineering of Trinity College and at the National Centre for Isotope Geochemistry, UCD.

The first instrument, a Varian Liberty ICP-AES was an axially-viewed sequential ICP-AES. (atomic emission spectroscopy). The instrument can measure concentrations of the elements in the parts-per-million (ppm) and parts- per-billion (ppb) range over a wavelength range of 189-940 nm. The samples are vaporized in an argon plasma torch operating at 10,000 °C (18,000 F) and the resulting atomic emission spectra were analysed to determine the elements and concentrations present in the sample. Major cations were also determined with an Agilent Technologies S110 ICP-OES with an SPS 4 Autosampler. P was analysed at a wavelength of 214.914nm using a calibration with standards at 1mg l^{-1} P, 10 mg l^{-1} P and 100 mg l^{-1} P. An independent QC at 40 mg l^{-1} was run to cross-check the calibration.

The second instrument used was a Thermo Scientific™ iCAP™ Q ICP-MS. After dilution in 0.2 M HNO_3, samples were measured by the laboratory technician at the National Centre for Isotope Geochemistry, UCD, in high matrix and both standard and collision cell mode, using He as the collision cell gas (4.85 ml min^{-1}). Samples were introduced by the technician into the mass spectrometer through a cyclonic, Peltier-cooled spray chamber with an ESI PFA-ST nebulizer at a rate of ~ 100 µl min^{-1}. Monitored masses were 7Li, 23Na, 24Mg, 39K, 52Cr, 55Mn, 56Fe, 59Co, 60Ni, 63Cu, 66Zn, 75As, 88Sr, 111Cd, and 208Pb, with a dwell time of 20 ms (200ms for 75As), one peak per mass, and 10 sweeps/run for 20 runs. Lithium, Sr, Cd, and Pb were measured in standard mode, all other elements in collision cell mode. For samples, a survey scan was performed in collision cell mode.

For quantification, external standardization with dilutions of a Sigma-Aldrich TraceCert periodic table mix 1 (Lot #BCBR7889V) was used for a concentration range between 1 and 10 ppb. Standards and on-peak blanks were measured at the beginning of each day, and blank intensities were automatically subtracted from subsequent measurements. Every 20 to 30 samples standardization was repeated to account for instrumental drift. Data were processed using the QTegra software package.

Calcium was measured separately on mass ^{44}Ca in collision cell mode, with additional interference monitoring of masses ^{42}Ca, ^{43}Ca, ^{47}Ti, ^{48}Ca, and ^{88}Sr, using a monoelement Ca reference solution (Fisher Chemical, Lot # 638128) for quantification. Washes between samples consisted of 80 seconds of 5% HNO_3 with accelerated peristaltic pump speed, followed by 80 seconds of sample take up for all methods.

3.4.1.8 Chlorophyll α

Chlorophyll α was determined by absorbance spectrophotometry after methanol extraction (Clesceri et al., 1989). The chlorophyll α net absorbance is the absorbance at 662 nm minus a turbidity correction (absorbance at 750 nm). The chlorophyll α concentration (in μg l^{-1}) was then calculated with Equation 3.1:

$$Chl\alpha = \frac{13.9 \times A \times v}{V} \qquad (3.1)$$

where

A is the net absorbance;

v is the volume of methanol used (in ml);

and V is the volume of water sample filtered (in litres).

3.4.1.9 Colour

Colour was determined spectrophotometrically at 445 nm after filtration (0.45 μm, Whatman GF/C filters) with a Hach DR/2000 Direct Reading Spectrophotometer (Eaton et al. 2005).

3.4.1.10 Turbidity

Turbidity was determined nephelometrically on unfiltered samples using a Hach 2100P Turbidimeter (Eaton et al., 2005).

3.4.2 Soil analyses

3.4.2.1 pH

Soil samples were mixed with deionised water (1:1 volume) to achieve a slurry. The slurry was shaken and let to stand for 30 minutes. The pH was then determined by potentiometry with a Mettler Toledo pH meter (Allen, 1989, Figure 3.40).

***Figure 3.40**. pH meter for soil pH determination.*

3.4.2.2 *Total carbon and nitrogen*

Total carbon and nitrogen were determined using a Elementar varioEL cube (for solids) elemental analyser according to Verado et al. (1990). This instrument operates a combustion of the sample to 1200°C and the detection is by a Thermal Conductivity Detector (TCD) for C and N. The absolute precision is <0.1% Samples of dried and ground soils (<2mm in size) were prepared in triplicates, weighed (about 1 g) and wrapped in tin foil to be inserted in the instrument's autosampler.

Organic carbon in the soil samples has been determined by Loss On Ignition (LOI). The amount of carbonate has been determined by ignition of the sample at 1000°C in order to find the amount of CO_2 resulting from the breakdown of carbonates. This amount was then multiplied by 1.36 (ratio between molecular weight of CO_3 and CO_2), according to Bengtsson & Enell (1986). The inorganic fraction was calculated as the difference between the total weight and the organic plus $CaCO_3$ fractions.

The weight of the samples were taken before and after each step. The organic carbon fraction was calculated using Equation 3.2 (Ball, 1964):

$$w_v = \frac{(m_b - m_c)}{(m_b - m_a)} \times 100 \qquad (3.2)$$

where

w_v is the loss on ignition of the dry mass of a solid sample, in percentages;

m_a is the mass of the empty crucible, in grams;

m_b is the mass of the crucible containing the dry mass, in grams;

m_c is the mass of the crucible containing the ignited dry mass, in grams.

***Figure 3.41**. Sieved and dried samples before being heated in the oven.*

3.4.2.3 Phosphorus

Total phosphorus was measured by ICP-OES (Inductively coupled plasma-Optical Emission Spectroscopy, with an LOD of 0.05 ppm) following 69% nitric acid digestion. A weighed amount of sample was made to 50 ml by adding nitric acid solution. The sample was left to digest in a glass vial and the solution was then filtered through a paper filter (Figure 3.42).

***Figure 3.42**. Digested soil samples passed through paper filters.*

The filtered solution was then analysed in triplicates by ICP-OES. P was analysed at wavelength 214.914nm using a calibration with standards at 1mg l^{-1} P, 10 mg l^{-1} P and 100 mg l^{-1} P. An independent QC was run at 40 mg l^{-1} to cross check the calibration % error, calculated as shown in Equation 3.3:

$$\% \text{ error} = (\text{accepted} - \text{experimental}) / \text{accepted} * 100\% \qquad (3.3)$$

3.4.3 Greenhouse gas analysis

The 10 ml vial samples taken on the field were analysed on a Clarus 500 Gas Chromatograph from Perkin Elmer with a flame ionization detector (FID), a ^{63}Ni Electron Capture Device (ECD) and a 30 m long Elite-plot Q column (inner diameter, 0.53 mm) (Figure 3.43). The detector temperatures were set at 300 °C (FID) and 375 °C (ECD). The analytes determined were CH_4 (detected by the FID) and N_2O (detected by the ECD).

Figure 3.43*. Perkin Elmer GC with autosampler.*

The FID equipped with a methaniser uses an H_2 and air flame to generate ions from the combustion of an organic compound and the detector collects and measures the concentration of these ions to determine the amount of compound in the sample. Standard gas canisters (Figure 3.44) were used to develop a calibration curve.

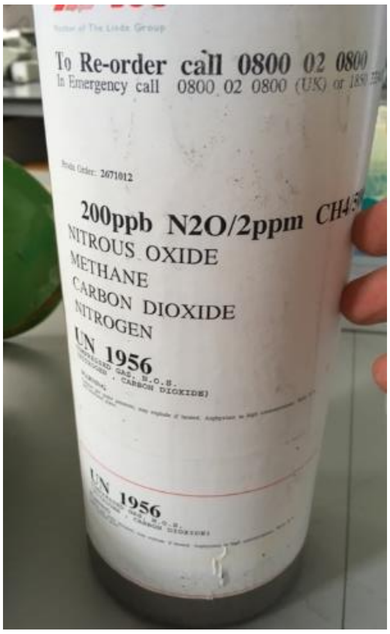

***Figure 3.44**. Gas canister with standard gas mixture.*

The canisters contained a mixture of N_2O, CH_4 and CO_2, with the following concentrations in ppm respectively: 0.2, 2, 200; 0.5, 5, 500; 1, 10, 1000; 5, 50, 5000. Glass vials were filled with the standard gas mixes and analysed together with the samples collected in the field (Figure 3.45).

***Figure 3.45**. Filling of vials with standard gas mixtures.*

The method was tested against the standards and the analytical data gave and accuracy of ±5% and a precision of ±3%. Gas method detection limits were 170 ppb and 20.7 ppb for CH_4 and N_2O, respectively.

The fluxes were calculated in Excel using the following method:

1. The area of the peaks in the chromatograph had a linear relationship with the concentration. The peak areas were therefore converted to concentrations through standards of known concentrations. Three standard gas mixes (2, 5 and 10 ppm CH_4 and 200, 500 and 1000 ppb N_2O) were measured at each GC run.
2. Data points were discarded if the GC measurements had been interrupted or had malfunctioned.
3. The R^2-value of the linear regression was used as quality control ($R^2 > 0.7$).

3.5 Greenhouse gas fluxes calculation

The increase of CO_2 in the chamber over time (an example can be seen in Figure 3.61) was used to calculate the Flux of CO_2 according to the ideal gas law, as explained in Equation. 3.4.

$$F = \frac{P \times V \times s}{A \times R \times T} \tag{3.4}$$

where:

F is the flux of CO_2 (in μmol mol^{-1} $m^{-2}s^{-1}$);
P is the pressure inside the chamber (in Pa);
V is the chamber volume (in m^3);
S is the slope of the increase of CO_2 with time (in μmol mol^{-1} s^{-1});
A is the area of the surface of the chamber (in m^2);
R is the universal gas constant (8.314Pam^3 K^{-1} mol^{-1});
T is the absolute temperature at the beginning of the measurement (K).

Linear regression was chosen as it was deemed suitable over the short chamber closure time used (up to 120 s) following Kandel et al. (2016), as it can be seen in Figure 3.46.

This flux represents the algebraic sum of the Gross Primary Production (GPP) and of the Ecosystem Respiration (ER). The three conditions measured on site (in the central hours of the day to be closed to maximum values of GPP) were: full light (the transparent chamber was in full light), partially shaded (a nylon cloth which provided some shading was used to cover the chamber) and fully shaded (the partially shaded cloth plus a black opaque cloth were used to cover the chamber).

The full light condition represented conditions at the time of measuring (minus a little shading due to the transparent Plexiglas). The partially shaded condition represented conditions between dawn and dusk and excluding the central hours of the day. The fully shaded condition represented night condition, therefore being very close to only giving ER (as photosynthesis stops for low levels of light). These three situations were used to build a regression curve, linking light levels with fluxes (Figure 3.47).

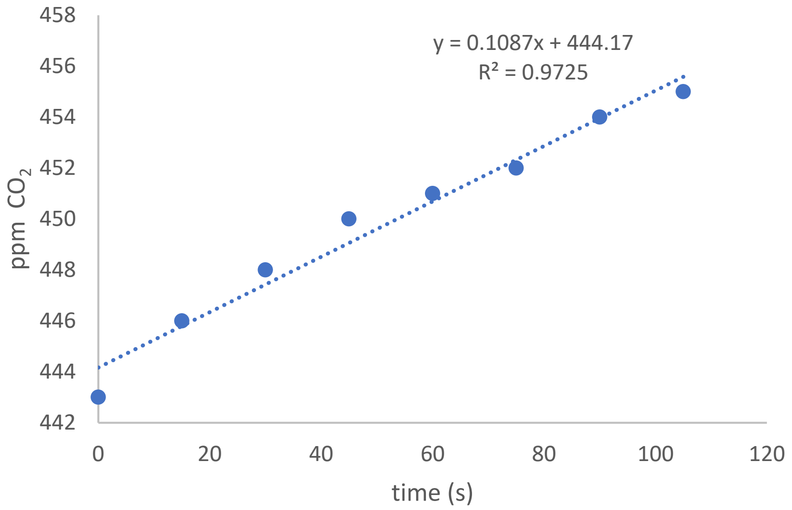

Figure 3.46. *Linear increase of CO_2 concentration with time in a chamber at Collar 1, Lough Gealain, 9 July 2018.*

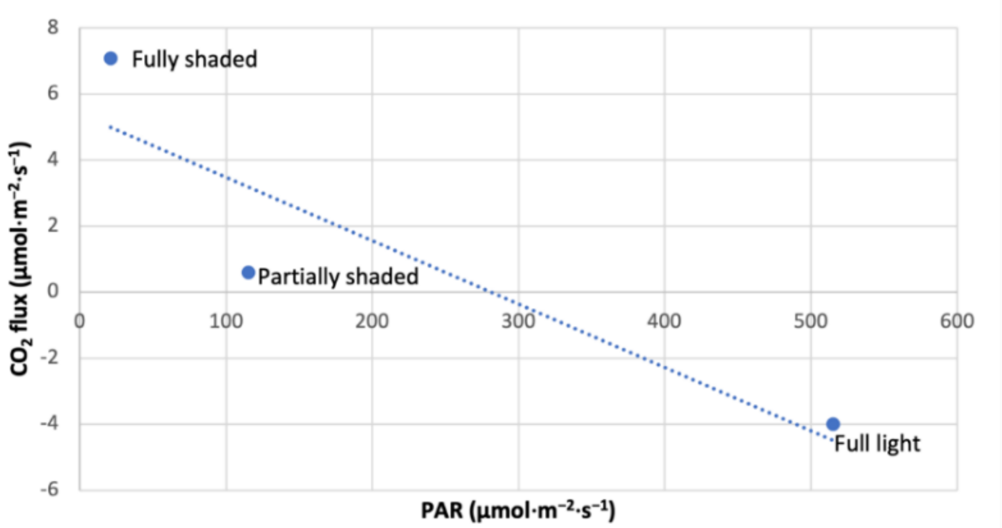

Figure 3.47. *Example of regression of CO_2 flux values (for a chamber on soil at Lough Aleenaun, 13 March 2019) over PAR (solar irradiance) values for conditions of full light, partially shaded and fully shaded. The intercept of the regression curve (5.3945) represents the ER (flux value at a 0 PAR value with no photosynthesis).*

Fluxes were then interpolated using half-hourly Photo Active Radiation (PAR) values taken from a meteorological station at Clara Bog (operated by the Botany Group of Trinity College) to give fluxes during the day at half-hourly intervals. This seasonal flux values for a day were then considered representative of the season in which they were taken and therefore the regression equation was applied to the PAR values measured at Clara bog to give regressed flux values over the whole season (see also Section 5.4.2.1).

Fluxes were calculated both on dry terrain and on wet surfaces (wet soil and water) with the floating chamber methodology, as explained in Section 3.3.3.2. An example of the calculation can be found in Table 3.6. The fluxes calculated at each of the four chambers at each turlough were averaged to give a single average seasonal value (separated between wet and dry measurements). In the example in Table 3.6 a negative flux was calculated, signifying that carbon was being absorbed by vegetation through photosynthesis).

Table 3.6. *Example of the spreadsheet in Excel used for the calculation of the Flux of CO_2 for a chamber at Caranavoodaun on 5 Sep 2019. The negative flux indicates carbon sequestration.*

T (C)	**ATMP (hPa)**	**PAR (µmol/m^2/s)**	**CO_2 (ppm)**	**time (s)**	**slope**	**N mol of air**	**F CO_2 (µmol mol^{-1} m^{-2}s^{-1})**
18.4	1023	222	385	0	-0.003	4.558	-0.04
18.4	1022	222	385	15			
18.5	1023	228	381	30			
18.5	1023	237	380	45			
18.5	1023	240	384	60			
18.6	1022	240	383	75			
18.6	1023	240	386	90			
18.7	1022	237	385	105			

Slope = this is the slope of the regression curve of the concentration with time
n (mol of air) = This equals $\frac{PV}{RT}$
F CO_2 (µmol mol^{-1} m^{-2}s^{-1}) = the flux of CO_2 in the chamber

3.6 Estimation of organic carbon stocks

The soil organic carbon (SOC) stock was determined with the procedure explained below. The maps of SOC fractions and their stocks can be used for modelling SOC dynamics and forecasting changes in SOC stocks as response to land use change, management, and climate change.

The procedure followed to obtain SOC stocks was to first calculate average values and standard deviations (when more than one sample was available per soil unit) based on each single soil unit mapped in Waldren et al. (2015) using the values obtained from the loss on ignition procedure explained in Section 3.4.2.2 and the values from Waldren et al. (2015), when they were not statistically different from the ones from this thesis (Statistical tests can be found in Appendix F, as well as normality tests before the application of Welch's t-tests. When the groups were not normally distributed, a Mann Whitney test was performed instead). Averages of SOC were calculated for each soil unit, by using the results from the soil samples taken in those units.

To then obtain the stocks of SOC, Equation 3.5 was used:

$$SOC_{kg/_{m^2}} = d \times BD \times SOC_{g/_{kg}} \times \left(1 - \left(\frac{st}{100}\right)\right) \quad (3.5)$$

where:

SOC_{kg/m^2} is the SOC (in kg/m^2);

d is the soil depth (in metres);

$SOC_{\mathrm{g/kg}}$ is the soil organic carbon percentage;

BD is the bulk density (in kg/m^3);

st is the stoniness (% volume).

The depths reached by the sampling were between 10 and 30 cm for mineral and organic soils, while a depth of 1 m was used for peats (following the guidelines by FAO and by the Global Soil Partnership (Batjes et al., 2017a).

Values of bulk density were taken from Waldren et al. (2015). These values were multiplied by the SOM percentage and converted to SOC using a conversion factor of 0.47. It is commonly assumed, that organic matter contains an average of 58% organic carbon (the so-called Van Bemmelen factor 1.724; for non-organic horizons: SOC = SOM/1.724). For organic horizons, conversion factors range from 1.9 to 2.5 (Nelson and Sommers, 1982). For peat a carbon proportion of 0.5 was used (Yu, 2012).

Stoniness was calculated as % volume from the weight of stones (fraction >2mm in size) for each sample.

4 RESULTS: FIELDWORK AND LABORATORY ANALYSES

4.1 Water quality

This section illustrates the results of the surveying of waters from the turloughs. The first part shows the outcomes of the surveying of the 55 turloughs which was carried out on a once-off basis, to give an overview of the water chemistry of Irish turloughs. The hydrochemical data, together with historical data collected on these turloughs, were used to attempt to value them using a benefit transfer approach based on the in-depth valuation performed on the seven turloughs. The second part deals with the seven turloughs studied in depth and monthly over a hydrological year.

4.1.1 Preliminary investigation of 55 turloughs

Water samples were collected from the 55 turloughs between February and April 2018 and February 2020 to provide a broad overview of the water quality of Irish turloughs and give indications on the provision of ES. The results of the chemico-physical and chemical analyses can be found in Appendix C, Tables C1 and C2.

4.1.1.1 Principal Component Analysis (PCA) of major elements

PCA helps explore multivariate data and visualise the factors that determine variation in the data. This technique has been applied to several subgroups of the chemical variables. In a first one, the main cations have been considered (Na, K, Ca, Mg, Fe), then major and minor cations were used.

The PCA of major cations (Figure 4.1) highlights several turloughs with extreme values/scores. For example, Breandrum and Ardmullan have high Fe contents, while Tullynafrankagh has high Ca and Na contents. Separate groups of turloughs according to location or geological characteristics of the substratum were not found.

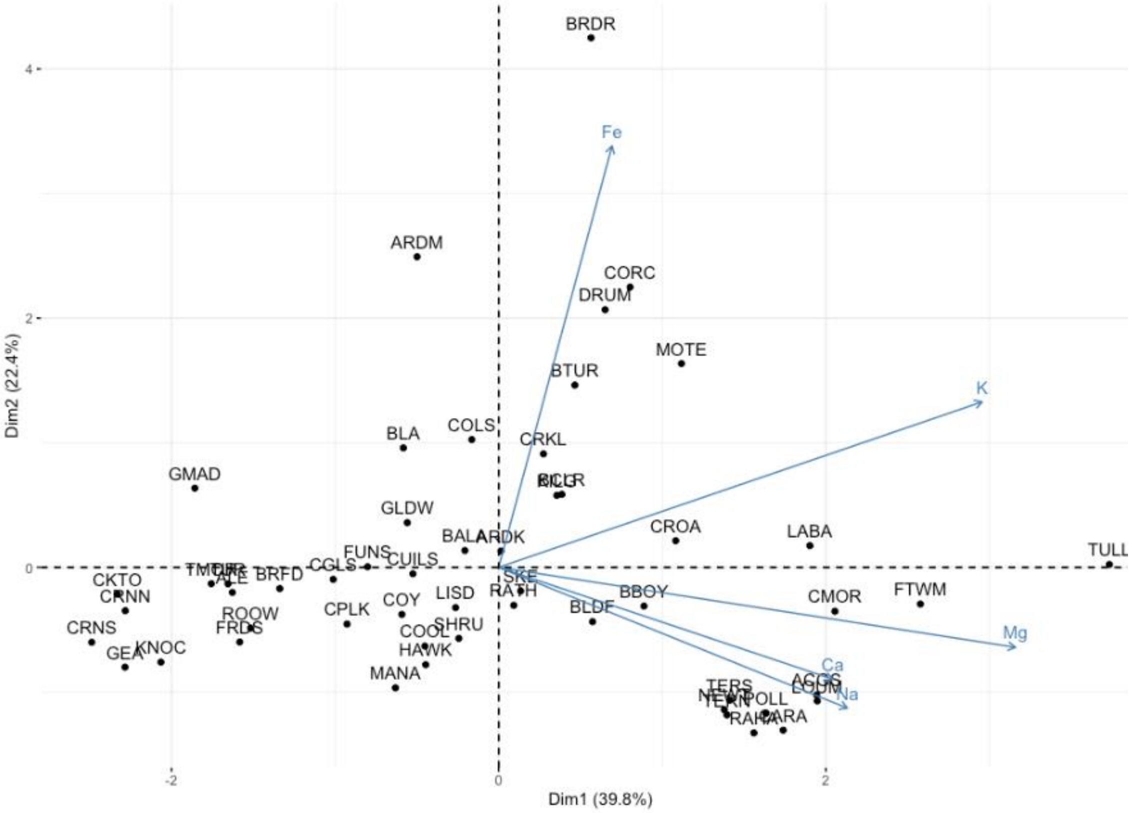

***Figure 4.1**. PCA of major elements. See Table 3.1 for site names.*

4.1.1.2 Principal Component Analysis of minor elements

The PCA of minor elements (Figure 4.2) highlights that Blackrock has the highest Ni content, Ballinturley high Co and As, Coole, high Cu and Lough Aleenaun high Cu, Zn and low Sr. These values could point to potential pollution sources and therefore have an impact on biodiversity and habitat quality.

4.1.1.3 PCA of chemico-physical parameters and nutrients

The factors considered in this PCA can be observed in Figure 4.3 (a). The PCA in figure 4.3 (b) allows to highlight Breandrum, Polldowagh, Labane, Tulla, Moate and Rahasane as standing out of the main group of the other turloughs. Breandrum shows high E.C., Total Dissolved Solids (TDS), colour, alkalinity. Polldowagh high E.C., alkalinity, TN, SRP and TP and low colour. Labane has high E.C., TDS and TN. Tulla high TDS and E.C and low ORP. Moate has low ORP and high alkalinity. Rahasane has high TDS and low colour.

Electrical conductivity varied between 163 μS cm^{-1}(Carrowkeel) and 647 μS cm^{-1} (Rahasane), while TDS between 110 mg l^{-1} (Four Roads) and 342 mg l^{-1} (Polldowagh).

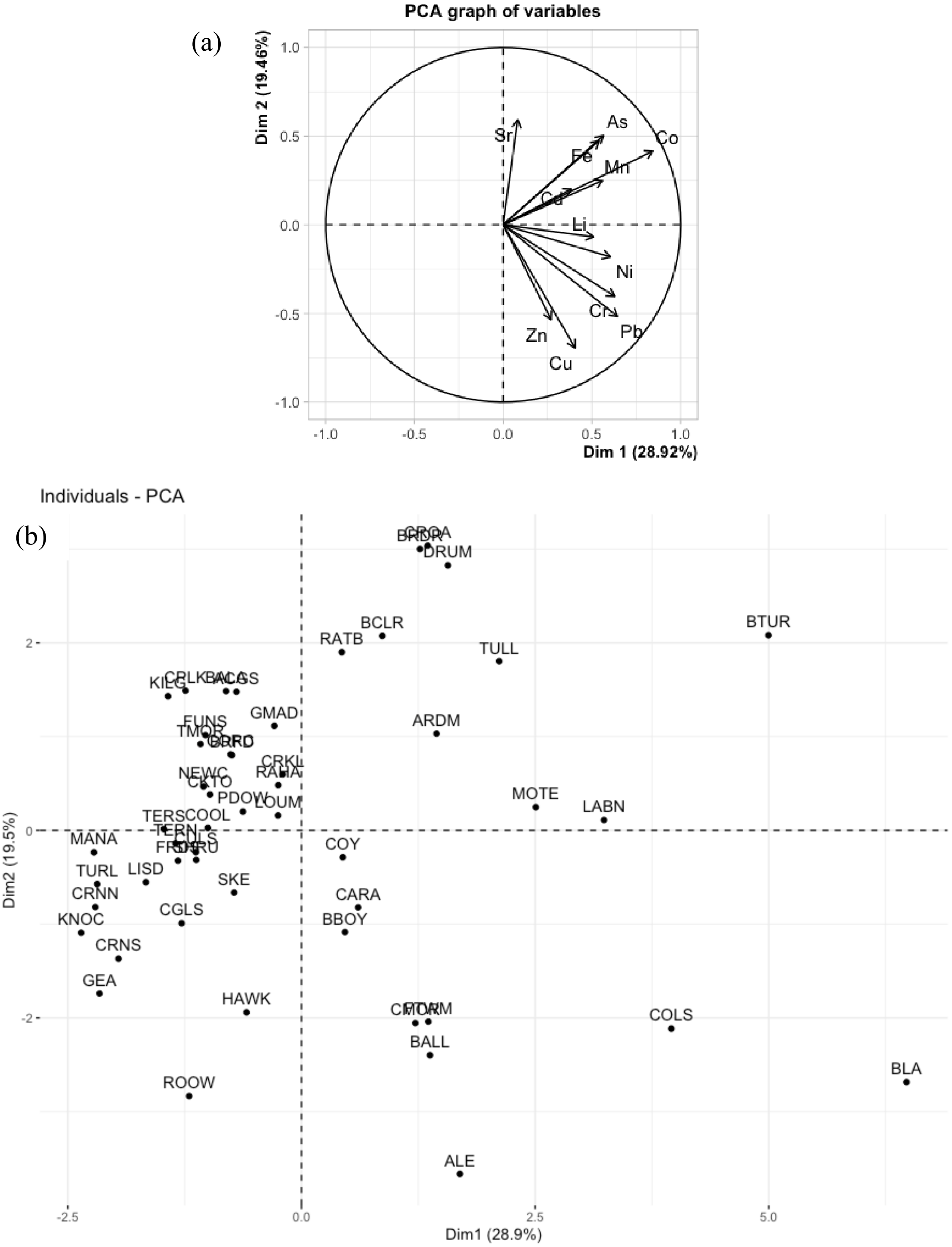

__Figure 4.2__. PCA of minor elements: (a) graph of variables. (b) Components 1 and 2. See Table 3.1 for site names.

The pH values varied between 7.1 (Carrowkeel) and 8.83 (Roo West), with an average of 8.38. Alkalinity values were between 83 mg l^{-1} (Four Roads) and 365 mg l^{-1} (Belclare), with an overall average of 179.5 mg l^{-1}.

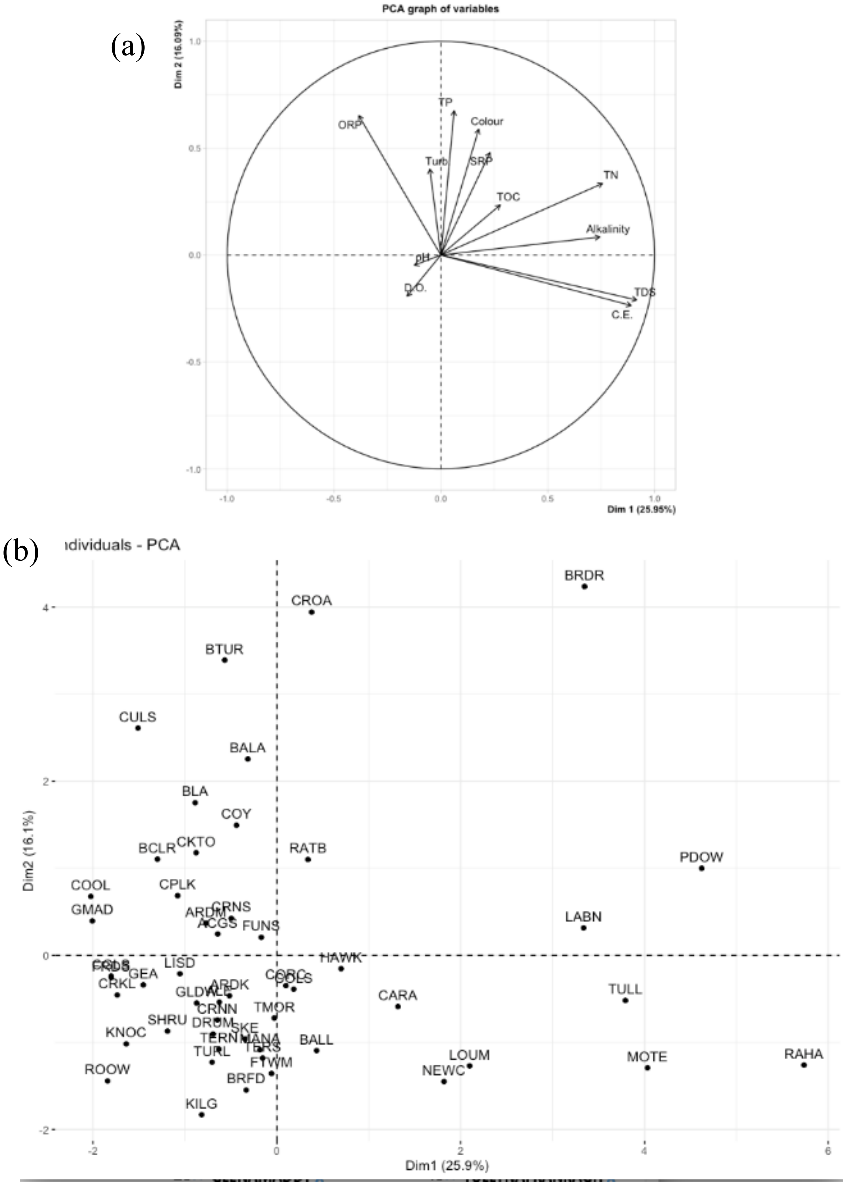

***Figure 4.3**. PCA of chemico-physical variables and nutrients. (a) graph of variables. (b) Components 1 and 2. See Table 3.1 for site names.*

Turbidity ranged between 0.5 NTU (Ardmullan) and 15.3 (Balla), with an average of 2.3. Colour for each turlough varied between 3 (Polldowagh and Kilglassan) and 211 units Pt/Co (Breandrum), with an overall average of 27 units Pt/Co. High values are also shown by Blackrock (73 units Pt/Co), Belclare and Croaghill (61 units Pt/Co), and Glenamaddy (51 units Pt/Co). Turloughs in the Burren area (Lough Gealain and Lough Aleenaun) show low values.

Dissolved oxygen (DO) varied between 34.2% (Cockstown) and 91.7% (Turloughnagullaum), with an average of 70.5%, or between 3.73 mg l^{-1} and 10.88 mg l^{-1} (average 7.87 mg l^{-1}).

The turloughs show a high variability in both SRP and TP as SRP ranged from <2 μg l^{-1} (for several turloughs) to 87.1 μg l^{-1} (Fort William) (average 9 μg l^{-1}), while TP ranged from 5 μg l^{-1} (Carran north) to 256 μg l^{-1} (Breandrum), with an average of 42 μg l^{-1}). TN ranged from 0.21 mg l^{-1} (Hawkhill) to 1.67 mg l^{-1} (Caranavoodaun) (average 0.52 mg l^{-1}), while TON between 0.01 and 141 mg l^{-1} (average 41 mg l^{-1}).

A summary of the turloughs with characteristics deviating from average can be found in Table 4.1. These will be discussed in Chapter 6.

***Table 4.1**. Turloughs with characteristics that deviate from average. In bold, the 7 turloughs studied in depth.*

Turlough	parameters
Ardmullan	High Fe, Low turbidity
Balla	High turbidity
Ballinturley	High Co and As
Belclare	High colour and alkalinity
Blackrock	High Ni, high colour
Breandrum	High E.C., TDS, colour, alkalinity, Fe, TP
Caranavoodaun	High TN
Carran north	Low SRP
Carrowkeel	Low E.C. and pH
Cockstown	Low D.O.
Coole	High Cu
Croaghill	High colour
Fort William	High SRP
Four Roads	Low alkalinity
Glenamaddy	High colour
Hawkhill	Low TN
Kilglassan	Low colour
Labane	high E.C., TDS and TN
Lough Aleenaun	High Cu and Zn, low Sr
Moate	low ORP and high alkalinity
Polldowagh	High E.C., alkalinity, TN, SRP and TP and low colour
Rahasane	High TDS and E.C. and low colour
Roo West	High pH
Tulla	high TDS and E.C and low ORP
Tullynafrankagh	High Ca and Na
Turloughnagullaum	High D.O.

4.1.1.4 Nutrients and trophic status of the 55 turloughs

The classification of the 55 turloughs from the results of these single samples according to the trophic state (The Organisation for Economic Co-operation and Development (OECD) classification, 1992 and Phosphorus Regulations' standards for TP in Irish lakes, McGarrigle et al., 2002) can be found in Appendix C, Table C.1. The majority of turloughs are mesotrophic (TP between 10 and 35 μg l^{-1}). The oligotrophic turloughs are Brierfield, Glenamaddy, Kilglassan, Knockaunroe, Moate, Skealoghan (according to the sample taken in 2018) and Lough Gealain (TP<10 μg l^{-1}). The eutrophic turloughs are Ardmullan, Breandrum, Carran South, Croaghill, Hawkhill, Lough Coy, Lough Funshinagh, Lisduff, Managh, Rahasane and Tullynafrankagh (TP between 35 and 100 μg l^{-1}). Balla, Ballinturley, Cuillan S. and Polldowagh are hypertrophic (TP>100 μg l^{-1}).

4.1.2 Survey of the 7 turloughs over a hydrological year

Monthly sampling of the 7 chosen turloughs was carried out from December 2018 to November 2019. An overview of the chemico-physical and chemical parameters, including range and standard deviation can be found in Table 4.2. The monthly data for each analyte can then be found in the tables further down in this Section.

4.1.2.1 pH and alkalinity

pH values ranged from 6.89 (Coolcam in February 2019), to 8.84 (Lough Coy in June 2019) (Figure 4.4). Alkalinity varied between 112.4 mg l^{-1} (Blackrock in October) and 289 mg l^{-1} (Caranavoodaun in August) (Figure 4.5).

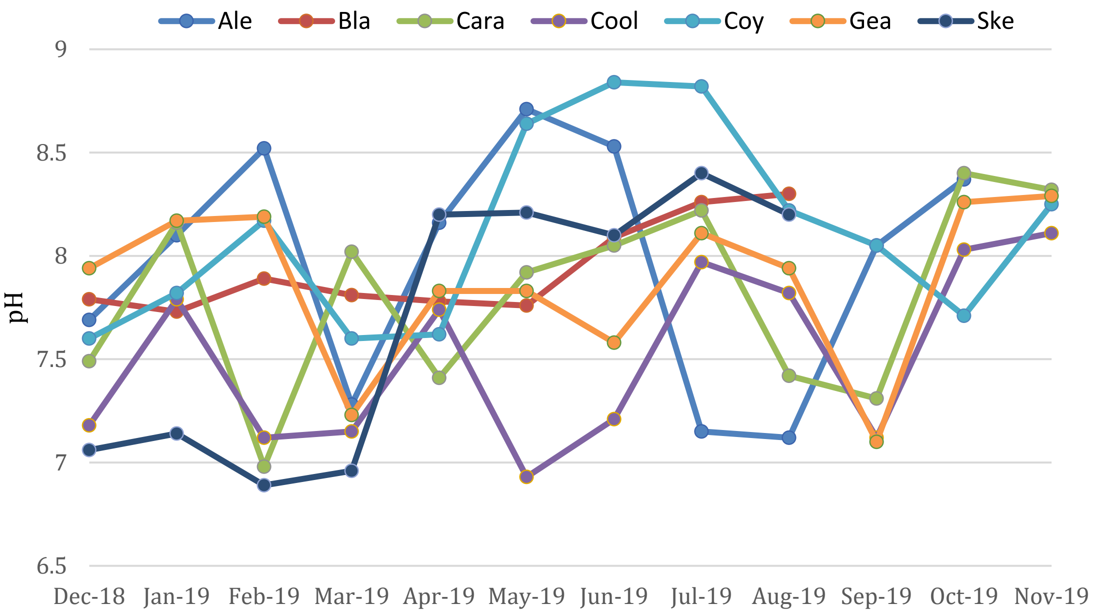

Figure 4.4. *Water pH during the hydrological year at the turloughs.*

Coolcam shows significantly higher values than all turloughs but Caranavoodaun, while Lough Gealain has lower values than Coolcam, Skealoghan, Caranavoodaun and Lough Aleenaun.

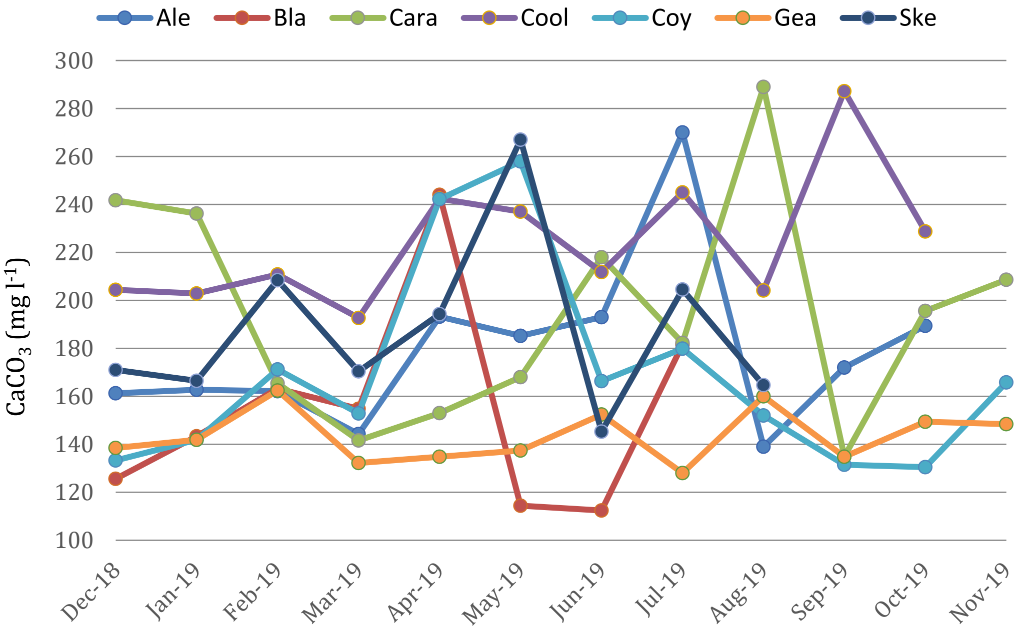

Figure 4.5. *Water $CaCO_3$ concentrations during the hydrological year at the turloughs.*

***Table 4.2**. Summary of the parameters surveyed at the 7 turloughs during the hydrological year (average ± standard deviation, mg l^{-1} where not indicated). Where standard deviation is not indicated, a single measurement for the analyte was done.*

	pH	E.C. (µS cm^{-1})	Turb. (NTU)	Alkalinity	Colour (units Pt/Co)	TN	TON	TP (µg l^{-1})	SRP (µg l^{-1})	DOC
ALE	7.97±0.58	261±72	5.98±6.16	179.29±35.41	23.27±18.83	1.47±1.51	0.76±0.38	30±15	15±9	15.54±15.63
BLA	7.93±0.22	290±44	5.41±2.84	154.91±43.35	103.63±36.71	1.36±0.39	1.07±0.49	35±21	17±13	28.77±9.82
CARA	7.81±0.46	307±62	11.04±9.84	194.53±46.14	33.25±27.94	2.08±1.72	1.51±0.92	48±26	13±9	23.99±14.39
COOL	7.51±0.43	363±110	5.38±6.01	224.27±27.38	24.50±23.70	0.77±0.61	1.35±1.88	21±20	8±7	24.82±22.47
COY	8.11±0.46	284±52	4.82±4.40	168.78±41.40	68.58±28.52	1.21±0.63	1.04±0.63	56±42	27±30	23.01±15.00
GEA	7.87±0.39	253±24	3.58±4.10	143.36±11.09	15.42±14.07	0.58±0.24	0.37±0.20	9±5	6±5	14.67±13.71
SKE	7.68±0.65	290±104	1.93±1.37	188.00±36.06	32.10±16.02	0.63±0.42	0.27±0.12	30±32	11±10	23.14±18.45

	Ca	K	Mg	Na	sulphates	chlorides
ALE	65.95	1.22	1.93	9.10	3.33±3.09	16.65±6.26
BLA	50.91	2.20	3.82	10.04	5.88±3.12	14.88±2.74
CARA	87.37	3.47	5.84	12.18	1.83±3.19	27.03±9.83
COOL	62.69	1.98	5.04	8.66	3.15±3.46	15.57±1.56
COY	54.69	2.34	3.80	10.24	7.57±3.96	19.09±6.43
GEA	50.45	0.80	2.17	8.88	1.80±0.88	13.26±3.37
SKE	79.17	2.56	4.46	8.75	1.87±1.41	12.57±3.92

µg l^{-1}	Fe	Li	Cr	Mn	Co	Ni	Cu	Zn	As	Sr	Cd	Pb	Silica
ALE	23.36	0.52	0.22	3.99	0.08	1.12	10.32	10.52	0.33	50.33	0.03	0.15	0.45
BLA	152.23	0.99	0.40	11.78	0.15	9.06	8.30	6.00	0.68	80.51	0.02	0.26	2.53
CARA	24.84	0.25	0.29	6.73	0.09	0.66	3.54	2.82	0.46	80.00	0.02	0.15	1.46
COOL	37.22	0.18	0.09	4.57	0.05	0.27	1.13	7.88	0.43	204.28	0.02	0.02	0.17
COY	51.87	0.42	0.19	11.23	0.07	1.03	2.80	4.90	0.51	83.21	0.03	0.05	0.53
GEA	16.86	0.10	0.18	2.84	0.02	0.24	4.38	3.80	0.13	64.81	0.01	0.03	0.58
SKE	28.16	0.20	0.18	2.19	0.06	0.56	3.68	223.33	0.37	89.49	0.02	0.07	0.09

4.1.2.2 Electrical conductivity and Total Dissolved Solids

Values of electrical conductivity varied between 146 µS cm^{-1} (Lough Aleenaun in May) and 421 µS cm^{-1} (Caranavoodaun in February). There is a trend of decreasing values during recharge and increasing values during discharge which might be due to dilution effects (Figure 4.6).

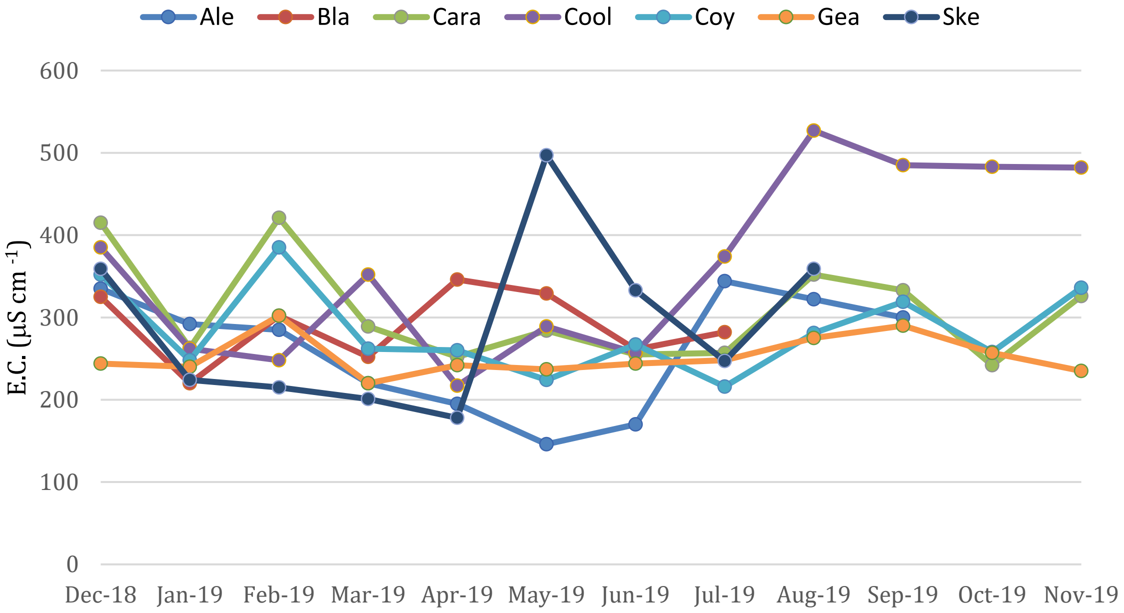

Figure 4.6. *Electrical conductivity values during the year.*

4.1.2.3 Colour

Colour values ranged from 4 units Pt/Co (Lough Gealain in November 2019) to 156 units Pt/Co (Blackrock in August 2019). Blackrock and Lough Coy, which belong to the south Galway (Gort) network and have significantly darker waters owing to the fact that they draining the peaty Slieve Aughty mountains (Cunha Pereira et al., 2010). There is a trend of increasing colour values during the drainage period (Figure 4.7).

4.1.2.1 Turbidity

Turbidity values varied between 0.54 NTU (Lough Gealain in January 2019) and 23.6 NTU (Lough Aleenaun in May 2019). Skealoghan shows significantly lower turbidity values than Lough Aleenaun, Blackrock, Caranavoodaun and Lough Coy. Figure 4.8 shows increasing turbidity values during the recharge period, while values decrease during the draining phase.

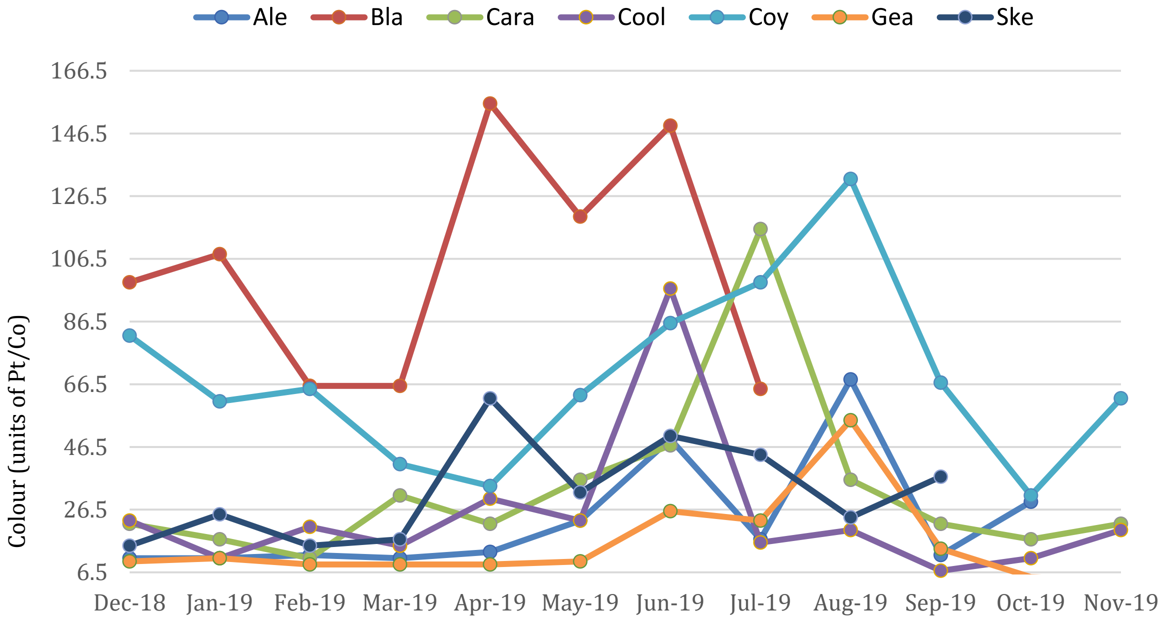

Figure 4.7*. Colour values during the year.*

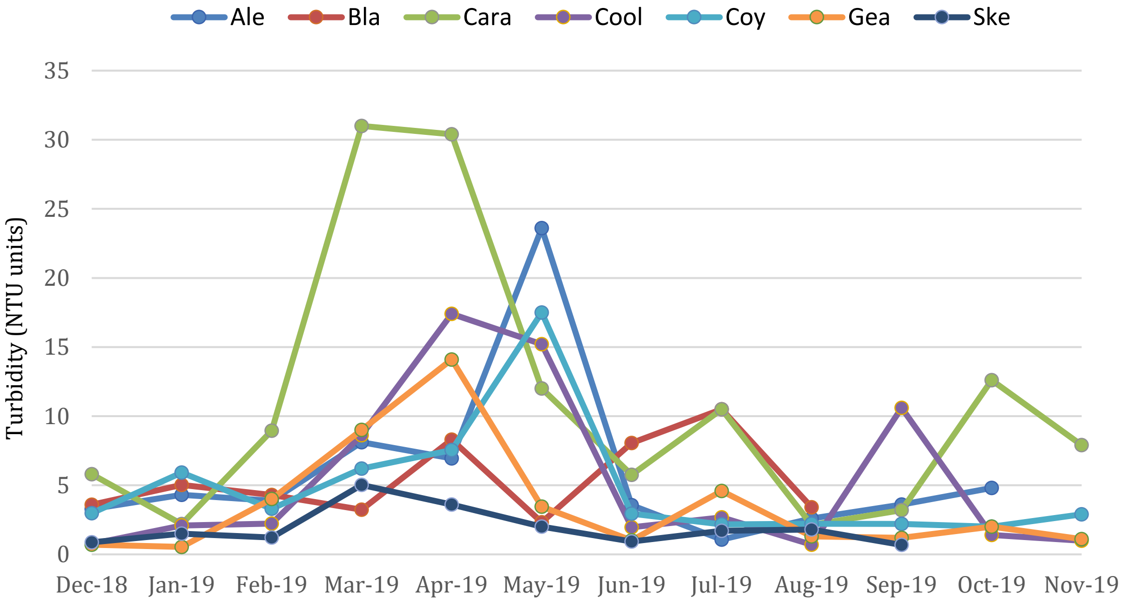

Figure 4.8*. Values of turbidity during the year.*

4.1.2.2 Dissolved Organic Carbon

Dissolved Organic Carbon (DOC) values varied between 3.85 mg l^{-1} (Lough Gealain in May 2019) and 79.33 mg l^{-1} (Coolcam in October 2019). Lough Aleenaun shows significantly lower levels than Blackrock. Peaks in TOC seem to correspond with the start of the flooding season (October 2019, Figure 4.9).

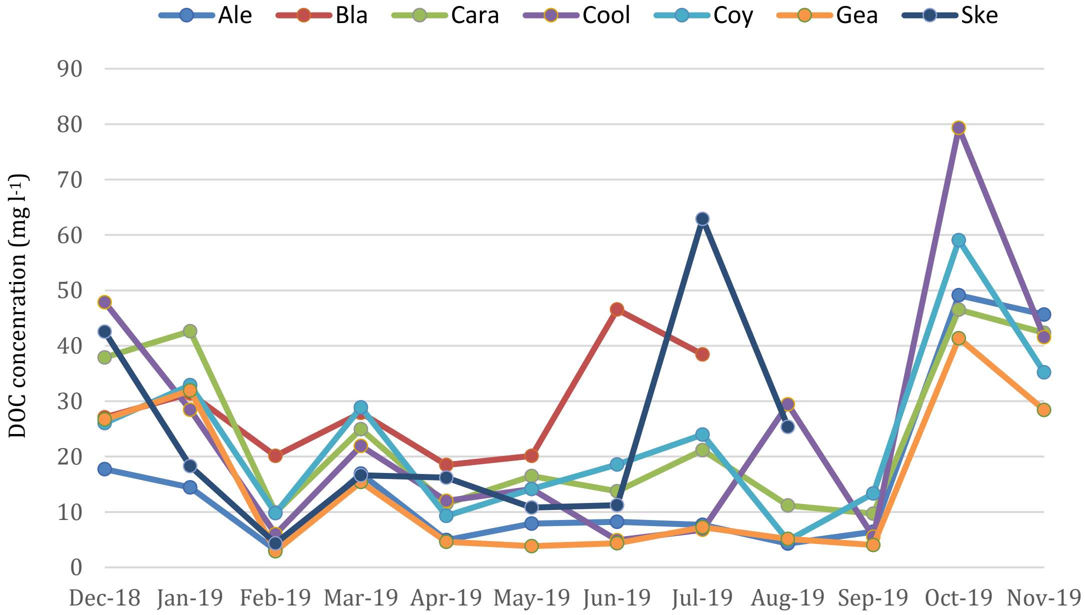

***Figure 4.9**. Values of DOC at the turloughs during the year.*

4.1.2.3 Total Nitrogen, Total Oxidised Nitrogen and nitrates

Total Oxidised Nitrogen (TON) values at the turloughs ranged from <0.01 mg l^{-1} (Coolcam in June 2019) to 5.95 mg l^{-1} (Coolcam in February 2019), while TN varied between <0.01 (Coolcam in June 2019) to 5.81 mg l^{-1} (Caranavoodaun in February 2019) (Figures 4.10 and 4.11). Caranavoodaun shows a relatively high nitrogen content. TN at Caranavoodaun is significantly higher than Lough Gealain, while TON is significantly higher than Lough Gealain and Skealoghan.

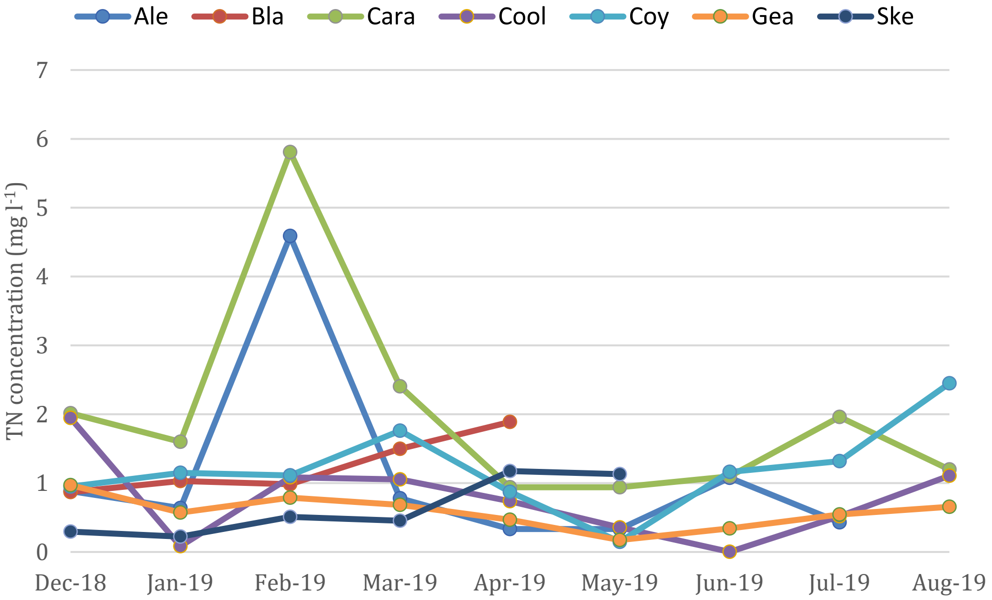

***Figure 4.10**. Values of TN during the year.*

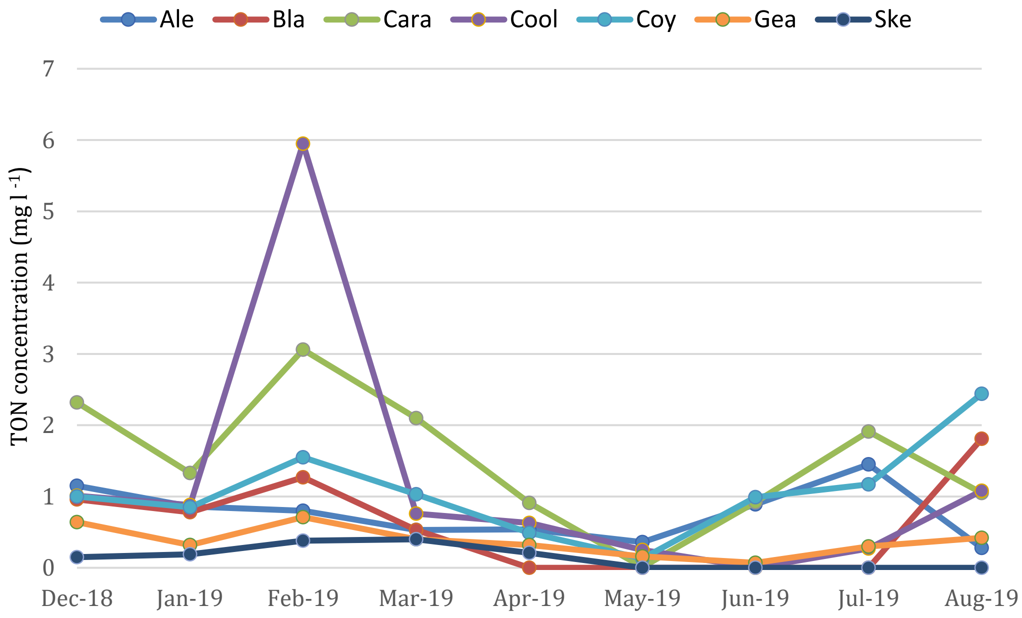

***Figure 4.11**. Values of TON during the year.*

Nitrates varied between less than 0.04 mg l^{-1} for several turloughs in June, July and August and 5.76 mg l^{-1} (Lough Aleenaun in November 2019). Figure 4.12 shows increasing values during the recharge period. Though only measurements from June to November 2019 are available because of issues with analytical equipment, nitrate analyses could be carried out from June to November 2019 to integrate the missing months of TON results. Skealoghan shows the lowest median nitrate concentration which is significantly lower than at Blackrock.

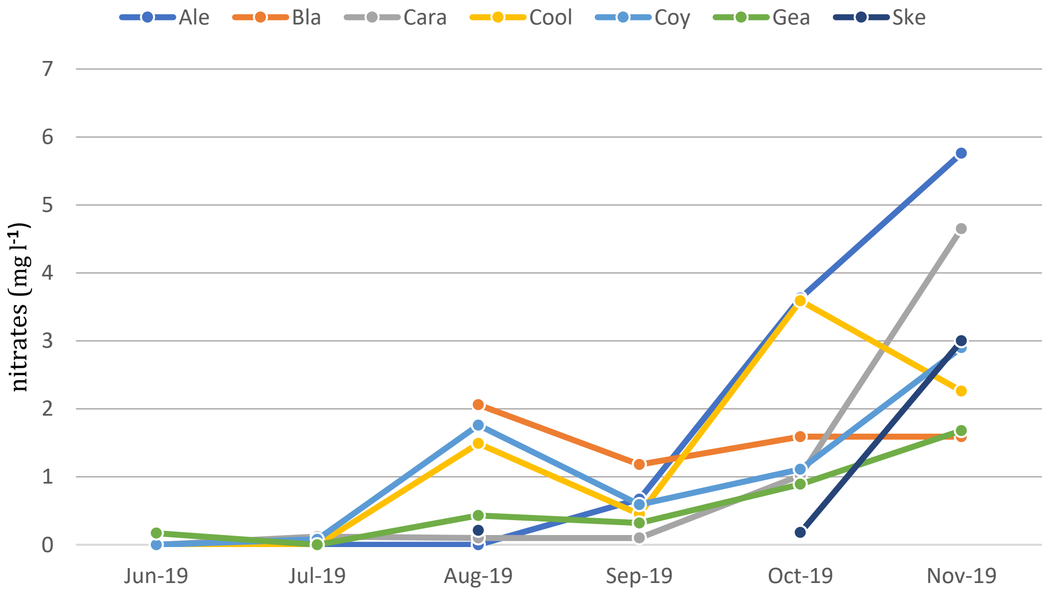

***Figure 4.12**. Nitrate concentrations during the surveyed year.*

4.1.2.4 Soluble Reactive Phosphorus and Total Phosphorus

Soluble Reactive Phosphorus (SRP) and Total Phosphorus (TP) analytical results can be found in Table 4.1. SRP varied between <0.002 mg l^{-1}) (Lough Gealain and Skealoghan March 2019) and 0.112 mg l^{-1} (Lough Coy in January 2019), while TP ranged from 0.002 mg l^{-1} (Lough Gealain in March 2019) and 0.131 mg l^{-1} (Lough Coy in February 2019). Lough Gealain shows concentrations of both SRP and TP that are significantly lower than Lough Aleenaun, Blackrock, Caranavoodaun and Lough Coy (Figures 4.13, 4.14). TP values at Coolcam are significantly lower than Lough Aleenaun, Blackrock and Caranavoodaun. There is a trend of increasing phosphorus levels during the recharge period (especially for TP).

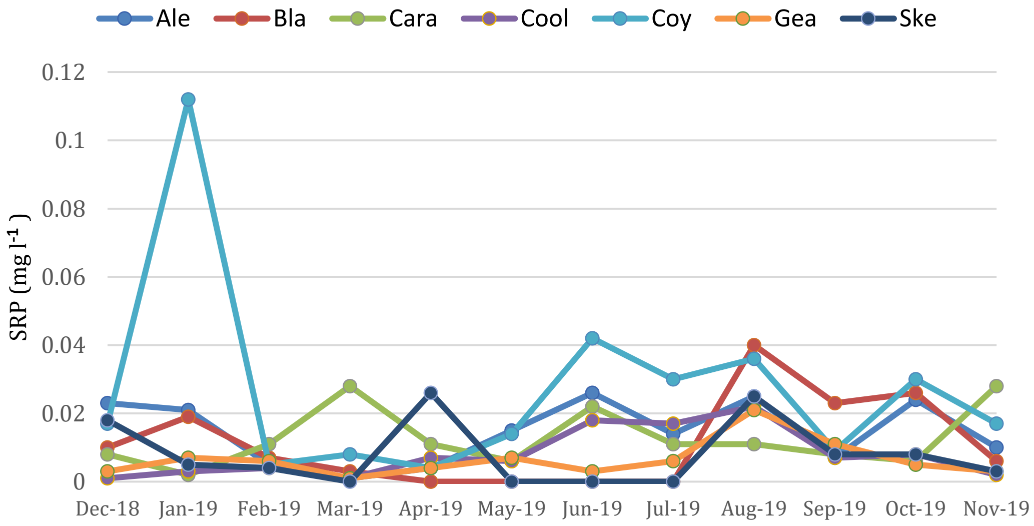

***Figure 4.13**. Values of SRP through the year.*

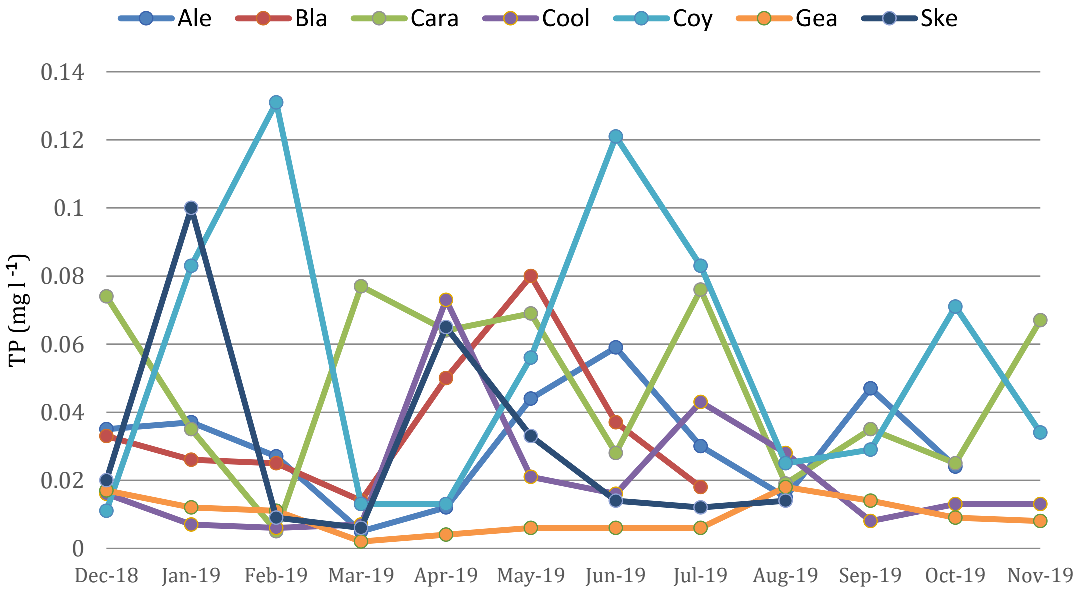

***Figure 4.14**. Values of TP during the hydrological year.*

4.1.2.5 Chlorides

Chlorides varied between 7.71 mg l^{-1} (Skealoghan in September 2019) and 29.99 mg l^{-1} (Lough Coy in August 2019). Caranavoodaun shows significantly higher values than Blackrock, Coolcam, Lough Gealain and Skealoghan. There is a trend of increasing concentrations in the recharge season (Figure 4.15). Measurements were only possible from June to November 2019 due to issues with analytical equipment.

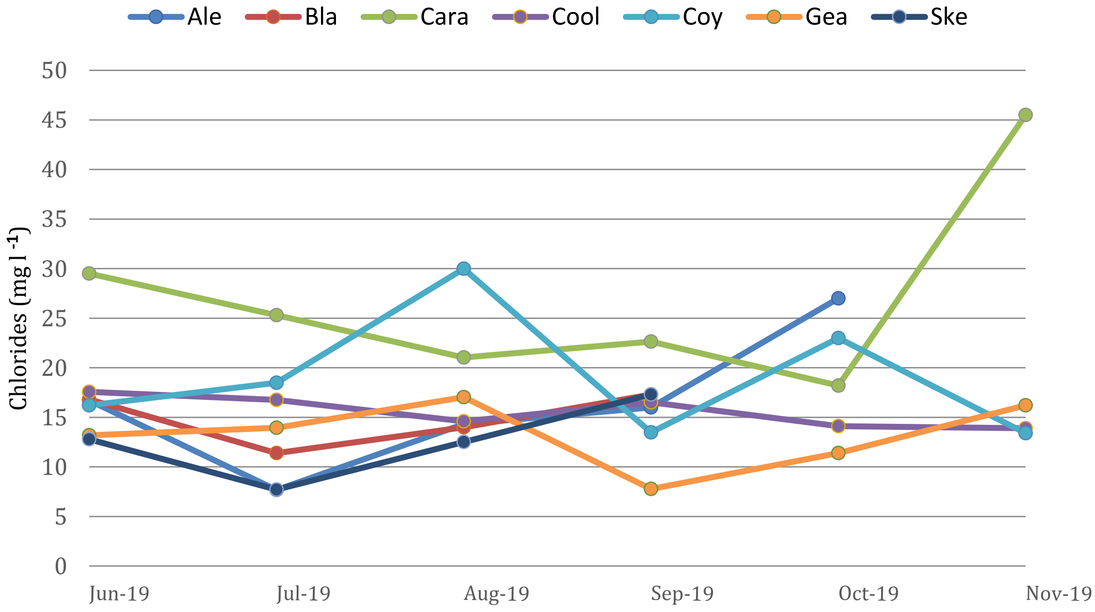

Figure 4.15. *Values of chloride concentrations during the surveyed year.*

4.1.2.6 Sulphates

Concentration of sulphates vary between 0.7 mg l^{-1} (Caranavoodaun in July 2019) and 16.08 mg l^{-1} (Lough Coy in August 2019). Blackrock and Lough Gealain show significantly higher values than Caranavoodaun, Coolcam, Lough Gealain and Skealoghan (Figure 4.16). Several turloughs show a peak in concentration in August 2019. Measurements were only possible from June to November 2019 due to issues with analytical equipment.

4.1.2.1 Chlorophyll α

Values of chlorophyll α as surveyed over the hydrological year range between less than 0.62 µg l-1 (Caranavoodaun in December 2018) and 320.3 µg l-1 (Caranavoodaun in November 2019). Peak values can be seen in autumn and winter months.

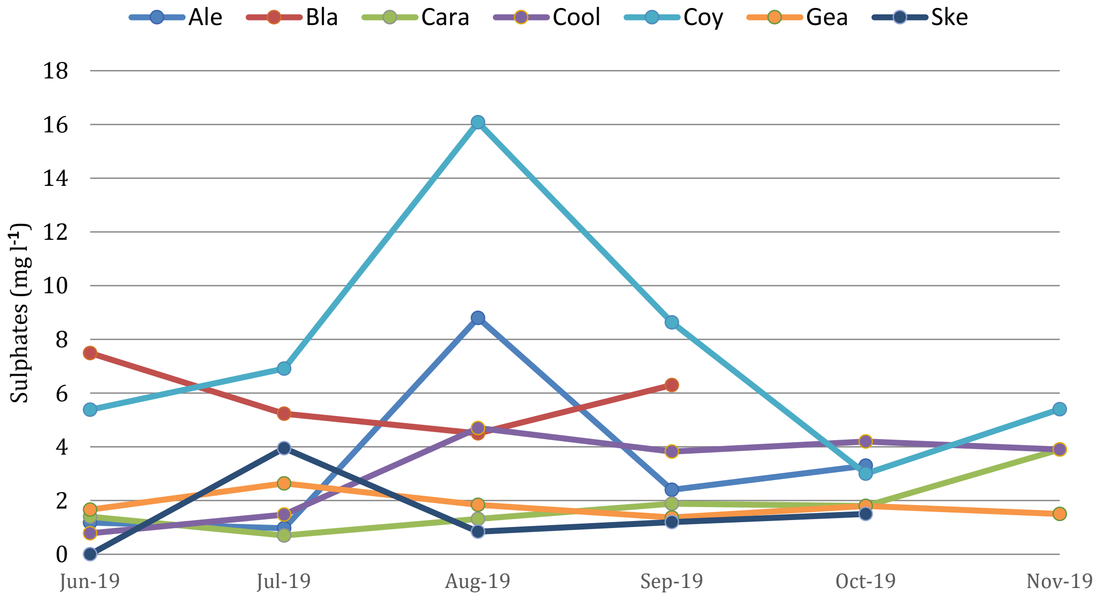

Figure 4.16. *Values of sulphate concentrations during the surveyed year.*

Caranavoodaun shows very high values from January to May 2019 and in July 2019, however it has a very wide range, with values also lower than the detection limit (<0.62 μg l^{-1} in December 2018, Figure 4.17). Chlorophyll α has been used together with TP values to determine the trophic status of the turloughs (Refer to Section 4.1.2.11).

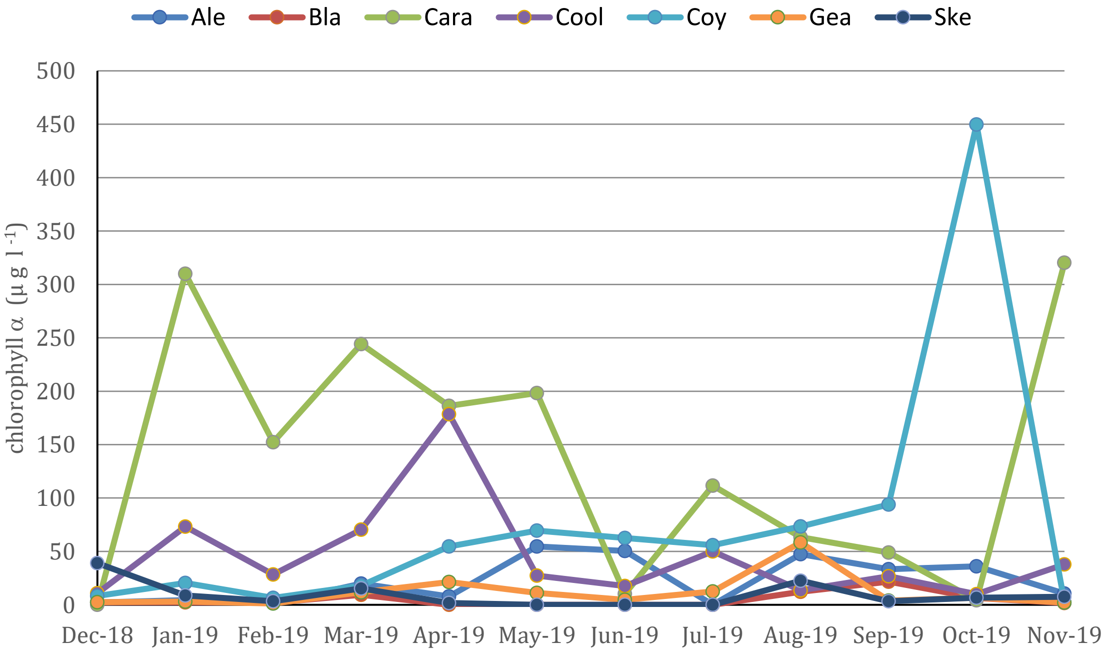

Figure 4.17. *Values of chlorophyll α concentrations during the surveyed year.*

4.1.2.2 Trophic classification of the turloughs

Turloughs were classified according to their TP and chlorophyll α contents following the OECD classification (OECD, 1992) (Tables 4.3 and 4.4). Since samples were not taken from the center of the turloughs, some of the chlorophyll α results might be elevated because of stagnant water conditions. The more conservative TP classification should therefore be considered. Using this classification, only Lough Gealain is oligotrophic, Lough Aleenaun, Blackrock and Coolcam are mesotrophic and Caranavoodaun and Lough Coy are eutrophic.

***Table 4.3**. Trophic classification scheme for lake water proposed by the OECD (OECD, 1992), relative to total phosphorus and chlorophyll α concentrations.*

Lake category	TP (mg m^{-3})	Chlorophyll α (mg m^{-3})	
	Mean	Mean	Max
Ultra-oligotrophic	<4	<1.0	<2.5
Oligotrophic	<10	<2.5	<8.0
Mesotrophic	10-35	2.5-8.0	8-25
Eutrophic	35-100	8-25	25-75
Hypertrophic	>100	>25	>75

***Table 4.4**. Classification of the trophic state of the turloughs based on the OECD classification and using TP and chlorophyll α concentrations (OECD, 1992).*

Turloughs	**Trophic status**	
	TP	**Chlorophyll α**
ALE	Mesotrophic	Mesotrophic
BLA	Mesotrophic	Mesotrophic
CARA	Eutrophic	Hypertrophic
COOL	Mesotrophic	Hypertrophic
COY	Eutrophic	Hypertrophic
GEA	Oligotrophic	Eutrophic
SKE	Mesotrophic	Eutrophic

4.2 Soils

The locations of the soil samples and the dates of sampling can be seen in Appendix B (Table B.3). The results of the analyses performed on the soil samples can be found in Appendix D, Table D.1.

A Principal Components Analysis (PCA) was performed of the soil characteristics surveyed (Figure 4.18). The highest percentage of variation (indicated by principal components (PC) PC1 and PC2) is captured by SOM and inorganic component (Inorg) (both almost aligned with PC1) and by $CaCO_3$ and pH along component PC2, indicating the importance of these variables in the characterization of the soils.

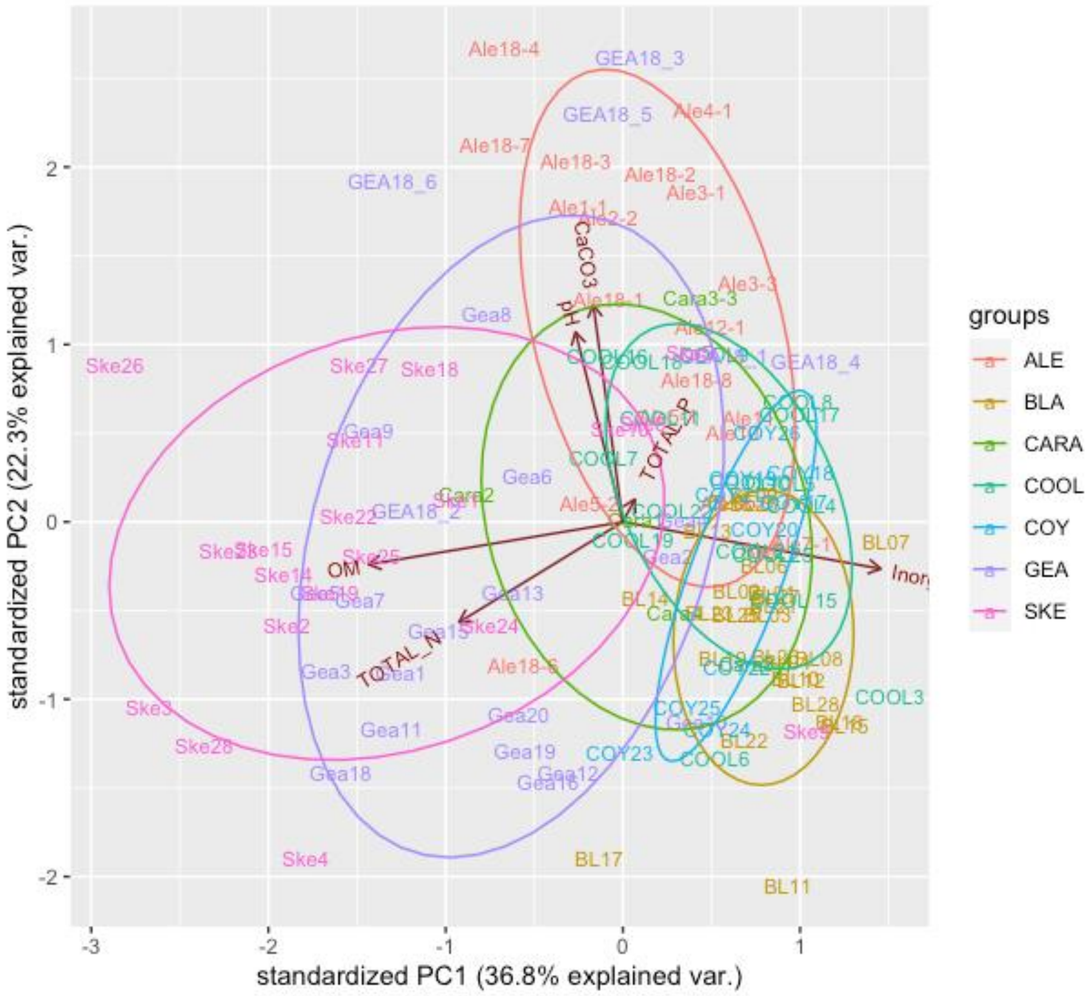

Figure 4.18. PCA of the surveyed soil characteristics.

Several samples taken at Lough Aleenaun (e.g. Ale 18-4, 4-1, 18-7, 18-3, 18-2) show a high carbonate component and high pH, while Skealoghan and Lough Gealain have high organic carbon (several of their samples can be seen having the highest scores on the direction of the arrow for pH and $CaCO_3$). Lough Gealain and Skealoghan also show the higher total nitrogen scores for several samples. Both Lough Gealain and Coolcam also show lower soil total phosphorus values than the other turloughs (also see Figure 4.23).

There was no clear distinction between mineral and organic turloughs regarding TP concentrations.

4.2.1 Soil pH

The list of the samples with the pH analytical results can be found in Appendix D, Table D1. Average values according to each soil type can be found in Table 4.5, while averages for each turlough are shown in Figure 4.19.

Table 4.5*. Average soil pH in the different soil units. Where the standard deviation is not present it was due to too few samples to calculate it.*

Soil type	**turloughs**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW	8.2	6.40±0.642			5.8		
BMinSW		6.02±0.37					
BMinVSP					7.01±0.59		
BminSP		6.29±0.76		7.3			
BMinSRPT							
BOrgVSW	7.37±0.23		6.70±0.47				6.59±0.88
BorgSW							
BOrgVSP	7.22±0.43					6.77±0.47	
FenPt							7.15±0.32
PtMRL							
AlluvMRL						7.32±0.35	
AlluvMIN				7.07±0.23			

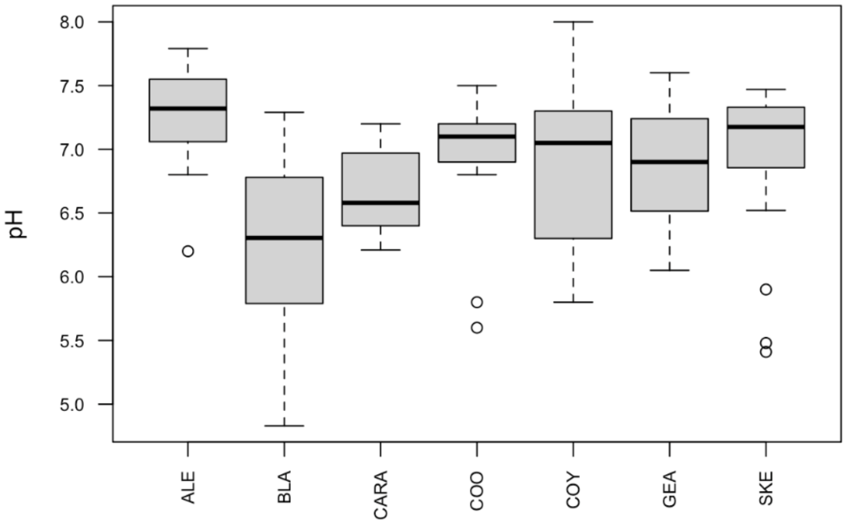

Figure 4.19*. Boxplots of soil pH values for the different turloughs.*

Lough Aleenaun shows pH values which are statistically significantly higher than Blackrock and Caranavoodaun. Blackrock sticks out as having lower values than most of the other turloughs. This makes sense in light of the fact that Lough Aleenaun has a marly substrate and that Blackrock has mineral soils and is partially fed by surface waters from the Slieve Aughty mountains (containing peat deposits). AlluvMRLPT and BorgSW have statistically higher values than the rest of soil units, while the mineral soils BMinSW, BMinDP and BMinVSP have statistically lower values than most others.

4.2.2 Soil organic matter

The results from loss on ignition and elemental analyses can be found in Appendix D, with average values calculated according to soil type and for each turlough shown in Table 4.6. Averages for each turlough are shown in Figure 4.20. Blackrock, Coolcam and Lough Coy show the lowest content of organic carbon. Lough Gealain and Skealoghan show the highest contents of organic matter (significantly higher than the rest of the turloughs).

***Table 4.6**. Average soil organic matter (%) in the different soil units. Where the standard deviation is not present it was due to too few samples to calculate it. See Appendix A, Table A.4 for a description of the soil types.*

Soil type	**turloughs**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		14.0±1.17			26.2		
BMinSW		14.0±3.0					
BMinVSP		12.6			15.9±5.1		
BMinSP		14.8±4.0		8.0			
BOrgVSW	16.2±5.2		27.4±14.2			36.3±20.7	14.9±7.2
BOrgSW							
BOrgVSP	18.7±5.4					41.8±12.2	40.1±1.3
FenPt			55.0±5.9				69.2±4.8
PtMRL							
AlluvMRLPT						25.1±17.4	
AlluvMRL				14.9±7.21	17.7		

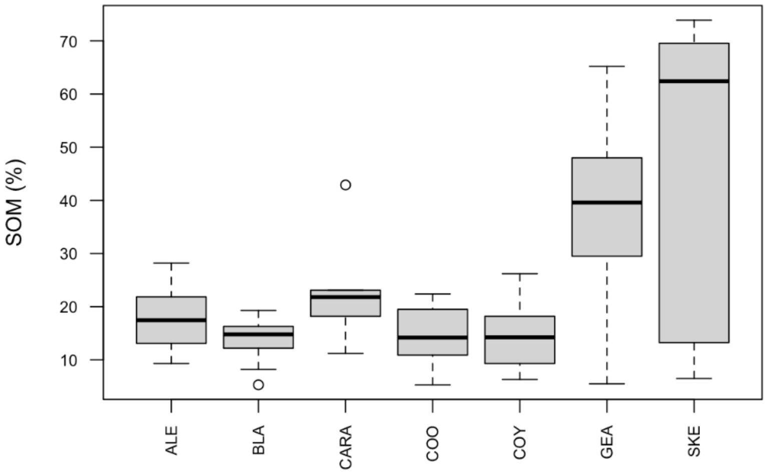

***Figure 4.20**. Boxplots for the soil organic matter at each turlough.*

4.2.3 Soil carbonates

Soil averages for every soil type can be found in Table 4.7, while averages per turlough can be found in Figure 4.21.

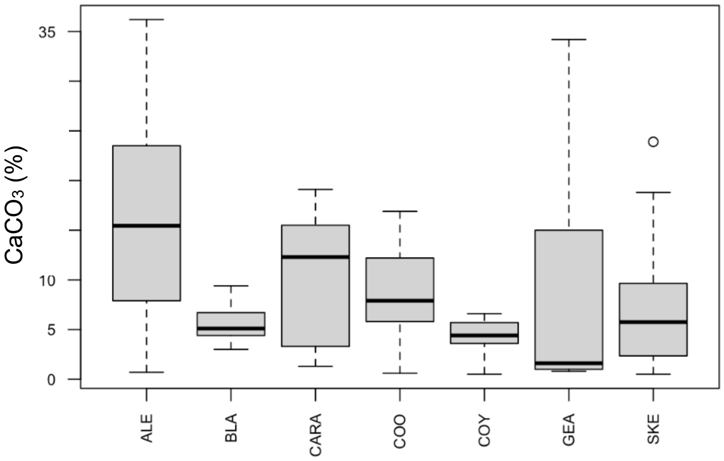

***Figure 4.21**. Boxplots for soil carbonates at each turlough.*

***Table 4.7**. Average soil carbonates in the different soil units. Where the standard deviation is not present it was due to too few samples to calculate it. See Appendix A, Table A.4 for a description of the soil types.*

Soil type	**Turlough $CaCO_3$ (%)**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		5.24±1.37		5.35±6.63	6.56		
BMinSW		6.58±2.08					
BMinVSP					3.98±1.85		
BMinSP		5.44±1.92		9.56			
BOrgVSW	17.0±7.7		9.80±8.82				10.2±4.6
BOrgSW							
BOrgVSP	16.8±11.5					6.28±8.5	
FenPt							6.0±5.7
PtMRL							
AlluvMRLPT							
AlluvMRL						20.8±11.9	
AlluvMIN				8.56±4.74	4.25*		

4.2.4 Soil total nitrogen

It is important to consider soil total nitrogen (TN, Table 4.8) because of exports to water and also because it is linked to the cycle of C and therefore it also has a strong impact on organic carbon sequestration (Elbasiouny et al., 2014). As also highlighted by Waldren et al. (2015), Lough Gealain shows a relatively high TON concentration (Figure 4.22) while Coolcam has the lowest average value.

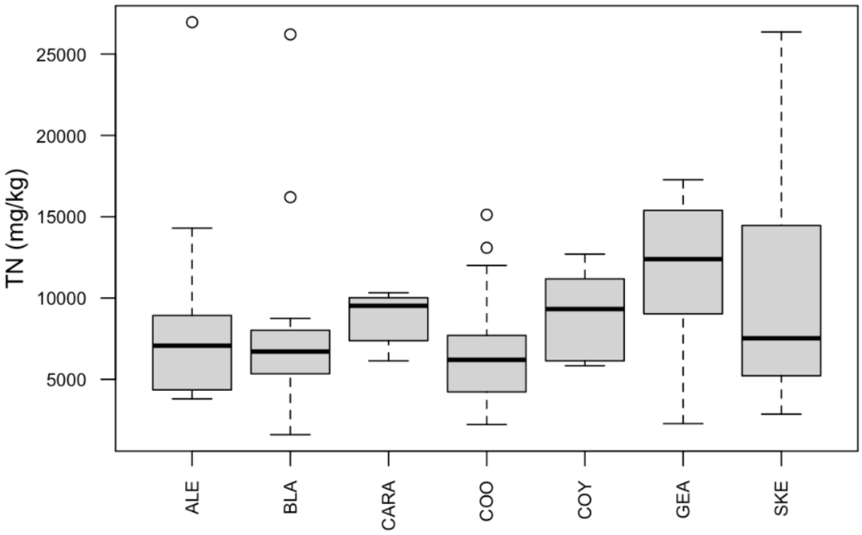

Figure 4.22. *Boxplots for TN for each turlough.*

Table 4.8. *Average TN in the different soil units. Where the standard deviation is not present it was due to too few samples to calculate it. See Appendix A, Table A.4 for a description of the soil types.*

Soil type	**TN soil concentrations (mg Kg^{-1})**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		8050±6886			12700		
BMinSW		6643±1509					
BMinVSP					8562±2444		
BMinSP		6685±3535		3410			
BOrgVSW	6293±2542		8265±1822				6686±4672
BOrgSW							
BOrgVSP	9066±6458					11863±4486	
FenPt							16402±10334
PtMRL							
AlluvMRL PT			10937±8153				
AlluvMRL						9704±5938	
AlluvMIN				7138±3618			

4.2.5 Soil total phosphorus

Boxplots from ICP-OES analyses for total phosphorous (TP) can be found in Figure 4.23, while differences at soil type level can be seen in Table 4.9.

***Table 4.9**. Average TP in the different soil units. Where the standard deviation is not present it was due to too few samples to calculate it. See Appendix A, Table A.4 for a description of the soil types.*

Soil type	**Average soil TP (mg Kg^{-1})**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		672±152		257±50	351		
BMinSW		787.5±100					
BMinVSP					890±381		
BMinSP		808±185		247			
BOrgVSW							
BOrgSW	1280.7±644.3		890±171				566±167
BOrgVSP	1119.0±600.9						
FenPt			900±249			463.3±111.3	944.8±189.0
PtMRL							773.5±347.1
AlluvMRLPT	1020.5		590±346				
AlluvMRL						181.2±231.2	
AlluvMIN				291±96			

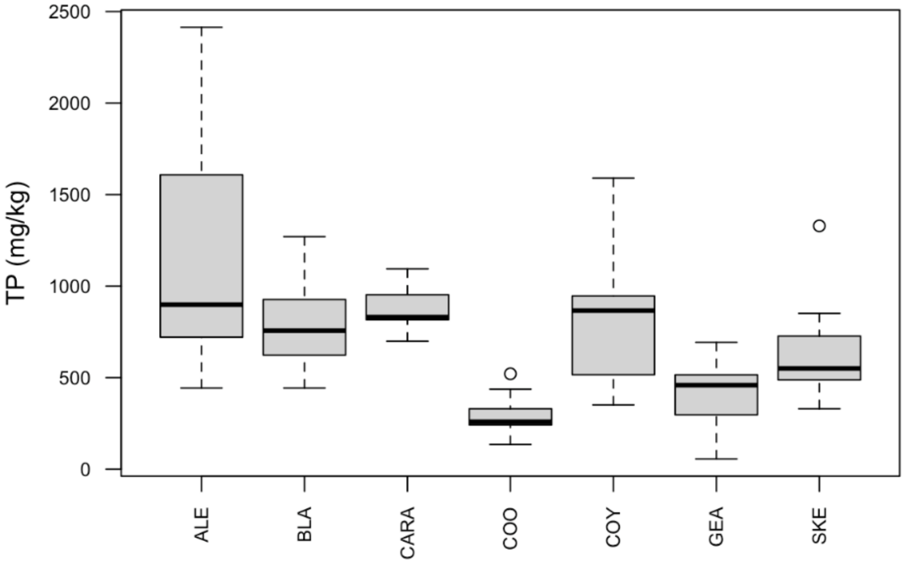

***Figure 4.23**. Boxplots for soil total phosphorus for each turlough.*

Coolcam and Lough Gealain show significantly lower TP than most turloughs. There was no clear distinction between mineral and organic turloughs regarding TP concentrations.

4.3 Greenhouse gas sampling and calculation of fluxes

4.3.1 Carbon dioxide fluxes

The averages of the calculated fluxes of CO_2 using the chambers between 2019 and 2020 (see Appendix B for exact dates of measurement and Appendix E for calculated fluxes) can be found in Table 4.10.

Table 4.10 shows the average fluxes at each turlough in the different conditions of lighting. They vary from -14,696 nmol mol^{-1} m^{-2} s^{-1} (Lough Gealain, dry soil and full light in summer 2019) to 11,680 nmol mol^{-1} m^{-2} s^{-1} (Cool, dry soil, dark measurement in summer 2019, Appendix E, Table E.1). Lough Coy (both on dry land and on water) shows significantly higher CO_2 emissions than several other turloughs. It can also be seen that the highest positive flows are for measurements in the dark and in summer for most turloughs.

***Table 4.10**. Average of CO_2 fluxes for each turlough (measured on land (dry) and on water (wet) (nmol mol^{-1} m^{-2} s^{-1}). F: Full light; P: partially shaded; D: dark.*

		F	P	D
ALE	dry	-2,355±1,515	1,063±657	4,559±624
	wet	-1,279±1,042	373±463	1,661±446
BLA	dry	-1712±2,568	418±181	3,169±3,154
	wet	-608±1,051	1,254±978	2,402±2,487
CARA	dry	-1,352±307	833±648	1,770±733
	wet	-517±93	57±193	552±175
COOL	dry	-4,337±6,491	1,696±2,382	4,500±4,876
	wet	-415±706	544±369	1,061±662
COY	dry	-219±584	4,587±3,122	5,578±1,764
	wet	203±616	1,765±1,998	2,757±2,707
GEA	dry	-3,791±7,274	549±373	1,001±771
	wet	-147±4	130±90	176±32
SKE	dry	-2,456±2,719	626±2,435	3,333±2964
	wet	-438±604	106±114	650±461

4.3.2 Methane fluxes

The average fluxes of methane (average for each turlough at each seasonal sampling) vary between -0.58 nmol mol^{-1}m^{-2}s^{-1} (Coy, dry flux in summer '19) and 5.22 nmol mol^{-1}m^{-2}s^{-1} (Lough Gealain wet flux, winter 2019) with highest values in summer, while averages over the year are shown in Table 4.11. The variation of methane fluxes during the surveyed year can be found in Appendix E, Table E2.

Wet fluxes of methane are significantly higher than dry fluxes (t=1.76, p=0.03). As it can be seen from Figure 4.24 there is a good correlation between wet and dry fluxes. This correlation was used to interpolate fluxes when one of the two did not give a meaningful analytical result.

***Table 4.11**. Average of methane fluxes for each turlough (measured on land (dry) and on water (wet). F: Full light; P: partially shaded; D: dark. When standard deviations are not indicated, too few samples were taken to calculate it.*

		Flux (nmol mol^{-1} m^{-2} s^{-1})
ALE	dry	1.4±0.6
	wet	1.8
BLA	dry	0.4±0.3
	wet	1.2
CARA	dry	1.0±0.1
	wet	1.4±0.1
COOL	dry	1.4±0.8
	wet	n.a.
COY	dry	0.6±1.2
	wet	0.2±0.2
GEA	dry	0.6±0.8
	wet	1.4±2.6
SKE	dry	1.7±0.7
	wet	2.6

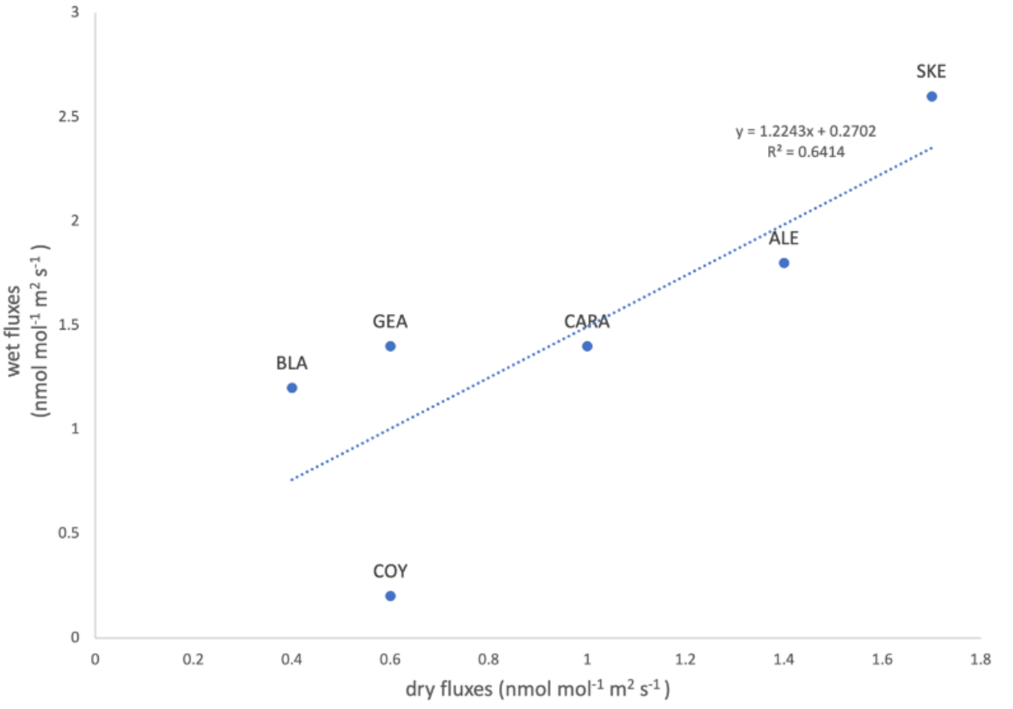

***Figure 4.24**. Methane wet and dry fluxes.*

4.3.3 Nitrous oxide fluxes

Average nitrous oxide fluxes ranged from 0.0 nmol mol^{-1} m^{-2} s^{-1} (Lough Aleenaun, wet fluxes, Skealoghan, dry and wet fluxes) to 1.2 nmol mol^{-1} m^{-2} s^{-1} (Coolcam, dry fluxes) (Table 4.12). The variation of nitrous oxide fluxes during the surveyed year can be found in Appendix E, Table E.3.

***Table 4.12**. Average of nitrous oxide fluxes for each turlough (measured on land (dry) and on water (wet). F: Full light; P: partially shaded; D: dark.*

		Flux (nmol mol^{-1} m^{-2} s^{-1})
ALE	dry	0.5±0.7
	wet	0.0±0.0
BLA	dry	0.1±0.1
	wet	0.2±0.3
CARA	dry	0.6±0.6
	wet	n.a.
COOL	dry	0.8±1.2
	wet	n.a.
COY	dry	0.2±0.2
	wet	0.1±0.1
GEA	dry	0.1±0.1
	wet	0.5±0.9
SKE	dry	0.0±0.0
	wet	0.0±0.0

5 RESULTS: ECOSYSTEM SERVICE QUANTIFICATION AND VALUATION

In this chapter data from Chapter 4 were used to calculate the ES of turloughs through various methods and for each turlough. Sections are divided into provisioning, regulating, and cultural services.

5.1 Methodology for the derivation of indicators of ecosystem service provision

The data gathered through literature review and field work were used to derive indicators of the provision and utilisation of ES. These indicators are representative of each ES.

Additionally, an economical valuation was performed for most of the services and using the economic techniques reviewed in Chapter 2. A distinction has been made between the potential to provide some ES (for example water, forage and water quantity regulation) and the actual provision of ES. Following the SEEA-EA only the latter category was included in the final monetary valuation. The final sums of the monetary valuations can be found in Table 5.23.

The stocks of organic carbon in soils are important as they provide resilience to habitat changes and support vegetation, therefore contributing to good habitat conditions and to the provision of ES. These are presented in Section 5.2.

Ecosystems with a relatively lower habitat condition will not necessarily provide fewer ES, however these ES might be generated in a non-sustainable way, therefore deteriorating the condition of such habitats (SEEA, 2014). This might therefore lead to a decrease in the provision of ES in the future, but also an increase in others (there are trade-offs between ES). Land-use change can lead to such deterioration of the quality of habitats. No significant land-use change has been noted during fieldwork, compared with data from Waldren et al. (2015).

5.2 Quantification of the stocks of organic carbon

The stocks of soil organic carbon, quantified by the method described in Section 3.7, can be found in Table 5.1. The highest stock is shown by Lough Gealain, followed by Skealoghan and Caranavoodaun, all containing organic soils. The soil type containing more organic carbon is FenPt. Expressed in tonnes per hectare, the lowest stock is shown by BOrgVSW at Lough Aleenaun (22.5 t ha^{-1}), while the highest one is found for FenPt at Skealoghan (499 t ha^{-1}).

Table 5.1. *Soil organic carbon stocks in the seven turloughs and for each soil type. Area left indicates the difference between the areas from the soil maps and the total area of the turlough. To these areas (not containing a soil sample), an average of the carbon concentration for that specific turlough was applied (indicated as "av.").*

Soil type	**Turlough SOC stocks (t)**						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		2,733.4 (53.15)			144.0 (57.48)		
BMinSW		901.3 (174.05)					
BMinVSP					492.7 (52.96)		
BMinSP		1,874.0 (161.92)		21.2 (124.8)			
BMinSRPT				10.8av.			
BOrgVSW	108.4 (22.48)		916.8 (80.97)			618.1 (47.96)	675.4 (90.35)
BOrgVSP	336.6 (71.64)					1,795.1 (82.19)	
FenPt			7,371.7 (499.42)				9,321.0 (499.4)
Lac				78.6av.			
AlluvMRLPT	259.4av.		291.0av.				
AlluvMRL				20.9 (143.88)		2,676.2 (143.88)	
AlluvMIN				4,562.5 (94.92)	94.2 (94.92)		
Area left	248.4	2,627.3	2,676.0		260.5	7,740.9	1,877.8
Total (t)	952.8	7,057.1	11,255.6	4,694.0	991.4	12,212.2	11,874.2
Total (t ha^{-1})	69.5	119.0	325.8	60.1	39.2	341.2	363.3

Indicator to include in the framework: stock of soil organic carbon.

5.3 Provisioning services

5.3.1 Water provision

5.3.1.1 Potential drinking water provision

Turlough water is not used at present for drinking water, though they could be used as emergency sources of water (after treatment). The values calculated here are therefore potential and will not be considered in the final monetary value of the ES of turloughs.

The cubic metres of water in the turloughs can be taken as an indicator for this ES. Volumes in the turloughs vary during the year, with some turloughs drying up completely, as shown in Figure 5.1. Each turlough has a different hydrological regime and therefore the stored volume of water can vary faster in the ones with a more flashy response (i.e. Lough Aleenaun and Blackrock) while others can provide a more stable amount of water during the year (e.g. Coolcam). These volumes can be found in Table 5.2. Though a more thorough modelling of potentially extractable water is needed (to avoid damage to habitats), the average water volumes will be considered here. Treatment costs will also have to be subtracted from the calculated values when performing and economic valuation.

Table 5.2. *Average water volumes at each turlough.*

	Average volume (10^3 m^3)
ALE	7.0
BLA	575.0
CARA	165.3
COOL	806.6
COY	1,494.7
GEA	453.0
SKE	299.2

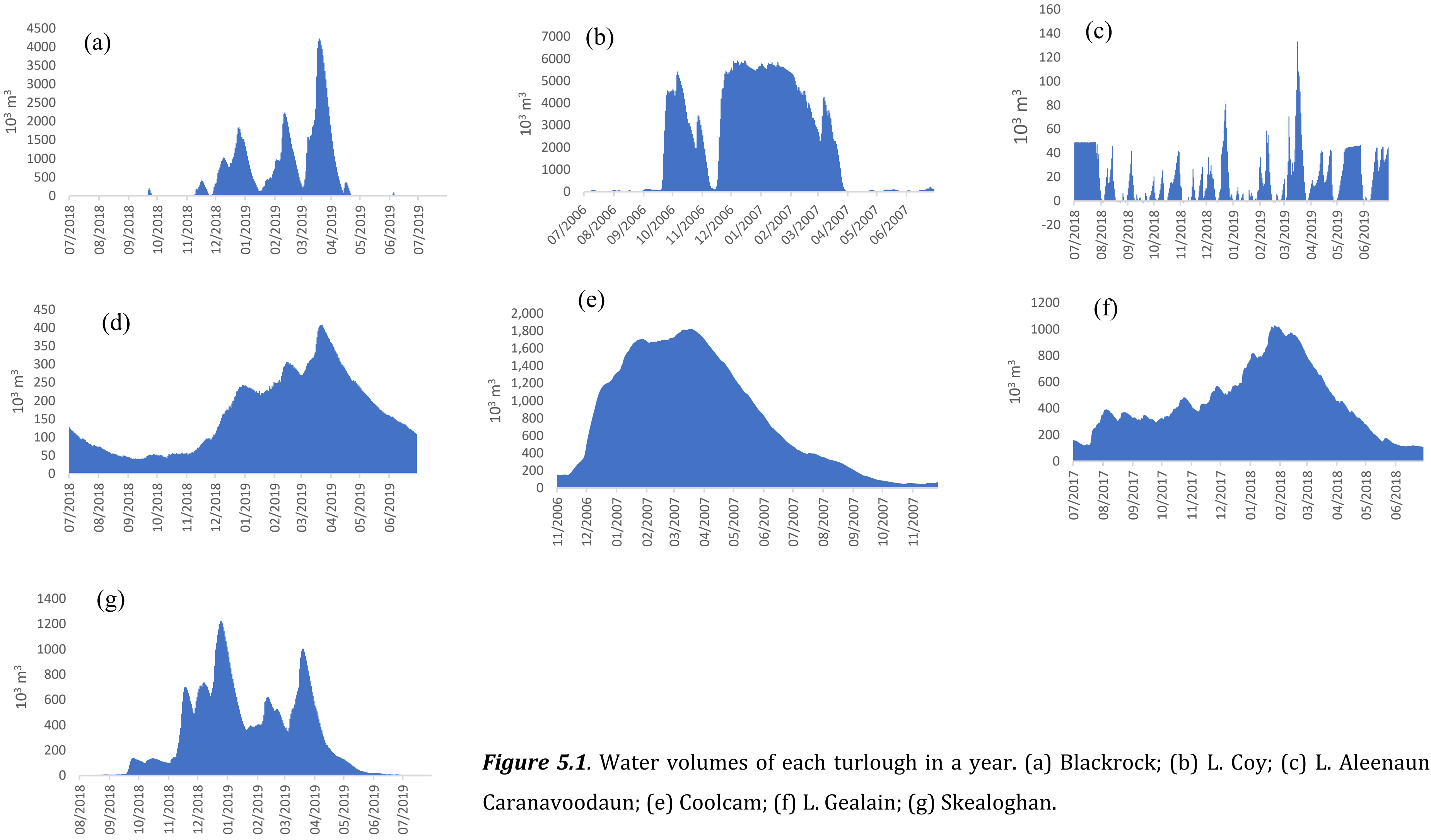

Figure 5.1. Water volumes of each turlough in a year. (a) Blackrock; (b) L. Coy; (c) L. Aleenaun; (d) Caranavoodaun; (e) Coolcam; (f) L. Gealain; (g) Skealoghan.

5.3.1.2 Actual water provision

Turloughs are grazed by domestic livestock in the summer months and they support relatively low-intensity farming owing to their inaccessibility for much of the year (Sheehy-Skeffington & Gormally, 2007).

At the moment the realised value of the water provision ES is that of the water used by cattle grazing the grassland that is contained in the turloughs.

The provision of this service can be calculated by considering the number of animals using the water, their daily water consumption and the number of days they use the resource (Tables 5.3 and 5.4).

Table 5.3. *Average water consumption by farm animal (Parker & Brown, 2003).*

Grazing animals	**Average Typical Water Use (L day^{-1})**
Cattle	
Dairy calves (1-4 months)	9
Dairy heifers (5-24 months)	25
Milking cows	115
Dry cows	41
Feedlot cattle: Backgrounder	25
Feedlot cattle: Short keep	41
Lactating cows with calves	55
Dry cows, bred heifers & bulls	38
Average for cattle	43.6
Horses	
Small (500 lb)	16.5
Medium (1,000 lb)	32.5
Large (1,500 lb)	49
Average for horses	19.3

Data on the number of livestock at the sites from Waldren et al. (2015) have been used in this project as, by consultation with the local farmers at the turloughs and with personnel from NPWS (Gemma Weir, personal communication), it has been indicated that the number of animals has not changed significantly. This is possibly due the turloughs being included in SAC's (which limits the number of animals allowed).

Table 5.4. *Number of animals per turlough (from Waldren et al., 2015) with total water consumption and monetary value. gd=grazing days.*

	Grazing days (number)			**Total water consumption (m^3 yr^{-1})**	**Monetary value (€yr^{-1})**
	Cattle	**Horses**	**Sheep**		
L. Aleenaun	60 (56 gd)	0	0	146.5	274
Blackrock	25 (156 gd) + 15 (56 gd)	4 (56 gd)	0	211.0	395
Caranavoodaun	10 (100 gd) + 25 (14 gd) + 40 (112 gd)	4 (168 gd)	0	254.3	476
Coolcam	10 (56 gd)	0	0	24.4	46
L. Coy	20 (42 gd) + 15 (112 gd) + 12 (96 gd) + 15 (112 gd)	0	0	233.3	436
L. Gealain	0	0	0	0	0
Skealoghan	3 (165 gd) + 5 (10 gd)	0	0	23.8	45

The value of the water provision has been estimated by using the replacement cost technique (see Section 2) and specifically the cost that farmers pay per cubic meter of water (for non-domestic use), were they not to use water from turloughs. Being consumptions from each turloughs less than 1,000 cubic metres per year, the lowest tariff of €1.87 (valid from October 2022) per cubic metre applies (www.water.ie).

Indicator to include in the framework: number of animals grazing.

5.3.2 Fodder provision

The numbers of animals grazing at the turloughs was used as an indicator of the fodder provision for cattle.

An average daily intake of grass from pasture by cattle of 15 kg DM per day was used here and taken from existing literature (Dillon & Buckley, 1998, O'Brien et al., 2018) in the ES calculations. This amount was multiplied by the number of animals and the days spent grazing outside, to give the values in Table 5.5. These amounts were then valued by considering the cost that would be incurred by substituting the pasture grass intake with hay or silage grass.

Table 5.5*. Pasture grass consumption by animals at the turloughs and monetary value. gd: grazing days. AUE=Animal Unit Equivalent.*

Turlough	**Grazing days**		**Total grass consumption (kg)**	**Monetary value (€)**
	Cattle	**Horses**		
ALE	60 (56 gd)	0	50,400	5,897
BLA	25 (156 gd) + 15 (56 gd)	4 (56 gd), AUE=1.1	74,796	9,871
CARA	10 (100 gd) + 25 (14 gd) + 40 (112 gd)	4 (168 gd), AUE=1.1	98,538	14,889
COOL	10 (56 gd)	0	8,400	983
COY	20 (42 gd) + 15 (112 gd) + 12 (96 gd) + 15 (112 gd)	0	80,280	9,393
GEA	0	0	0	0
SKE	3 (165 gd) + 5 (10 gd)	0	8,175	956

The average price for pick up meadow baled hay for 2019-2021 was 100.6 £ t^{-1} (€117 t^{-1}) (https://ahdb.org.uk/dairy/hay-and-straw-prices). British Hay and Straw Merchants' Association for Great Britain and its regions). Horse hay has a price of €420 t^{-1} in Ireland in 2021 (€460 t^{-1}) (www.robinsonfarms.ie,).

5.4 Regulating services

5.4.1 Flood risk prevention (water flows regulation)

The valuation of flood risk prevention can be performed using the replacement cost method, as the cost to substitute the volume of water that is contained in the turloughs and applying a price for an equivalent constructed basin for water storage (as in Meng & Dong (2019)).

Equation 5.1 has been proposed by the UK Environment Agency to estimate the cost of flood defences (Keating et al. 2015):

$$Cost\ (£\ m^{-3}) = 11{,}239 \times \text{volume}^{-0.628} \qquad (5.1)$$

Applying this equation to the maximum volume of flood water that can be contained in the turloughs, the values in Table 5.6 were obtained.

Table 5.6. *Valuation of the flood prevention service offered by the turlough basins.*

	Maximum flooded volume ($10^3 m^3$)	**Value (10^6 €) following the Environment agency equation (Keating et al., 2015)**
ALE	355.6	1.62
BLA	11,446.4	5.87
CARA	722.7	2.10
COOL	1,908.9	3.01
COY	5,551.5	4.48
GEA	1,014.1	2.38
SKE	382.2	1.66

The economic valuation of the flood protection ES was based on the fact that turloughs are part of the natural groundwater flow therefore providing storage. Some of them (like Blackrock and Lough Coy) also present a flood hazard since properties and significant infrastructure (M8 motorway) are present in their flooding zone. This can be considered a disservice and were therefore subtracted from the value of the water flow regulation calculated. In the Gort area (where Blackrock and Lough Coy are located) for example, a flood prevention scheme is being implemented which includes the building of channels that drain to the sea. The total cost is estimated at €14 million euros (not including professional fees, ground investigation or compensation costs), with a benefit of €22 million. The scheme entails improvements in the existing overland flow path between the turloughs in the area and Kinvarra bay where the waters eventually flow. It will incorporate flood prevention measures such as 16 km of channels, flow control structures, raising roads, swallow hole maintenance and pumping facilities (Enda Gallagher, Senior Executive Engineer, Roads & Transportation Section, Galway County Council, personal communication). By consultation with Enda Gallagher, the costs associated with Blackrock (Skehanagh channel) can be estimated at €3 million, while those associated with Lough Coy (Coy / Ballylee / Castletown / Ballyloughan channel) at €3.7 million. It has to be remembered though, that the costs provided above for the alleviating of flooding from the Coy/Ballyloughan area include those for the additional flows that are proposed to be brought down from Blackrock. If flooding at Lough Coy was to be dealt with in an isolated scenario, where additional flow from Blackrock was not designed into the system and where the dumping of additional water downstream in to Ballyloughan/Castletown/Coole areas was not a concern, the cost would be dramatically reduced, albeit not solving flooding problems downstream. Similarly, if water was to be brought from Lough Coy directly to Kinvarra by a purpose-built channel, the cost would be different (much higher in this case).

By considering these costs the value of flood risk prevention provided by Blackrock and Lough Coy can be then lowered to €2.9 million and €0.8 million, respectively. The other turloughs only occasionally flood minor roads, which can cause inconveniences but can be ignored in the calculation of damages (following the approach taken by the Galway Council in the South Galway - Gort Lowlands Flood Relief Scheme, 2016).

5.4.2 Climate regulation

5.4.2.1 Carbon balance over a year

The Net Ecosystem Exchange (NEE) was modelled on a half hour basis (following the data structure from the meteorological station), to account for diurnal variation of photoactive radiation (PAR), which drives gross primary productivity (GPP) by plants and of temperature, which drives ecosystem respiration (ER).

The relationship between NEE and GPP can be illustrated by the following equation (5.2):

$$NEE=GPP-ER \qquad (5.2)$$

where

NEE = net ecosystem exchange;
GPP = gross primary production (in g C-CO_2 m^{-2} s^{-1});
ER = ecosystem respiration (in g C-CO_2 m^{-2} s^{-1}).

GPP was the flux of CO_2 measured by the closed chamber method seasonally which was then extrapolated to the non-measured days of the year based on the PAR data from the meteorological station, after being corrected using the PAR data measured at the turloughs with the EGM4 equipment (Table 5.7 and Figure 5.2).

***Table 5.7**. Values of PAR from Clara meteorological station against the ones measured at the sites.*

Clara PAR (μmol m^{-2} s^{-1})	site PAR (μmol m^{-2} s^{-1})	Date measured
689.5	224	11-Jul-18
767.7	350	13-Mar-19
1,303	470	31-Jul-19
1,645	976	4-Aug-19
570.2	312	09-Sep-19
1,146	708	27-Jul-19
380.5	150	28-Sep-19

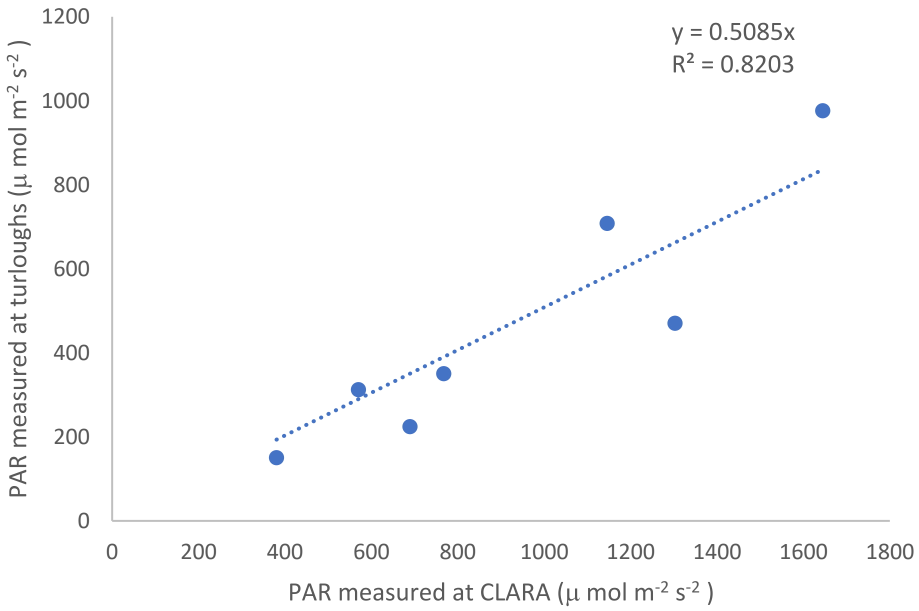

***Figure 5.2**. PAR from the Clara meteorological station vs data measured on the field.*

The Michaelis-Menten equation, using meteorological data from the nearest available meteorological station, data of air temperature and photoactive radiation (PAR) was used to calculate GPP (Equation 5.3). These PAR data were correlated with the PAR data acquired during measurements with the closed chambers thanks to the EGM4 portable infrared CO_2 equipment which had a sensor that measured PAR, giving a reading in μmol m^{-2} s^{-1}.

$$GPP = -a * \frac{PAR}{PAR+b} \tag{5.3}$$

where

a = maximum rate of GPP (at maximum PAR intensity);
b = light intensity at which the GPP is half of the maximum;
PAR = Photosenthetically Active Radiation (measured or calculated).

Applying this approach, the NEE balance over a year was worked out by multiplying the fluxes per square metre with the turlough surfaces. The final values for each turlough can be found in Table 5.8.

The emissions from dry terrain and wet surfaces were measured and modelled separately.

Table 5.8. *Flux of C-CO_2 from the turloughs over one year (2018-2019) (negative values indicate sequestration while positive ones indicate emissions). As the collars were fixed they have experienced different humidity conditions therefore also accounting for partially flooded conditions. Emissions from water were also taken from a boat (see Appendix B, Table B.5).*

turlough	g C-CO_2 m^{-2} yr^{-1}			Tonnes C-CO_2 yr^{-1}		
	dry	wet	total	dry	wet	total
ALE	186	77	263	192	79	271
BLA	384	76	460	92	53	145
CARA	0.023	0.003	0.03	0.001	0.008	0.009
COOL	64	8	72	15	52	67
COY	266	131	397	537	264	801
GEA	113	85*	198	42	31*	73
SKE	21	-324	-303	-595	38	-557

* The figures for the wet fluxes for Lough Gealain include the water basin which is always flooded (a source of 1 tonne per year) and the main basin with marls which dries out in summer (31 tonnes per year).

For Lough Gealain, a difference was also made between wet surfaces, main wetland basins that were always wet (and contained wetland plant communities), and elevated areas with grassland and scrublands which showed significantly different emissions. Total fluxes were then modelled based on the extension of each area at each hydrological stage.

Average CH_4 fluxes vary from 0.07 g CH_4-C m^{-2} yr^{-1} (Lough Gealain, dry flux) to 1.9 g C-CH_4 m^{-2} yr^{-1}, while average N_2O fluxes from 0.03 g N_2O-N m^{-2} yr^{-1} (Skealoghan, wet flux) to 0.48 g N_2O-N m^{-2} yr^{-1} (Coolcam, wet flux) (Table 5.9).

***Table 5.9**. Methane and nitrous oxide emissions from land and water at the turloughs. A global warming potential (GWP) of 25 and 298 (www.ecometrica.com)) for methane and nitrous oxide respectively was used to derive the total tonnes of CO_{2eq} carbon for each turlough.*

turlough	**CH_4**		**N_2O**	
	t C-CH_4 yr^{-1}	g C-CH_4 m^{-2} yr^{-1}	t N-$N_2$0 yr^{-1}	g N-$N_2$0 m^{-2} yr^{-1}
ALE	1.1 (0.3 dry, 0.8 wet)	1.9 (0.5 dry, 1.4 wet)	0.19 (0.05 dry, 0.14 wet)	0.19 (0.05 dry, 0.14 wet)
BLA	1.027 (0.62. dry, 0.41 wet)	0.63 (0.38 dry, 0.25 wet)	0.43 (0.26 dry, 0.17 wet)	0.26 (0.16 dry, 0.1 wet)
CARA	0.4 (0.11 dry, 0.29 wet)	0.9 (0.25 dry, 0.65 wet)	0.29 (0.08 dry, 0.21 wet)	0.64 (0.18 dry, 0.46 wet)
COOL	0.77 (0.3 dry, 0.47 wet)	0.82 (0.32 dry, 0.5 wet)	0.74 (0.29 dry, 0.45 dry)	0.78 (0.3 dry, 0.48 wet)
COY	0.96 (0.68 wet, 0.28 dry)	0.5 (0.35 dry, 0.14 wet)	0.46 (0.33 dry, 0.13 wet)	0.24 (0.17 dry, 0.07 wet)
GEA	0.18 (0.03 dry, 0.15 wet)	0.49 (0.07 dry, 0.42 wet)	0.14 (0.02 dry, 0.12 wet)	0.37 (0.06 dry, 0.031 wet)
SKE	2.77 (1.57 dry, 1.2 wet)	1.53 (0.87 dry, 0.66 wet)	0.15 (0.08 dry, 0.06 wet)	0.08 (0.05 dry, 0.03 wet)

Moderate correlations were found with depth for CO_2 and CH_4 fluxes (Figure 5.3, positive for CO_2 and negative for CH_4), while no correlation with depth was found for N_2O emissions.

***Table 5.10**. Average GHG emission data in relationship to the depth of the turloughs, as this is a factor for their production.*

Fluxes	**CO_2 (mol/mol/m^2/hr)**		**CH_4 (umol/mol/m^2/hr)**		**N_2O (umol/mol/m^2/hr)**		**turlough depth (m)**
	average dry	average wet	average dry	average wet	average dry	average wet	
ALE	16,414.3	5,979.7	5.0	5.8	1.7	0.0	2.6
BLA	11,407.8	8,646.0	1.5	4.5	0.4	0.7	6.8
CARA	6,372.0	1,985.7	3.1	5.5	2.3	0.3	1.4
COOL	16,200.5	4,630.3	5.1	6.4	2.8	0.4	2.0
COY	22,829.0	18,048.5	2.3	2.4	0.6	0.4	5.9
GEA	3,178.3	735.6	5.5	4.8	0.2	1.8	2.6
SKE	12,000.5	3,651.5	6.1	8.2	0.1	0.3	1.2

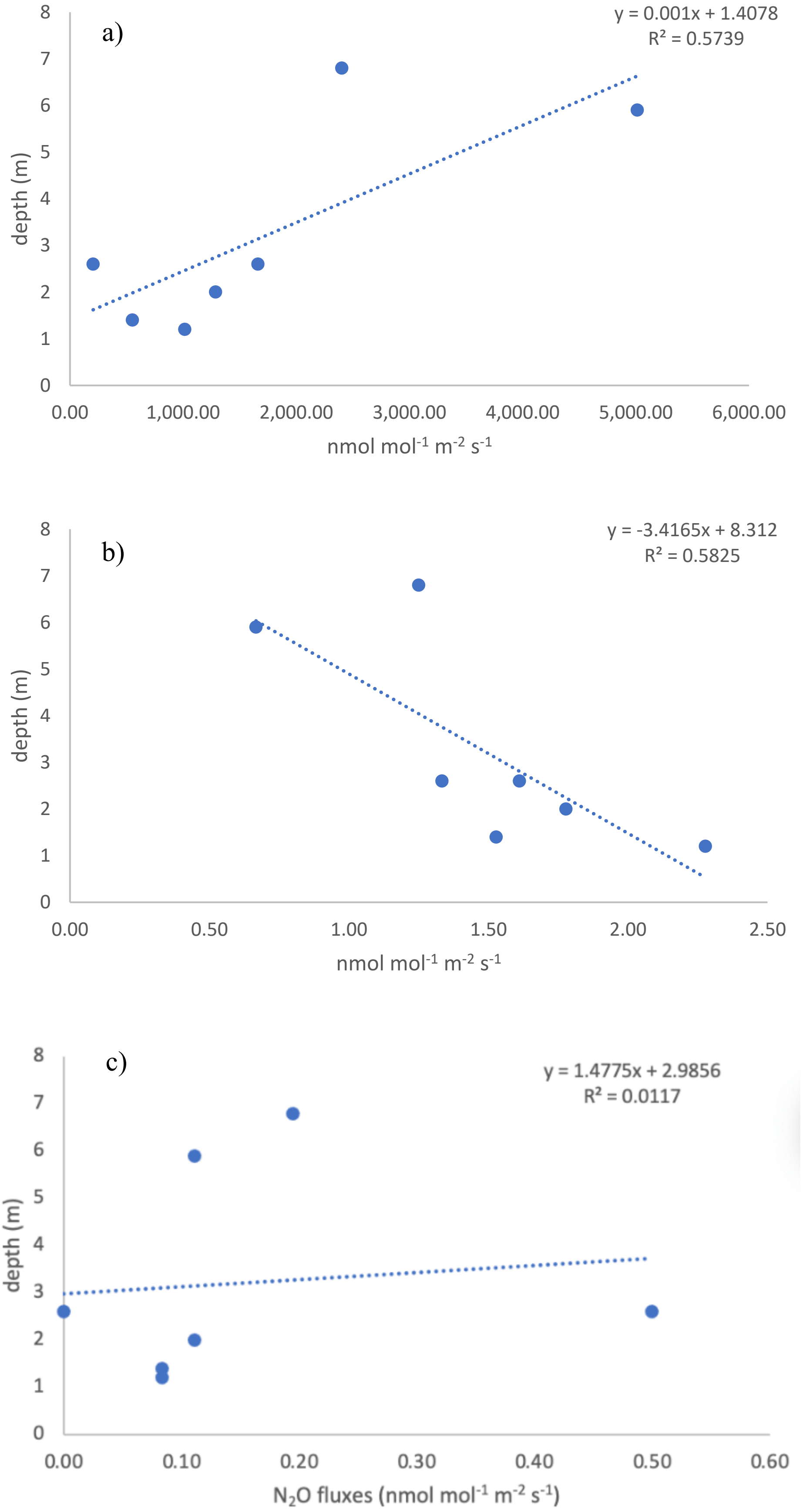

***Figure 5.3**. Correlations between turloughs average depth and (a) CO_2, (b)CH_4 and (c)N_2O wet fluxes.*

A direct relationship was found between CO_2 emissions from the flooded basins and TP (Figure 5.4).

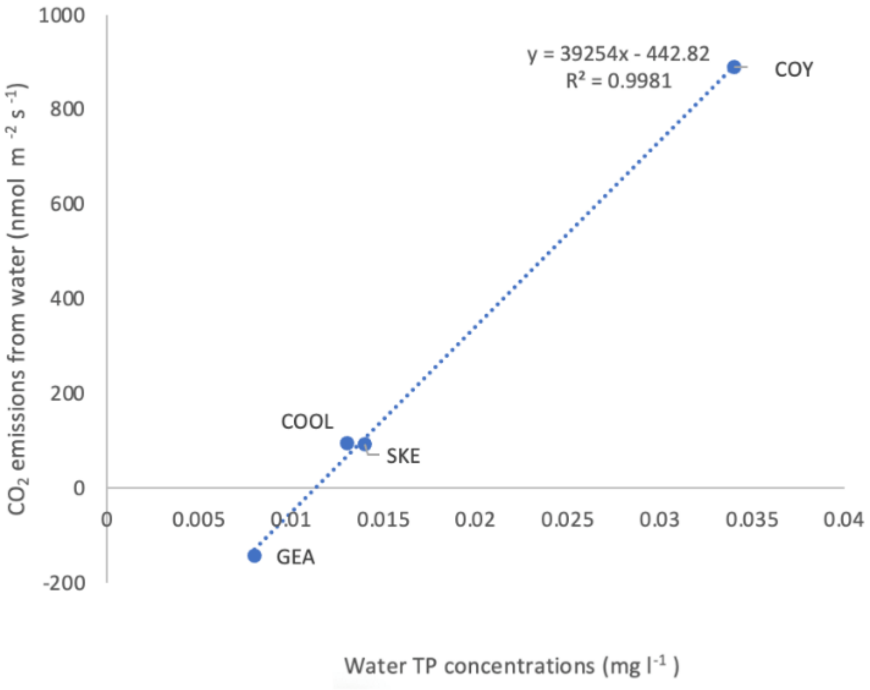

***Figure 5.4**. Relationship between TP and CO_2 emissions in the flooded stage.*

5.4.2.1.1 Aquatic carbon losses

Aquatic carbon losses considered were carbon evasion from open water (already estimated with the floating chamber method), DIC and DOC (that enter and leave the system with water from watercourses, swallow holes or estavelles). Following Evans et al. (2016) 90% of the DOC loss was assumed to be converted to CO_2 (and lost to the atmosphere) and 10% to long-term storage, while 100% of the DIC flux was assumed to be released to the atmosphere.

DIC consists of three constituents: free CO_2, the bicarbonate ion (HCO_3^-), and the carbonate ion (CO_3^{2-}). It can range from 20 µM to 5000 µM in highly alkaline hard waters but usually it ranges from 100 to 1000 µM (Cole & Prairie, 2014). CO_2 is usually supersaturated with respect to the atmosphere. It is assumed that 100% of DIC is lost as CO_2 to the atmosphere (when it finally resurfaces downstream of turloughs)

The values of DIC calculated using the Microsoft Excel-addon CO2SYS(Pierrot et al., 2006) can be found in Appendix C, Table C.3. DIC was calculated from salinity, pH and alkalinity values. CO2SYS allowed to calculate DIC, based on temperature, salinity, pH, and alkalinity. Salinity was derived from surveyed electrical conductivity values, using Equation 6.2 (Rusydi, 2018). The calculated values can be found in Table 5.11.

The variation of hourly water volumes (derived from water stages) was multiplied by DIC or DOC to calculate the dissolved carbon flux to and from the turloughs. A balance was worked out for a hydrological year.

As it can be seen from Figure 5.5, the maximum concentrations of DOC are reached from October through December, when turloughs are recharging, while values decrease to minimum values in the summer months (discharge). This trend is consistent through the various turloughs and can be interpreted as alloctonous inflow of organic matter. Following the approach of Evans et al. (2016), about 10% of this amounts precipitates and becomes part of sediments and soil and can therefore be accounted as sequestered carbon.

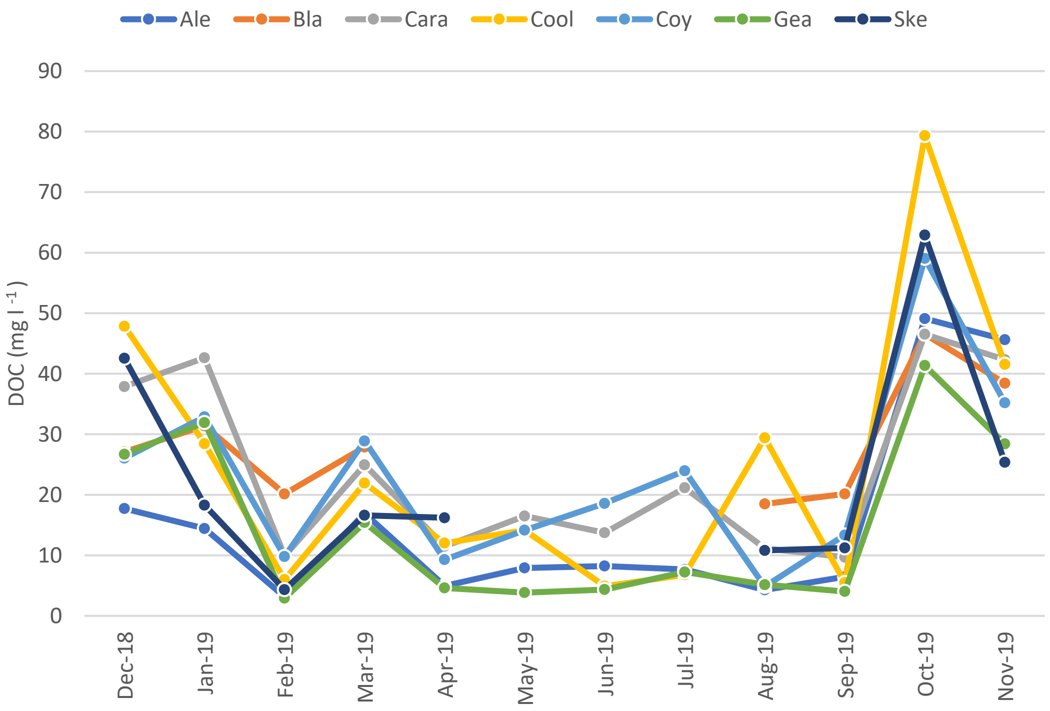

***Figure 5.5**. DOC concentrations over the surveyed period. Ale (Lough Aleenaun); Bla (Blackrock); Cara (Caranavoodaun); Cool (Cooolcam); Coy (Lough Coy); Gea (Lough Gealain); Ske (Skealoghan).*

The total carbon exchange from and to the system due to dissolved carbon in water (in terms of tonnes of carbon) can be found in Table 5.11.

Table 5.11. *Organic and inorganic carbon dissolved in water. Positive values indicate imports of carbon, while negative ones indicate exports. 90% of DOC is assumed to be emitted to the atmosphere following Evans et al., (2016), while 100% of DIC is assumed to be emitted.*

turlough	DIC (kg C)	DOC (kg C)
Ale	0.01	14
Bla	0.0	72
Cara	1.7	32
Cool	-0.4	-57
Coy	0	0
Gea	2,229	-381
Ske	-7	5

5.4.2.1.2 Animal grazing contribution

For a complete carbon balance in an agricultural setting where there are animals grazing, exports of biomass as well as emissions due to enteric fermentation and manure must also be considered. It should be noted that Lough Gealain on the Burren is the only site which historically is reported as ungrazed (though some grazing has been reported but no specific numbers).

Livestock emits CH_4 from enteric fermentation, N_2O from use of nitrogenous fertilizers and CH_4 and N_2O from manure management and deposition of animal manures on pastures. Some CO_2 is also produced on animal farms from fossil fuel and energy usage (O'Mara, 2012).

CH_4 and N_2O emissions from the pasture are captured by the closed chamber method, however the emissions from enteric fermentation and from dung (which was not measured) are assumed to not be included in the balance. Hence, the portion of CO_{2eq} (CO_2 equivalent) emissions that happened while the cows were grazing on the turloughs also needs to be considered (which is linked to the grazing days as reported in Table 5.5).

Production of methane from ruminants has been estimated to 250-500 litre per day per cattle head and it represents the biggest contribution to GHG emissions (Johnson & Johnson, 1995). As 1 mole of CH_4 weighs 16 g and occupies 22.4 l at STP, 250-500 litres correspond to 178.6-357.1 g of CH_4 or 134.0 – 267.8 g of C per day per animal (or an average of 201 g). This value was multiplied by the days that cattle spent on the field (Table 5.12). This data were taken from Waldren et al. (2015) and from field observations. In the case of Coolcam, no animals were reported, however during field visits about 10 cows were observed and so were accounted for in the calculations. An average value of 56 grazing days was used. Horses were considered as being equivalent to 1.1 cows and the emissions corrected accordingly. Parker et al. (2018) found that enteric emissions of N_2O from cattle amounted to 6.93 ±2.99 mg N_2O Kg^{-1} of DMI (dry matter intake) per day, while manure emissions were 558-108 times higher than this. Considering an average (from a weaned calf to a suckler cow at peak lactation (https://ahdb.org.uk/), dry matter intake of 8.7 kg this gives about 60 mg of N_2O from enteric fermentation and 6.5-33.5 g N_2O from manure emissions per day. Considering then a GWP over a 100 year of 25 for CH_4 and 298 for N_2O (www.ecometrica.com), this corresponds to a total of about 20 g N_2O per day or 6.0 kg of C from N_2O contributions.

Table 5.12*. Contributions to GHG emissions from animal grazing. Horses are considered to be 1.1 AUE (Animal Unit Equivalent).*

	Grazing days (number)		**GHG emissions (t CO_{2e})**			
	Cattle	Horses	Cattle		Horses	
			CH_4	N_2O	CH_4	N_2O
ALE	60 (56 gd)	0	16.8	21.4	0	0
BLA	25 (156 gd) + 15 (56 gd)	4 (56 gd), AUE=1.1	23.6	28.1	1.1	1.4
CARA	10 (100 gd) + 25 (14 gd) + 40 (112 gd)	4 (168 gd), AUE=1.1	29.1	34.7	3.7	4.5
COOL	10 (56 gd)	0	2.8	3.3	0	0
COY	20 (42 gd) + 15 (112 gd) + 12 (96 gd) + 15 (112 gd)	0	26.8	31.7	0	0
GEA	0	0	0	0	0	0
SKE	3 (165 gd) + 5 (10 gd)	0	2.7	3.2	0	0

5.4.2.1.3 Final carbon balance

The NEE, CH_4 and N_2O fluxes, aquatic losses and animal grazing contributions were added and expressed as tonnes of carbon in Table 5.13, together with the estimated value in euros (1 tonne of carbon is priced at €85.22, as of 1 December 2022) on the European Union emission trading market scheme (www.ember-climate.org).

Emissions range from 162 tonnes CO_{2eq} yr^{-1} for Lough Gealain to 1,092 tonnes CO_{2eq} yr^{-1} for Lough Coy, for a disservice of € yr^{-1} 13,763 and 93,069, respectively. Skealoghan is the only turlough that shows carbon sequestration of 401 tonnes CO_{2eq} yr^{-1} and therefore a positive value of the climate regulation ES of €34,156 yr^{-1}.

***Table 5.13**. Final GHG balance from all sources and monetary value. Negative values in the last column indicate a disservice. Monetary values from 2022.*

turlough	**CO_{2eq} (t yr^{-1})**							
		From habitats		Dissolved in water		From grazing animals	TOTAL	Monetary value
	From CO_2	From CH_4	From N_2O	DIC	DOC	CH_4 +N_2O		(€ yr^{-1})
ALE	271	20.0	56.8	0	0	53.6	401.4	-34,207.3
BLA	145	25.7	128.6	0	0	121.3	420.6	-35,843.5
CARA	0.009	10.0	86.7	0	0	81.8	178.5	-15,212.5
COOL	67	19.2	221.2	0	0	208.7	516.1	-43,982.0
COY	801	23.9	137.5	0	0	129.7	1092.1	-93,068.8
GEA	73	4.5	41.9	2.2	0.4	39.5	161.5	-13,763.0
SKE	-557	69.1	44.8	0	0	42.3	-400.8	34,156.0

Indicators to include in the framework: habitats, depth of the basin, water TP, number of grazing animals.

5.4.3 Nutrient retention

Strictly speaking nutrient retention should be calculated as a balance considering the difference between the concentrations of nutrients in the water and in the soils, as well as losses to air through processes like denitrification. Conditions upstream and downstream should be also considered to have a clearer picture of nutrient dynamics. In the present study the nutrient retention service was estimated by calculating a nutrient balance over a hydrological year by using the concentration of nutrients in waters as surveyed and by estimating the volumes of waters present at each hydrological stage using regression curves developed by Naughton et al. (2011).

A nutrient balance for SRP, TP, TON, TN and TOC was carried out. Turlough stages (m. AOD) were linked to water volumes by Naughton et al. (2011). Based on these relationships, quadratic and linear functions were used to interpolate between stages and obtain volumes for each stage in the turlough hydrographs. Stage level for the monitored year (2018-2019) were not available for Coolcam, Lough Coy and Lough Gealain. For these turloughs older available levels were used.

Subsequently, the nutrient concentrations obtained through field surveys were multiplied by water volumes to obtain nutrient masses in Kg. Where water levels were only available for years for which direct samples have not been taken, nutrient values from Waldren et al. (2015) were used (Appendix A, Table A.1). Otherwise the nutrient concentrations were multiplied by the volumes at the exact time and date of sampling. An example of the calculation can be found in Table 5.14.

The difference in nutrient masses in the waters at the start and end of hydrological years would then be nutrients that have migrated to/from soils or to the air in the case of denitrification. This however is only over a hydrological year and therefore not indicative of long-term trends.

***Table 5.14**. Example of calculation of nitrate mass, with difference between two Stages at Coolcam. The sum of the differences between the Stages over a hydrological year gave the final estimation of the nutrient retention/release.*

Date	Coolcam Stage (mAOD)	Volume (m^3)	Nitrates, concentration ($g\ m^{-3}$)	Nitrates, total mass (kg)	Nitrates (mass difference)
04/11/2006	82.245	148,200.358	1.157	171.467	0.000
05/11/2006	82.252	150,365.393	1.157	173.972	2.505

The amounts of nutrients in kg that were exported from turloughs (negative values) or accreted in the system (positive values) over a hydrological year can be found in Table 5.15.

***Table 5.15**. Balance of nutrients over a hydrological year for each turlough.*

Turlough	**Total N (Kg)**	**SRP (Kg)**	**TP (Kg)**	**TOC (Kg)**
Ale	0	0	0	14
Bla	0	0	0	72
Cara	-0.2	0	0	32
Cool	-57	0.9	0.4	-57
Coy	0	0	0	0
Gea	-26.9	-0.4	0	-381
Ske	0.1	0	0.1	4.6

For the monetary valuation of this service a cost-based approach was taken. More precisely, a shadow project approach was followed. The proxy used as a replacement is constructed wetlands, following the approach taken in La Notte et al. (2017).

Constructed wetlands provide similar ecosystem services as natural wetlands, especially water purification. The replacement cost method is particularly appropriate because it refers to ecosystem engineering cost. Constructed wetlands are able to remove even low concentrations of nitrogen. La Notte et al. (2012) following a review by Cuttle et al. (2007) propose a value of €2,463 per tonne (€2,689 in 2022, or €2.6 Kg^{-1}) of nitrogen removed by the constructed wetland. By applying these values to the quantities found with the nutrient balance performed here, the water purification service can be quantified and the values can be found in Table 5.16.

Table 5.16. *Monetary value of the water purification ES. Negative values indicate a disservice (as nutrient are exported from the turlough). Monetary values from 2022.*

Turlough	**TN ($kg\ y^{-1}$)**	**Monetary values (€ y^{-1})**
Ale	0	0
Bla	0	0
Cara	-0.2	-0.54
Cool	-57	-153.9
Coy	0	0
Gea	-26.9	-72.63
Ske	0.1	0.27

A value of zero means that the system is in equilibrium between the capacity it has of retaining nutrients and the actual nutrients it receives from its catchment. A negative value means that nutrients are exported, therefore the potential nutrient retention capacity is exceeded and nutrients leave the turloughs. Values range from -57 Kg yr^{-1} of nitrogen for Coolcam (a loss to groundwaters) to 0.1 Kg yr^{-1} for Skealoghan (nutrients that are retained in the habitats of turloughs), for a value of -154 to 0.3 € y^{-1}).

5.4.4 Habitat provision/biodiversity conservation

5.4.4.1 Description of habitat quality

The main habitat present at the sites and in Annex 1 of the EU Habitats directive is “3180 Turloughs”, however other habitats are present, notably “Hardwater lake habitats", "Alkaline fen", "Chenopodion vegetation" and "Limestone pavement" (NPWS, 2019).

Biological quality was summarised by using indicators of biological value. A qualitative index was then assigned to each turlough concerning its Structure and Function, Site Conservation condition and Future Prospects. Points were given for the presence of important species and are taken away for the presence of species indicating ecological disturbance (like *Rumex*) or for bad water quality. Waldren et al. (2015) identified the following as positive turlough indicator species: *Potentilla fruticosa, Viola persicifolia, Teucrium scordium, Limosella aquatica, Plantago maritima, Rorippa islandica and Frangula alnus* (Steve Waldren, pers. comm.; Waldren, 2015).

An estimate of relative values is proposed in Table 5.17 (see Appendix A, Tables A.10 to A.16 for the calculations of the biological response index). These were modified from Waldren et al. (2015) to a scale of 1 to 11 to account for the fact that even the sites with less favourable conditions provide ES, have a good hydrological function and are able to host important plant and animal communities.

***Table 5.17**. Summary of structure and function (S&F)assessment for the 7 turloughs. Green=Good (and very good), Orange=Inadequate and Red =Bad (modified from Waldren et al., 2015). B=bad, I=intermediate, V.G.=very good.*

Turlough	Soil type	Hydrological Functions Assessment	Water Quality Assessment	Biological Responses Assessment	Overall S&F Assessment	Biological response index
ALE	ORG	🟩	🟧	🟥	🟧	1 (B)
BLA	MIN	🟩	🟥	🟧	🟧	4 (I)
CARA	ORG	🟩	🟩	🟩	🟩	10 (V.G.)
COOL	MIN	🟩	🟧	🟧	🟧	5 (I)
COY	MIN	🟩	🟧	🟧	🟧	6 (I)
GEA	MAR	🟩	🟩	🟩	🟩	11 (V. G.)
SKE	ORG	🟩	🟧	🟧	🟧	5 (I)

Table 5.18 lists the source of data for this assessment. Lough Gealain and Caranavoodaun are the only ones of the 7 turloughs that show good and very good structure and function for water quality, hydrology, and biodiversity.

The national expenditure for protected areas for the Republic of Ireland in 2018 was €184 million (€218 million in 2022) (Morrison & Bullock, 2018).

Table 5.18. *Source of data used for the assessment of the habitat provision service.*

Typology of data	Source
Hydrological function assessment	Most recent data available from GSI surveys
Water Quality Assessment	Monthly water sampling at the 7 turloughs
Soil quality assessment	Soil sampling at the 7 turloughs, Waldren et al. (2015)
Biological response Assessment	Waldren et al. (2015), O'Connor (2017), Bhatnagar et al. (2021), field observations Habitat assessment by NPWS (April 2022)

Since 1,603 protected areas are present in the Republic of Ireland (SPA, SAC and NHA), an average expenditure of €135,995 can therefore be assigned to each site. By using the relative biological values in Table 5.17, this amount can be assigned accordingly (an average site would score 6 in this system). The values in Table 5.19 are therefore proposed.

Table 5.19. *Proposed monetary values for habitat preservation based on national expenditure. Monetary values from 2022.*

Turlough	Monetary values (€ yr^{-1})
Ale	22,670
Bla	90,680
Cara	226,700
Cool	113,350
Coy	136,020
Gea	249,370
Ske	113,350

5.5 Cultural services

5.5.1 Scientific value

This thesis is already an indication of the scientific value of turloughs, as a total of €125,000 (€145,010) was allocated to this project and therefore to the study of the ES of turloughs. Having 7 turloughs been studied in more details, €20,716 can be allocated to each one of them. Furthermore, the budget for the Waldren et al. (2015) study on the hydrology and ecology of turloughs was about €800,000 (€874,877 in 2022). Since the turloughs in that study were 22, an average value of €39,767 can also be allocated to each turlough and contribute to the total cultural value of turloughs.

5.5.2 Ecotourism

The only turlough, among the ones studied, which is a significant tourist destination is Lough Gealain, located in the Burren National Park. No significant tourism or recreational activities are known for the other sites. A search on Flickr for the names of the sites, or the names followed by “turlough” and “lough” seem to confirm that Lough Gealain is the most relevant for ecotourism/recreation. The search in fact returns 44 pictures for Lough Gealain, 1 for Coolcam and one for Blackrock. There is a bias in Flickr, particularly in user representativeness and measurement uncertainty (Havinga et al., 2020). because users tend to be in the age range 25-34. As for the other turloughs, individuals have been noted in the around 20 visits to each of these sites carried out for water, soil and GHG sampling. The visitors met while at the sites (2 at Lough Aleenaun, 3 at Blackrock, 3 at Coolcam, 1 at Lough Coy and 1 at Skealoghan) consisted in either the owners of the private parcels in which the turloughs were divided, or neighbours taking a stroll or walking their dogs. The only international visitors were noted at Lough Gealain, where there were usually car parked in the nearby car park and visitors walking along the road or the several trails of the Burren National Park. It is difficult to extrapolate these values though over a whole year. In fact, though numbers might possibly higher, they will be mainly locals returning to the same places for most of the turloughs.

Lough Gealain is situated in the Burren National Park. This is one of the most popular visitor destinations in Ireland (www.lonelyplanet.com). The Park includes the glaciokarst landscape in the northwestern County Clare with scenic limestone sedimentary rocks, but also sandstones and siltstones, all of Carboniferous age. A syncline overlooking Lough Gealain, Mullachmore is a beautiful addition to the attractiveness of the place (Figure 3.19). A geopark was introduced in 2011 which also includes the famous cliffs of Moher as well as turloughs like Lough Gealain and Knockaunroe. The area is internationally renowned and visited for ecotourism, geotourism, speleology. Several touristic trails are present in the area (Figure 5.6) which attract thousands of visitors every year (Table 5.20).

It also features tourist centres and the Outdoor and Education Centre, outdoor activity and adventure trails. Other centres present in the area are the boghill centre and the Burren Yoga and meditation centre. The Burren ecotourism Network has also been established, with the aim of promoting the Park as well as training and certifying member as ecotourism promoters (www.burrengeopark.ie) .

The sum of the visits to the Blue, Green and Red trails for 2018 give a value of 32,200 visits. It should be noted that these visits represent the crossing of a point in the trail twice by each visitor, therefore numbers have been halved (Table 20). This is consistent with different data reported by the Burren Geopark who reported that an average of 3,000-4,000 tourists visit the site at high season (June and July), while 200-1,000 tourists visit from Mid-October to March. Assuming a linear increase/decrease between the peak months and the winter months it can be estimated that the average visitors in that year amounted to 17,200. An average figure of 16,650 visitors per year can then be taken.

***Figure 5.6**. Touristic trails in the Burren Geopark. Lough Gealain is indicated by the red oval.*

***Table 5.20**. Number of visits in 2018 (most recent data) at the different trails surrounding L. Gealain (NPWS personal communication). Only the Blue, Green and Red trail directly surround L. Gealain (personal communication, Burren Geopark).*

	Blue trail	White trail	Green trail	Red trail	Orange trail	Total visits adjacent to L. Gealain
Number of visitors	13,390	16,427	15,984	2,826	6,073	16,100

According to Tourism Ireland, a total of 11.3 million tourists visited Ireland in 2019, spending €5.9 billion. They came mainly from the UK (42%), the US (15%), Germany (7%), & France (5%). They spent an average of €560 and stayed for 6-7 nights (www.tourismireland.com). Assuming that they spent one day visiting the area and spending 1/7 of the total amount, it gives a yearly spending of €1,332,000 (€1,502,236 in 2022 value).

No significant tourism or recreational activities have been reported for the other sites. A search on Flickr for the names of the sites, or the names followed by "turlough" and "lough" seem to confirm that Lough Gealain is the only one relevant for ecotourism/recreation. The search in fact returns 44 pictures for Lough Gealain, 1 for Coolcam and one for Blackrock. There is a bias in Flickr, particularly in user representativeness and measurement uncertainty (Havinga et al., 2020). because users tend to be in the age range 25-34.

As for the other turloughs, individuals have been noted in the around 20 visits to each of these sites carried out for water, soil and GHG sampling. The visitors met while at the sites(2 at Lough Aleenaun, 3 at Blackrock, 3 at Coolcam, 1 at Lough Coy and 1 at Skealoghan) and consisted in either the owners of the private parcels in which the turloughs were divided, or neighbours taking a stroll or walking their dogs. The only international visitors were noted at Lough Gealain, where there were usually car parked in the nearby car park and visitors walking along the road or the several trails of the Burren National Park. It is difficult to extrapolate these values though over a whole year. In fact, though numbers might possibly higher, they will be mainly locals returning to the same places for most of the turloughs.

Goodwillie (1992) proposed a ranking of the turloughs based on ecological value (see Table 5.21).

Table 5.21*. Ecological importance of turloughs and relative ranking (Goodwillie, 1992, limited to the ones present in this thesis). In bold the turloughs studied more in depth.*

International	National	Regional	Local
Newtown/Coole	Lough Mannagh	**Caranavoodaun**	**Lough Aleenaun**
Rahasane	Croaghill	**Skealoghan**	Turloughmore
Carran	Lough Croan	Castleplunket	
Caherglassaun	Ardkill	Brierfield	
Knockaunroe	Balla	Fortwillaim	
Shrule	Lisduff	Turloughnagullaun	
Ballinturly	Carrowkeel	Kilglassan	
Glenamaddy		Belclare	
Coolcam		Termon	
Garryland		Rathbaun	
		Rathnalulleagh	

Coolcam is ranked as having international importance, while Caranavoodaun and Skealoghan have regional importance and Lough Aleenaun is of local importance. Lough Gealain, not mentioned here, is however just a few metres away from Knockaunroe, which is indicated as having international importance (and ranked higher than Coolcam). It is therefore reasonable to assume that Lough Gealain shares those characteristics too and in fact it attracts international tourists, as described in Section 5.5.1.

Using the monetary value calculated for Lough Gealain and doing a benefit transfer to the other turloughs based on the biological scores (which are an important indicator for the attractiveness of the sites for ecotourists) in Table 5.17 and the relative importance in Table 5.21, a potential monetary value for cultural services can be worked out (Table 5.22). These values will not be considered for the final monetary valuation of turloughs but indicate a potential for the cultural development of the sites.

Table 5.22. *Potential value of ecotourism* (€) *based on benefit transfer from Lough Gealain and indicators in Table 5.27.*

	ALE	BLA	CARA	COOL	COY	GEA	SKE
Monetary value (potential)	136,567	546,268	1,365,669	682,835	819,401	1,502,236*	682,835

*Calculated through actual numbers of visitors for Lough Gealain and the travel cost method and therefore included in the final ES monetary value.

Beyond the already mentioned cultural values, aspects like cultural and spiritual influence are also relevant for turloughs, but are difficult to value. For example, for Lough Gealain, several cultural and gastronomical events take place in the area. The area has also said to have been an inspiration for J.R. Tolkien's Lord of the Rings saga. All these events, though not strictly on Lough Gealain, are connected as walks round Lough Gealain are a popular activity as part of the Burren National Park trails (Figure 5.6).

5.6 Monetary sum of the calculated ES values

The monetary values calculated in the Sections of this chapter can be summed to give a total value for each turlough. As already noted, these figures represent estimates that do not include all values (especially the non-use ones). Also, they do not represent the potential of the ecosystems to provide the services (which has anyway been discussed), but the actual value provided. The totals calculated can be found in Table 5.23. They vary between €898,144 yr^{-1}(Lough Coy) and €4,181,079 yr^{-1} (Lough Gealain).

***Table 5.23**. Total calculated values of the ES of the turloughs studied (in € yr^{-1}). Negative values represent disservices. n.a.: not applicable.*

Turlough	**Provisioning services**		**Regulating services**				**Cultural services**	**TOTAL**	**TOTAL ha^{-1}**
	Water for cattle	Fodder	Flood risk prevention	Climate regulation	Nutrient retention	Habitat preservation			
Ale	274	5,897	1,619,565	-34,207	0	22,670	60,483	1,674,682	122,150
Bla	395	9,871	2,870,230	-35,844	0	90,680	60,483	2,995,815	50,528
Cara	476	14,889	2,100,694	-15,213	-0.54	226,700	60,483	2,388,028	69,118
Cool	46	983	3,014,961	-43,982	-154	113,350	60,483	3,145,687	40,267
Coy	436	9,393	784,881	-93,069	0	136,020	60,483	898,144	35,556
Gea	n.a.	n.a.	2,382,826	-13,763	-73	249,370	1,562,719	4,181,079	116,823
Ske	45	956	1,657,458	34,156	0	113,350	60,483	1,866,448	57,113

Values of zero for nutrient retention for Lough Aleenaun, Blackrock and Lough Coy indicate the that natural potential nutrient retention of the turloughs is balanced by the nutrients that reach the turloughs from the catchment. The negative values indicate that the nutrient retention potential is exceeded by the actual amount of nutrients which flow into the turloughs.

Negative values for the climate regulation ES indicate that the turlough emits more carbon than it sequesters, therefore providing a disservice.

5.7 Indications on the ES of the 55 turloughs

Using results from the water sampling (only taken once) and data retrieved from the NPWS website (www.npws.ie) and from the GSI website (www.gsi.ie), a number of turloughs are highlighted here as potentially having a higher than average value for their ES.

This information should partly be taken as indicative, as statistical tests (Appendix F, Tables F.6 and F.7) showed that many of the water quality parameters surveyed vary significantly during the year and are not represented by a sample taken near flooding peak. Seasonal sampling should therefore be performed to confirm the indications provided here.

Oligotrophic waters are a first indicator of hydro-ecological quality, as well as the rarity of plant and animal species. This is also testified by the presence of a protected area (SAC and/or SPA).

Values of TP were used to characterise the trophic state of the turloughs as oligotrophic, mesotrophic and eutrophic (with a few turloughs showing hypertrophic characteristics, Appendix C, Table C.1).

Dissolved Oxygen is a predictor of invertebrate abundance (Croijmans et al., 2021) therefore higher values point to a relatively higher abundancy of insects. Saturation of DO is about 11 mg l^{-1} at around 10 °C (temperature when these waters were surveyed) therefore concentrations above 10 mg l^{-1} are notable of good habitats for fauna.

Conditions are worse in the summer months, where algal growth and reduced water volumes will decrease oxygen concentrations.

High values of alkalinity help buffering against acidification due to pollution from organic pollutants, therefore being indicative of more resilient water habitats. High values of TOC can point to organic pollution or drainage of peaty deposits (as is the case for Blackrock and Lough Coy) therefore the cause should also be investigated.

Higher TDS and EC can point to pollution, which should be verified by further sampling. This is also true for higher values for colour, which also decrease the presence of photosynthesising algae therefore affecting carbon sequestration.

An example of turloughs that rank higher for their provision of ES are Rahasane and Coole/Garryland.

Rahasane is a 257.2 ha wide turlough (the widest turlough) and part of both an SAC and an SPA therefore internationally important for migrating birds listed as Special Conservation Interests (*Cygnus cygnus*, *Anas penelope, Pluvialis apricaria, Limosa limosa and Anser albifrons flavirostris*). It contains silty clay marls, no peat and it soils have a high Ca concentration. It will therefore score high in habitat preservation. It is reported as "at significant risk" for diffuse agricultural pollution and domestic waste water (EPA, 2021) (the measured E.C. of 647 $\mu S\ cm^{-1}$ could point to this) and should therefore be monitored, at least seasonally.

Coole/Garryland (included in the Coole/Garryland Complex SAC) is another important complex of turloughs which also host a tourist centre and is important culturally (Refer to Chapter 2). They are located in County Galway, 25 ha wide and characterised by a conduit system. They contain the following habitats of conservation importance: Natural Eutrophic Lakes, *Chenopodium rubri* pp. Vegetation, Juniper Scrub, Orchid-rich Calcareous Grassland, Limestone Pavement and Yew Woodlands. They are considered unique as the most diverse, based on physiography and vegetation and also in being associated with woods. Several important mammals like otters, lesser horshe bat and pine marten are also present. Several birds species of conservation importance have also been recorded, like whoopers swan, Bewick's swan, wigeon, and mallard. The site will therefore score high in habitat preservation. The complex, with a maximum flooded volume of over 60 million m^3 will also score high for water flow regulation. The presence of a tourist centre where important poets resided (See Section 2.8) also gives the site further value for cultural ES.

On the other hand, turloughs that showed elevated values of nutrients, the eutrophic and hypertrophic ones, should be further investigated to understand the causes for this characteristic. In particular, Balla, Droomadoon, Four Roads and Polldowagh all showed values higher than 100 $\mu g\ l^{-1}$ of TP (hypertrophic) (Appendix C, Table C.1).

5.8 Description of a framework for the ES quantification of turloughs

When quantifying and valuing ES, the specific ecohydrological nature of turloughs must be taken into consideration. The filling and emptying cycles in the turloughs are in fact the most important factor in the determination of several processes like carbon and nutrient turnover, vegetation growth, greenhouse gas balance.

The quantification process can vary based on the amount of data available. Ideally, the following data should be gathered to perform an estimation at site level:

- Hydrological cycle of the turloughs, either by direct in-situ investigation, or estimation from satellite images or expert knowledge;
- Hydrochemistry, including organic carbon, phosphorus and nitrogen species, E.C., colour, turbidity, chlorophyll α, through sampling at least once near the peak of flooding; alternatively gathering this information from the EPA or GSI, if available;
- Soil characteristics, via existing maps and/or field samples. Parameters to be investigated: SOM, TN, TP, bulk density, stoniness, soil depth;
- GHG emissions by direct measurements or from literature on emission factors: CO_2, CH_4, N_2O;
- Land-use, by direct investigation, land-use maps, or expert knowledge;
- Vegetation communities present at the site, either by direct survey or existing data and secondary indicators;
- History of the land-use of the site, if comparison of the ES between two points in time are needed;

- Investigation on the cultural/recreational activities carried out at the site, either by direct observation or by using proxies like presence of public roads, cycle ways, national parks. Pictures on social media can be also considered;
- Location of the site in a protected area like SAC or SPA.

The data described above were analysed as illustrated in Figure 5.18.

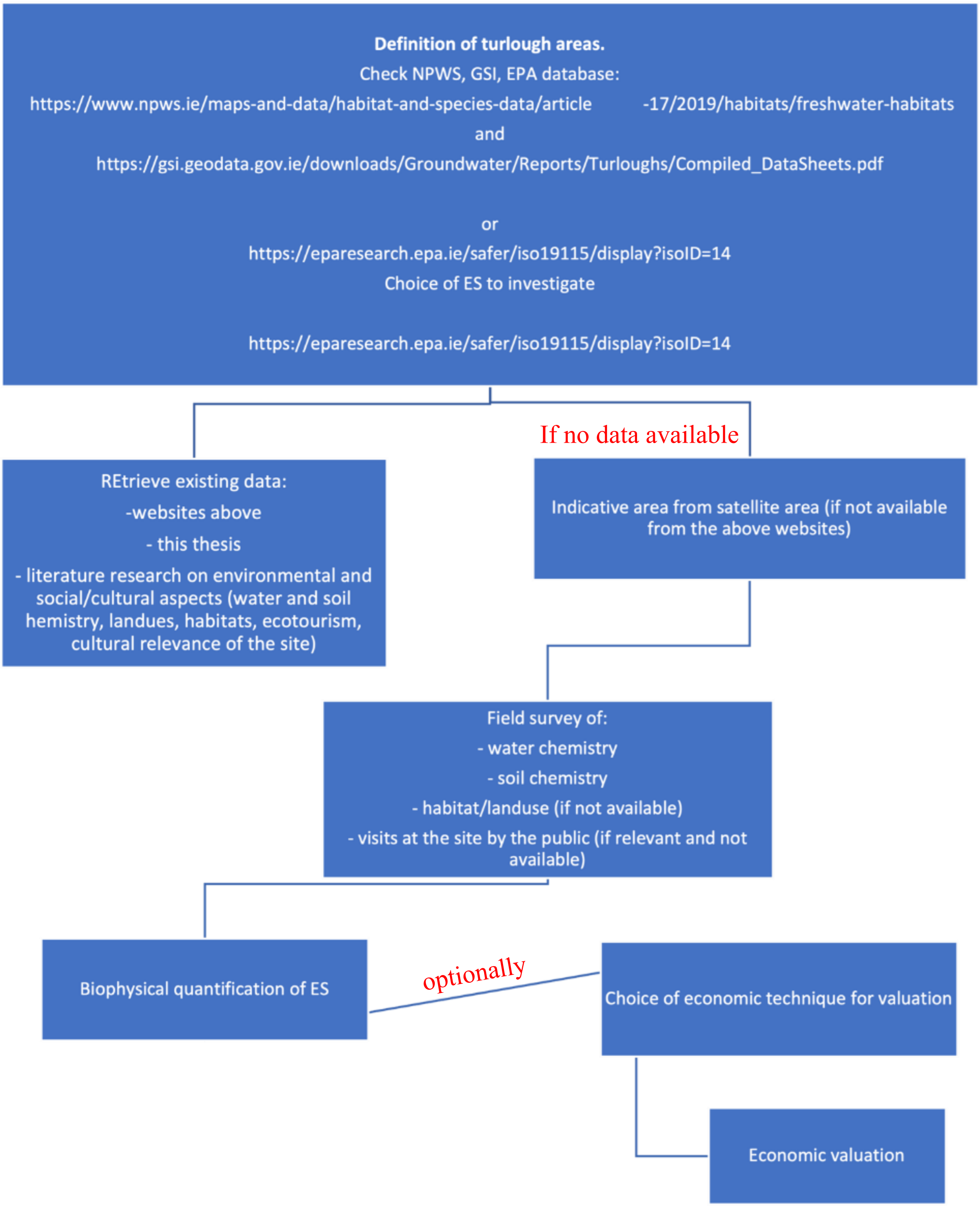

Figure 5.18. *Proposed framework for the quantification and valuation of the ES of turloughs.*

5.9 Most important indicators for the quantification of the ecosystem services of turloughs

Table 5.24 shows a summary of the indicators proposed for the quantification of the ES of turloughs in biophysical terms and useful when direct data are not available. These were based on the work by Egoh et al. (2012) and also on the specific characteristics of turloughs ecohydrology, which require specific indicators.

***Table 5.24**. List of indicators proposed for the quantification of the ES of turloughs.*

Hydrology	**Water quality**	**Soils**	**Provisioning ES**	**Regulating ES**	**Cultural ES**
Length of flooding	Water TP and TN	SOC%	Numbers of animals grazing	Habitats and climate	Number of tourists
Frequency of flooding	Chlorophyll α	TP%		Soil type (granular size distribution), permeability and depth	Cultural and social events
Flood depth	Colour	TN%	Grassland extension,species and NEE Volume of basin	Average area, average depth, NEE, TP, DO, number of grazing animals (GHG emissions)	Pictures on social media
Flood timing	Turbidity	Soil type (granular size distribution) permeability	Water levels	Hydrological characteristic,vegetation maps (carbon seq., water regulation)	Scientific education/research programs
Meteorological data	pH		Land use	Flooded area	Presence of roads and public entrances
	alkalinity		Foraging	Habitat extension, condition and type	Foraging
Flooded area				Soil type ande depth (nutrient retention)	Water turbidity, colour and chlorophyll α (aesthetic value)

6 DISCUSSION

The results of the field work campaigns of waters, soils and greenhouse gases, and of the modelling of the ES of turloughs are discussed in this chapter, with a view to reaching the aims of the research and placing these findings in the context of the existing literature.

6.1 Site selection and upscaling of ecosystem services quantification and valuation

The turloughs selected, as already mentioned, present heterogeneity of hydrological behaviour, water chemistry, soils, habitat, conservation state, which represents both a strength and a weakness of the study. It is a strength because most of the variability in Irish turloughs has been captured (though, for example, turloughs smaller than 10 hectares and with less valuable habitats have not been studied) and a weakness, because replicates of the same type of turlough are not present (they are all different for at least an environmental component) and therefore it is difficult to isolate the factors that control the provision of ES.

Nonetheless this study represents the first assessment of the ES provision of turloughs at site level and also proposes a framework for the study of the ES other turloughs. The indicators proposed in this study can in fact be used also for other studies, with data that can be acquired from existing sources or from remotely sensed data. Values could also be extrapolated to sites showing similar hydrological regimes, soils and habitats.

6.2 Water quality of the turloughs

Some of the characteristics of the 55 turloughs that deviate from average and shown in Table 4.1 are due to the turlough substrate and from the catchment geology (such as the high colour in Blackrock being due to the runoff from the peaty soils in the Slieve Aughty mountains). Some chemical species like TN and TP are linked to the use of fertilizers in the catchments, as well as Cu, As, Mn, Ca, Na, K, Mg, SO_3^-,NO_3^-,Cl^- (Mateo-Sagasta et al., 2017). Equally, the presence of livestock is indicated by high TP and TN, high turbidity, and low D.O.

Increased chlorides in groundwater can signal salinization and have important ecological implications and induce a variety of changes in aquatic plants and animals. This is however highly unlikely in the case of the turloughs in a climate like the west of

Ireland with high rainfall, but might become an issue with climate change predictions of increased drought periods in the summer time. The average values of chlorides found in this study are significantly smaller than the ones found by Cunha Pereira (2011) for Blackrock, Lough Coy, Caranavoodaun and Lough Gealain (Appendix F, Table F.9). Sulphate values on the other hand, are significantly larger than the ones in Waldren et al. (2015) for Blackrock, Lough Gealain and Lough Coy. No significant differences are apparent for nitrates. The main sulphate sources are atmospheric deposition, marine evaporites and also sewage (Torres-Martinez et al., 2020). Pressure from sewage, particularly from small wastewater treatment systems, could be the cause for the elevated concentrations in some of the studied turloughs, but further investigation is needed to determine whether that is the case. Microbiological investigations would also be able to determine whether this is the case.

Blackrock stands out in terms of water chemistry for several parameters, as also found in Waldren et al. (2015). It has a higher colour and lower chlorophyll α than the other turloughs, while Lough Coy stands out for sulphates and Caranavoodaun for TN. Colour values have been found to increase during the draining season, probably associated with the high concentrations of colloid particles from organic soils (peat). Lough Coy and Blackrock also show peaks corresponding to main rain events as they receive drainage from peaty hills (Slieve Aughty mountains).

While Blackrock and Lough Coy have similarly coloured waters (which should restrict algal growth), Blackrock has a very low concentration of chlorophyll α (as expected), but Lough Coy has an average concentration which is about ten times that of Blackrock. This differs with what was reported in the Waldren et al. (2015) study, where both Lough Coy and Blackrock showed lower levels of chlorophyll α. This might be due to the difference in nutrients at the turloughs: average TP is in fact 35 μg l^{-1} for Blackrock and 56 μg l^{-1} for Lough Coy. A differentiation in the chemistry of the different sub-basins at Lough Coy during recession has also been noted. Chlorophyll α monitoring is important for water quality control together with nutrients, to warn about significant enrichment, which could impact on the plant and animal species present at the turloughs. It should also be noted that the recharge period is a sensitive one, as nutrients are mobilised in the catchment. It has also been shown (Del Potro, 2017) that chlorophyll α concentrations are linked to GHG emissions, especially methane, and this can be seen at least for Lough Coy. As also found by Cunha Pereira (2011) there was a sharp increase in chlorophyll α at Blackrock in March. In general, values increase in spring/summer due to higher temperatures. However, Caranavoodaun and Lough Coy also show peaks in winter and autumn (Figure 4.17).

Healthy waters should generally have DO concentrations above 6.5-8 mg l^{-1} (Horne and Goldman, 1994). When DO values are higher than 8 mg l^{-1} no hypoxic conditions are present, as also found in McCormack et al. (2012). Some turloughs were, moreover, found to be near saturation (DO > 10 mg l^{-1}: Four Roads, Kilglassan, Lough Aleenaun). Turloughs with DO concentrations lower than 6.5 mg l^{-1} are Cockstown (3.73 mg l^{-1}), Coole (Park), 5.68 mg l^{-1}, Hawkhill (5.26 mg l^{-1}), and Tullynafrakagh (6.19 mg l^{-1}). For these turloughs regular sampling should be carried out and if these low values were confirmed, the cause should be investigated. The 7 turloughs were all found to have significantly lower concentrations of DO than those found in the Waldren et al. (2015) study. However, DO was only measured once at the 7 turloughs due to problems with the instrument, therefore the value might not be representative of the average over a year. Measures should be therefore repeated at least seasonally.

pH was found to be significantly lower than in the Waldren study for Caranavoodaun, Coolcam and Lough Gealain, however alkalinity levels were not found to be significantly different. It is therefore difficult to infer any significant changes in the buffering capacity of these waters.

Among the 7 turloughs, high turbidity levels, like the one shown at Caranavoodaun (11.0 NTU) should be investigated. Turbidity (discounting possible interferences during sampling), can be due to algal growth, but also suspended sediment and organic matter from sewage discharges. The significantly higher values found at Cranavoodaun, Blackrock, and Skealoghan should therefore be investigated. High turbidity levels also lower the appeal of waters, having therefore a negative impact on cultural services. Low ORP values, like those found at Moate and Tullynafrankagh (Appendix ,C Table C.1) can also point to pollution, though further investigation is necessary (Račys et al., 2010). Turloughs in the Burren (Lough Gealain, Knockaunroe and Lough Aleenaun) have a lower average alkalinity (133 mg l^{-1}) than the overall average of the 55 turloughs surveyed in February-April 2018 (180 mg l^{-1}). The apparent difference is reduced though if the averages over a hydrological year are taken (143 mg l^{-1} Waldren et al., 2015). The reason is probably linked to the shallow soils that are present at the site which seem to influence alkalinity more than the calcareous substrate. Lower alkalinity values can also be noted for the turloughs in the Gort-Kinvarra chain (Blackrock, Lough Coy, Coole-Garryland, Caherglassaun, 143 mg l^{-1}) because they receive drainage waters from the Old Red Sandstone Slieve Aughty mountains. High alkalinity will offer more buffering against acids therefore offering more protection to phenomena like acid rain or lowering of pH due to organic matter decomposition. pH showed an increase during the flooding period (Figure 4.18), as also found in Waldren et al. (2015), which can be due to the lisciviation of calcareous sediments.

The winter peaks of both TN and TON (Figures 4.10 and 4.11) can be explained as losses from the catchment at the end of the growing season, as suggested in Waldren et al. (2015), which then decline as the catchment supply shortens (Johnsson et al., 1987; Kaste et al., 2003; EFMA, 2005). This is especially true for rapid flushing turloughs like Lough Aleenaun and Blackrock. Cunha Pereira et al. (2011) report that the trend of an N decline during winter at Blackrock is similar to that in the river Owenshree, which also points to the fact that this trend is due to nutrient processes in the zone of influence rather than in the turlough itself.

Cunha Pereira et al. (2010) indicated P as the main driver of turlough productivity. The same authors also suggest that nutrient leaching from soils in the turlough catchment, rather than soils within the turlough basin, is the main source of nutrient input into turlough waters. This seems to be confirmed by the weak correlation between soil and water TP (Figure 6.1). Nutrient control measure should therefore be taken at a catchment scale.

In contrast to nitrates and sulphates, phosphates are less mobile in most soils because of precipitation and adsorption to mineral surfaces, and leaching is therefore negligible, except in certain very sandy and organic soils (Wild, 1988). Dissolved organic phosphorus forms are in fact more mobile in soil than phosphates (Havlin & Westfall, 1984). Phosphorus may also be lost if surface soil particles are eroded because of runoff (Lehmann & Schroth, 2003). There is some evidence that phosphorus concentrations are driven by flushing due to rainfall, especially for the particulate fraction (therefore more evident in TP than SRP, Figure 4.13 and 4.14). Lough Coy shows peaks with very high concentrations for SRP in January 2019 and for TP in February and June 2019.

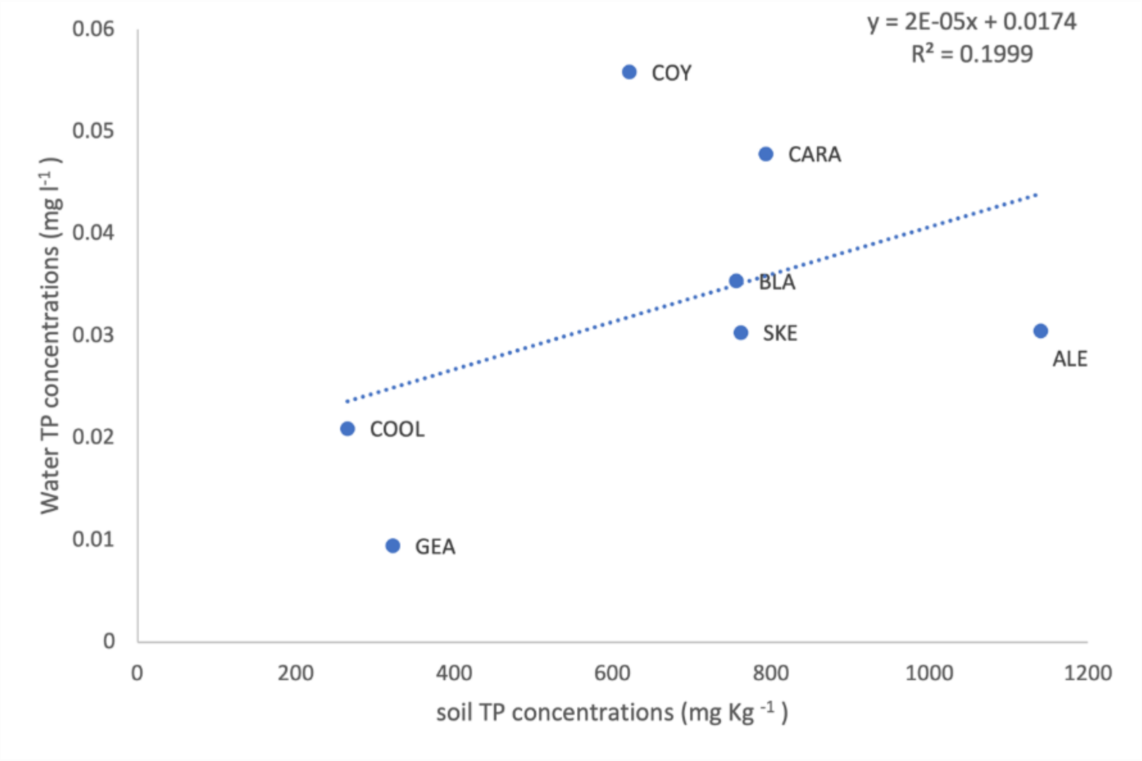

Figure 6.1*. Linear regression of average soil TP and average water TP.*

These may be due to nutrient mobilization due to flushing in the catchment which can happen pretty fast due to the conduit system present at Lough Coy. This dynamic strangely seems to occur independently from Blackrock which does not show corresponding peaks, despite being on the same conduit driven karst network receiving the same feed water and being in close proximity.

Turloughs have similar levels of chlorophyll α and nutrients to those reported for Irish and international lakes (Cunha Pereira et al., 2010a). Cunha Pereira et al., 2010a suggested that relationships between TP and chlorophyll α indicate P limitation of algal biomass in the majority of turloughs. Values of chlorophyll α are, however, statistically significantly higher from the ones found by Waldren et al. (2015) for Blackrock, Caranavoodaun, Lough Coy and Lough Gealain (see Appendix F, Tables F.8 and F.9). This could be due to differences in water sampling locations (algal growth was noted nearby sampling locations for some turlough in summer). An improvement in TP was found for Coolcam compared to the Waldren et al. (2015) study (21 μg l^{-1} TP in the present study, 34 μg l^{-1} in the Waldren study), while higher values were found for Caranavoodaun and Lough Gealain. Figure 6.2 seems to suggest a good correlation between TP and chlorophyll α. As also found by Cunha Pereira (2011) chlorophyll α could be higher near shorelines because of wind-driven accumulations caused by filamentous algae.

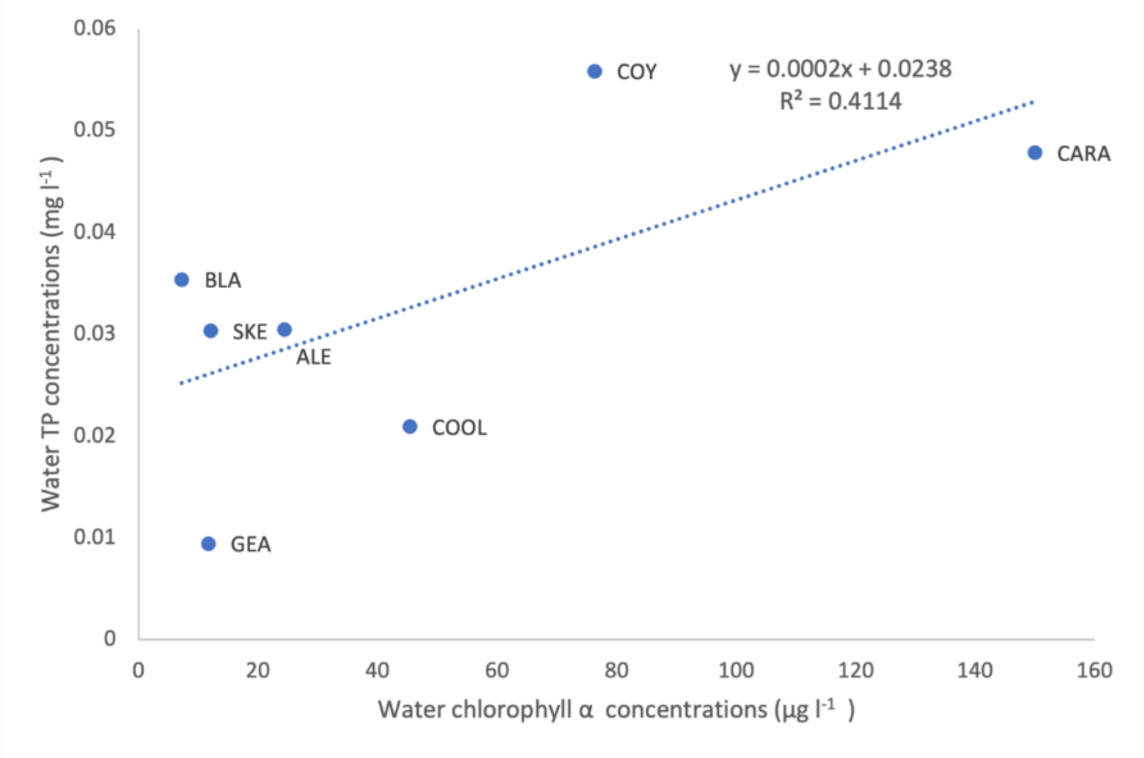

***Figure 6.2**. Linear regression of TP and chlorophyll α concentrations.*

A sample taken in the flooding season was found by Waldren et al. (2015) to be representative of the average chemistry of the turloughs. However, in the present thesis, statistical tests comparing all the parameters surveyed monthly with the ones taken once at the beginning of 2018, found that among the 66 statistical tests performed, 38 showed a significant difference between the single values taken at the start of 2018 and the averages of the monthly sampling. It can be therefore inferred that at least seasonal samples should be taken to have a representative picture of the variation of chemical and physico-chemical water parameters during the hydrological year.

Cunha Pereira (2011) found average chlorophyll α concentrations for Blackrock of 6.5 µg l^{-1} and of 1.9 µg l^{-1} for Caranavoodaun. Blackrock was found to have a similar chlorophyll α in this thesis (7.2 µg l^{-1}), while Caranavoodaun showed an average of 150 µg l^{-1} of chlorophyll α, potentially signalling a significant enrichment at this turlough compared to the situation in 2008 and this might affect the habitat value at the site. However, this might be also due to sampling in shallow waters.

Lough Coy and Caranavoodaun show peculiar peaks in autumn and winter which could be explained by corresponding peaks in TP (Figure 4.12). Water nutrients at Lough Coy show a pattern of reducing concentrations (in the 2018-2019 hydrological year) similar to the one observed for Blackrock. This can be explained by non-conservative nutrient removal or transformation occur within the turlough, which similarly to Blackrock could be due to denitrification as waters in this turlough are deep, therefore making it possible to have anaerobic conditions necessary for denitrification (McCormack et al., 2016).

Regarding trophic status, the oligotrophic turloughs are the ones where habitat quality and value are higher, but they are also more sensitive to nutrient pollution, and therefore monitoring needs to be more frequent (at least seasonal). This is the case for Lough Gealain, where the average TP over the 2018-2019 hydrological year was 9 μg l^{-1}, as compared to an average of 4 μg l^{-1} over the 2006-2007 hydrological year (Waldren et al., 2015). The cause for this rise should be investigated (grazing in recent years as personally communicated by NPWS personnel might be a factor). At the other end, hypertrophic turloughs are the ones that could show great benefits in reduction of nutrient enrichment. Skealoghan, that showed a TP of 9 μg l^{-1} in February 2018, has however an average TP over a year of 30 μg l^{-1} and for only three months shows a TP lower than 10 μg l^{-1} (February and March 2019). It can therefore be classified as mesotrophic (eutrophic if considering the chlorophyll α concentration). Caranavoodaun showed a much higher chlorophyll α concentration than in the Waldren et al. (2015) study and also higher SRP and TP values. While this might be due to sampling method differences, it is worth a deeper investigation, as the turlough was reported to have very good biodiversity, with important plants and aquatic invertebrates. If the nutrient enrichment can be verified, this might have impacted on the plant and invertebrate communities, therefore lowering the value of the habitat.

To return the eutrophic turloughs to a good state, the water should be brought back to a TP concentration <20μg l^{-1} (NPWS, 2021). At Blackrock, for example, the average TP from the 2018-2019 survey was 35±21 μg l^{-1} therefore still far away from the good state objective. It has, however, improved from the value of 52±16 $\mu g\ l^{-1}$ found during the Waldren et al. (2015) study.

Dissolved organic carbon (DOC) concentrations in stream waters have a seasonal trend due to temperature and precipitation and is also higher in late Summer/early Autumn, due to lisciviation of organic matter after summer. DOC concentrations are also much higher in peatland catchments (Caranavoodaun and Skealoghan). A similar pattern can be seen for the other turloughs (Figure 4.9). A warmer and more humid climate might increase the DOC levels in turloughs, as proposed in lakes by Rosen (2005). This might also increase CO_2 saturation and therefore increase emissions. Accretion and decay of DOC are stoichiometrically related to N and P so that C deposition and respiration are often positively correlated with N and P availability, with P being more likely to be the limiting nutrient in peatlands (Keller et al., 2006, Hill et al., 2014).

Chlorophyll α is a proxy for algal biomass which can serve as a substrate for denitrification and consequent N_2O production (Sirivedhin and Gray 2006). High algal biomass can also result in hypoxia, further causing denitrification. Finally, chlorophyll α may serve as an indicator of nitrogen loading, which can increase both algal growth (McCauley et al. 1989) and denitrification (Beaulieu et al. 2011).

6.3 Soil parameters

6.3.1 Soil carbon concentrations and stocks

Values of soil organic carbon (SOC) in the soils (an average of 8.1% for mineral soils and 15.8% for the organic ones) are partly coherent with thresholds found by the EPA funded STRIVE report (Kiely et al., 2009) that found SOC values <5% for mineral soils and between 5 and 45% for organo-mineral soils and with what found by Zhang et al. (2008) (a median value of 7% and a range from 1.4% to 55.8%, also including organic soils). The value found for peat soils (33.6%) is slightly lower than the one found in the Kiely et al. (2009) study (>45%). This might be due to local variability.

The average SOC stocks found for the soils studied are similar to those found by other authors for Irish soils. For example, values of SOC of about 54 $t\ ha^{-1}$ for the very shallow mineral soils (BMinVSW and BMinVSP) (Table 5.1) are comparable with the value of 55 $t\ ha^{-1}$ for grassland soils in Ireland (0-15 cm deep) found by Xu et al. (2011), while for the shallow mineral soils (BMinSW and BMinSP) a value of about 159 t ha^{-1} is comparable with the value of 145 t ha^{-1} found by Xu et al. (2011) for grassland mineral soils up to 30 cm deep. Values found for FenPt (fen peat) of 499 t ha^{-1} are somewhat higher than the value of 279 t ha^{-1} found by Xu et al. (2011), however these authors only considered the first 50 cm of depth, while in the present study a depth of one metre was considered.

The bulk densities used in this project and calculated using empirical equations based on SOC (averages of 0.72 for mineral soils and 0.44 for organic ones) are also within the ranges found by Kiely et al. (2009) (0.8-1.3 for mineral soils and 0.2 to 1.3 for the organic ones). Bulk densities remain the most neglected soil parameters according to Walter et al. (2016). It would therefore be helpful to measure bulk densities directly and at different depths, as this would make the calculation of the organic carbon stocks more accurate, so this is a recommendation for a future study.

T-tests between the SOC in samples from this study and from Waldren for the whole turloughs, did not find significant differences. However, t-tests at soil type level, found differences in the soil types AlluvMin at Coolcam and FenPt at Skealoghan (see Appendix F). In particular, AlluvMin shows an average of 8.7%±3.0% against a single value in Waldren et al. (2015) of 5.2%. FenPt at Skealoghan shows a value of 33.9±2.1% against a value from Waldren et al. (2015) of 43.5%±0.9%. This, being only limited to two soil types at two turloughs, could be due to the different sampling strategies. The stocks of SOC are therefore judged to be stable over this relatively short time period.

In the absence of significant land-use change and erosive processes though, accretion should happen at least in the patches of actively growing peat at Skealoghan and Caranavoodaun (with the former in fact showing an overall carbon sequestration from the GHG balance, see Section 5.2.2.1). This however, can only be appreciated on a longer timescale. The total fen peat surface is 342,736 m^2 and considering an accretion rate of 1-2 mm per year, this would give an additional peat volume of about 3,427 to 6,854 m^3 which multiplied by the bulk density and carbon concentration of peat gives 17.2 to 34.4 additional tonnes of carbon per year. The Waldren et al. (2015) soil samples were taken between 2006 and 2008, therefore there is a difference of about ten years with the present study, hence the difference in carbon should be around 172

to 344 tonnes and would need an accuracy of peat depth estimation to the centimeter, which was beyond the capacities of this thesis and also not achieved in Waldren et al. (2015) either.
SOC in fact, in the absence of significant land-use modifications, should only change on a in an appreciable way over a multi-decadal scale. Kiely et al. (2009) for example, state that to see a difference in carbon content of soils a period of at least 31 years is necessary, and a sufficient number of soil samples (Kiely et al., 2009).

The values reported in this thesis are indicative of being supportive of healthy vegetation as they are almost all above a quality objective for SOC of 5%. The lowest values are shown in Blackrock, (8.1%±2.1%), Coolcam (8.5%±3.1%), and Lough Coy (8.5%±3.1%) due to containing shallow mineral soils, while the highest are in Skealoghan, Lough Gealain and Caranavoodaun which contain organic soils and fen peats. Blackrock, Coolcam and Lough Coy are more susceptible to erosive processes due the steeper slopes present and, in the case of Blackrock, to a river flowing into it. While the habitats are stable at the moment, this is a cause of concern, especially with climate change that could cause soil desiccation in summer and more stormy events.

6.3.2 Soil nutrients

Different fractions of phosphorus and nitrogen have been explored, as they are linked to biodiversity and ultimately ES. It is important to consider soil total nitrogen (TN, Table 4.7) because of exports to water and also because it is linked to the cycle of C and therefore it also has a strong impact on organic carbon sequestration (Elbasiouny et al., 2014). As also highlighted by Waldren et al. (2015), Lough Gealain shows a relatively high TON concentration (Figure 4.22) (although being an oligotrophic turlough), while Coolcam has the lowest average value. As no point source agricultural impact or significant grazing are present at Lough Gealain, further investigations are needed to elicit the reason for this characteristic. The soil type with highest nitrogen concentrations is FenPT, consistent with the fact that it is a highly organic soil type.

Coolcam and Lough Gealain showed significantly lower values of TP in soils, possibly due to the relevant presence of alluvial soils in these two turlough, which show the lowest levels of TP, possibly due to leaching.

Comparing soil nutrient levels from this study to Waldren et al. (2015), significant differences were found at a turlough level for Skealoghan for both TN and TP, TN for Lough Gealain (all lower than Waldren et al., 2015). Analysing by different soil units, significant differences were found for TP in the FenPT of Skealoghan (a lowering) and in the BMinSP unit in Blackrock, for $CaCO_3$ in BOrgVSW in Lough Aleenaun, and for OM in the AlluvMin unit in Coolcam (an increase) and in the FenPt of Skealoghan (a lowering, see Appendix F). These differences could be due to the samples being taken in different locations as they do not seem to suggest a coherent change in any of the parameters. These differences are also not reflected in water nutrient concentrations.

6.4 Ecosystem service valuation

6.4.1 Provisioning services

6.4.1.1 Water

At present turloughs in Ireland are only used directly to provide water for grazing animals; however, they could potentially act as a direct source of water for humans after treatment. The exact amount of water that could be taken from turloughs will depend on the specific turlough because some of them have water volumes that vary quickly. Also, the potential damage to the ecohydrology of the turloughs from water abstraction would need to be considered in any abstraction scheme.

Brander et al. (2013) in their review of the value of wetlands in agricultural settings, estimate a value for water provision of 3,389 USD $ha^{-1}yr^{-1}$. In this thesis an actual average provision of 9 USD $ha^{-1}yr^{-1}$ for animals has been estimated, however there is a much higher potential for human consumption, as it can be seen from Section 5.3.1.1.

6.4.1.2 Fodder

The numbers of animals grazing at the turloughs can be taken as an indicator of the fodder provision for cattle. Following O'Brien et al. (2018), the average annual cow feed intake on a fresh matter basis ranges from 22.7 t to 24.8 t (between 2013 to 2015) and from 4.8 to 5.0 t (about 14 Kg d^{-1})on a DM (dry matter) basis for the same period. Forage, particularly pasture, is the largest component of the Irish cow diet, typically accounting for 96% of the diet on a fresh matter basis and 82% of dry matter intake. Within the cows' forage diet, grazed pasture was the dominant component and on average contributed 74 to 77% to the average annual cow fresh matter diet over the period. Grass silage was the second largest fresh component of the annual diet (18 to 19.2%) followed by concentrate feed (3.8 to 5.2%) (O'Brien et al., 2018).

Grazed pasture is also the dominant source of forage from March to October and usually contributes 95 to 97% of the diet as fed in the summer period. Irish dairy farms are therefore very reliant on forage, particularly pasture, regardless of whether it is reported on a DM basis or as fed (O'Brien et al., 2018). The average daily intake of grass from pasture by cattle is reported to be from 10.9 to 20.7 kg DM with the majority of values falling between 12 and 17 kg DM per day (Dillon & Buckley, 1998). An average of 15 kg DM per day was therefore be used here in the ES calculations.

There is a trade-off between fodder provision and other ES such as water purification and soil erosion and habitat provision as the grazing pressure increases. The actual amount of fodder consumed by the animals has been considered here, based on average daily consumptions by the animals. Where the grasslands in turloughs is generally unimproved (i.e., no chemical fertilizer or slurry is allowed) the capacity to provide fodder is much lower in comparison to improved grasslands.

Another aspect is foraging for berries and mushrooms which was noted at Lough Aleenaun in hedgerows along the road just outside the turlough and might be present at other turloughs. This aspect is however difficult to quantify and value, but is nonetheless important for foragers who also get exercise and wellbeing from this activity.

6.4.2 Regulating services

First estimates of the regulating ES of the turloughs can be taken from Brander et al. (2013, Table 6.1) for wetlands in agricultural landscapes. and from de Groot et al. (2012) (Table 6.1). The values for regulating services at the turloughs from this study vary from € 827,832(Lough Coy) to € 3,084,175 (Coolcam) (Table 5.23). Values per hectare per year range from € 32,772 (Lough Coy) to € 117,289 (Lough Aleenaun) and constitute a fraction from 62.6% (Lough Gealain) to 98% (Coolcam)) of the total value of the ES of the turloughs. The average value of regulating services per hectare per year for the 7 turloughs is € 62,027. Values are therefore substantially larger than the ones calculated by the two authors for temperate inland wetlands. In particular, the flood prevention service is about three orders of magnitudes larger (an average of € 2,061,516 yr^{-1}). This is mainly linked to the large amount of water contained in several turloughs. The nutrient recycling service is on the contrary much smaller (average of -€ 14 yr^{-1}) ,probably due to the specific ecohydrology of turloughs.

***Table 6.1**. Median values for regulating ES (Brander, 2013). Monetary values updated to 2022.*

	ES values (€ha^{-1} yr^{-1})		
	Brander et al. (2013))	De Groot et al. (2012)	Present study
Flood control	7,288		130,667
Nutrient recycling	6,093		-1
Total regulating services	16,145	18,285	133,512

De Groot et al. (2012) found a value for inland wetlands of $17,364 ha^{-1} yr^{-1} (€ 18,285 in 2022). Brander et al. (2013) found an average value per hectare of US$15,339 (€16,145 ha^{-1} yr^{-1} in 2022) (Table 6.2).

Turloughs are only partly wetlands (being ephemeral lakes) and the average values per hectare calculated for regulating services (€133,512) is significantly higher than what found by Brander et al. (2013) and influenced by the high value estimated for the flood risk protection service.

6.4.2.1 Flood risk

A hazard is defined as a source of potential harm, a situation with the potential to cause damage or a threat/condition with the potential to create loss of lives or to initiate a failure to the natural, modified or human systems (Tsakiris, 2007b).

Groundwater flooding is a significant source of flood risk in the west of Ireland, where prolonged flooding can occur from turloughs (Irish Government, 2019). The winters of 2009 and 2015/2016 were the worst for flooding in recent years. In the Gort lowlands several properties and services were impacted. For example, in the Skeanagh area close to Blackrock turlough, seven properties were impacted by the flooding in 2009 (Naughton et al., 2017). The transportation network in the Gort lowlands area was also affected, with 13.2 km of roads were flooded, with over 100 households with restricted or prevented access.

In general wetlands can both alleviate and exacerbate flood risk, depending on different factors, like position in the catchment and time of the year. Excess floodwater in winter is temporarily stored within turloughs, which provide attenuation of the more variable river and rainfall inputs (Naughton et al., 2017).

The flood attenuation of wetlands which are not in the lower parts of a catchment may be complicated to calculate (Bullock & Acreman, 2003). This is particularly true for turloughs, which show a great diversity of hydrological functioning and positions along the flood basin. Factors that can be considered when assessing this ecosystem service are the turlough position, basin volume, vegetation, encroachment of the basin (i.e., vegetation that can slow the flow of water), past flooding events and upstream storage areas. The hydrological regime of the turlough is also important, as the ones with the more flashy responses will in general pose a bigger threat (i.e. Blackrock and Lough Aleenaun).

Climate change predictions of higher intensity rainfall events in winter periods is expected to exacerbate flooding and make it more frequent, therefore threatening the delicate ecosystem equilibria. Plant species would also be forced to start their vegetative period later therefore having a reduced effect on the rising of flood waters (Morrissey et al., 2020). Morrissey et al. (2020) also found that the only viable measure to alleviate flooding around turloughs is through controlled engineered overflow channels draining directly into the sea. These measures are expected to have minimal to no impact on the normal ecohydrology of turloughs and possibly protect tree species from inundation. Hedges, dry stone walls and areas of long grass and vegetation also work to slow the flow of water down the hill. Therefore, controlling grazing by animals and ensuring an appropriate vegetation cover can also aid in slowing down flood waters.

Measures that could further attenuate flood risk are managing grazing and making sure that no significant erosion takes place in the turloughs. Slopes and channel banks could be stabilised by encouraging the development of soils, especially organic ones which would be able to contain more water, with the added benefit of sequestering more carbon.

It has to be remembered that turloughs flood every year and they are therefore an integral part of the landscape and it is only during exceptional events that they really cause damage from flooding. These events, however, are likely to become more frequent with climate change. The regulation of water flows provides the highest value among the ES of turloughs (Figure 5.23).

6.4.2.2 Greenhouse gas emissions and climate regulation

The overwhelming majority of wetlands act as long-term sinks for CO_2 (Bonneville et al., 2008, Gao et al., 2017). Lakes have also been found to have a disproportionate role in carbon cycling (in particular small ponds), with high greenhouse gas (GHG) emissions, but long-term continuous observations are missing (Reed et al., 2018). Pi et al. (2022) also found that smaller lakes (with an area smaller than 1 km^2) have a disproportionate contribution to GHG emissions. It should be noted that most of the turloughs in the present study fall in this category of being of small surface areas. To determine whether this is actually the case, GHG balances needed to be quantified, as there appear to have been no previous studies on this before.

Turloughs are a combination of grasslands, wetlands and lakes therefore show a combination of the characteristics of these ecosystems, with added variability due to changing flooding conditions, which also has an impact on GHG emissions. The highest CO_2 fluxes were found at Lough Coy, which might be due the depth of this turlough which favours water stagnation and formation of CO_2 (though CH_4 that should be favoured too was not measured to be at any higher values than in the other turloughs). On the contrary, for CH_4, shallow depths and frequent mixing mean less time for. CH_4 removal by oxidation (higher concentrations in water). Terrestrial carbon also provides substrate for microbial respiration (Holgerson & Raymond, 2016), therefore is a factor for increased CO_2 concentrations. Blackrock and Lough Coy which receive drainage from the peaty Slieve Aughty mountains, have higher DOC values. Lough Coy in fact shows the highest yearly emissions at 1,206 tonnes.

Lakes and other surface waters are globally significant emitters of CO_2, CH_4 and N_2O to the atmosphere (Tranvik et al. 2009; Bastviken et al. 2011), which seems to be the case for the studied turloughs. Accurate estimates of GHG fluxes to and from the atmosphere are important to understanding the global carbon budget as well as taking part in the bigger national carbon budget measurements (these wetlands are at the moment not considered in the national budgets).

Jones (2010) showed the potential for carbon sequestration in temperate grassland soils across Europe to range from 4.5 g C m^{-2} yr^{-2} (a C source) to -40 g C m^{-2} yr^{-2} (a C sink), while Soussana et al. (2007) in a study on nine grasslands plots scattered over Europe had a net sink of grasslands for atmospheric CO_2 of −240 ± 70 g C m^{-2} yr^{-2}.

The high values of GHG emissions shown in some of the turloughs studied (Table 5.13) could be due to enrichments due to grazing and fertilizer use. The high value of sequestration for Skealoghan (tropical wetlands for example have been reported to sequester 480 g C m^{-2}) should be investigated further.

Most lakes are a source of carbon, despite burying a substantial amount of carbon in their sediments. They are also supersaturated in CO_2 and therefore release some of it to the atmosphere (Sobek et al., 2005). This is particularly true for most turloughs with their high alkalinity waters. Some turloughs have waters with a fast turnover rate and these processes might therefore be sped up. It is also believed that the flooding of land is followed by massive emissions of gases (Tremblay et al., 2004). It has been found that large algal blooms can significantly lower carbon emissions from lakes (Ouyang et al., 2017). This could be true for Caranavoodaun, which shows the highest chlorophyll α average concentrations and also a near neutral carbon balance (only for carbon dioxide).

Grazed grasslands like the ones present in turloughs, are identified as an important source of ammonia and nitrous oxide (N_2O), which are implicated in acid rain, ozone depletion, and global warming (Saggar et al., 2006). Obrador et al. (2018) highlight the fact that small-scale lentic systems are hotspots of GHG emissions and can be an important factor in global greenhouse gas emissions.

In many lakes, CO_2 concentrations are best predicted by a negative relationship with DOC (or TOC) (Holgerson, 2015). Concentration of CO_2 are negatively correlated with depth and DO and positively correlated with DOC and TP (Holgerson, 2015). Holgerson also found that DO best predicted CO_2 concentrations, with chlorophyll α and pH being of secondary importance.

The carbon balance carried out in Section 5.2.2 suffers from some limitations. First of all, measurements were only taken seasonally, while turlough flooding conditions are inherently variable can literally change overnight for some of them. Differences in humidity can have a big impact on GHG, therefore ideally automatic field measurements should then be taken for water levels (when not already present), soil moisture (which has influence on the kind and amount of GHG produced) as well as a meteorological station to survey temperature and solar irradiance. The closed chamber method also has some limitations, however it is a cheap and established methodology. The most prominent one is that it does not capture the variation in GHG fluxes across the turlough surface given the chamber is only deployed at a few point locations. The risk is therefore missing important variability in greenhouse gas emissions at field scale. Also, some studies (Kutzbach et al., 2007) found that the deployment considerably changes the local environmental conditions such as temperature, humidity and air turbulence, which can lead to an underestimation of the CO_2 fluxes. An underestimation can also be due to neglecting the presence of water vapor (which was not monitored in the chamber headspace) and the corresponding dilution effect on the measurements (typically within 1-2%) (Pirk et al., 2016). Field measurement frequency should also be at least monthly and water vapour concentration in the chambers should be taken, as it can significantly reduce the estimation of gas fluxes (Hoffman et al., 2015). Wind speed and wind direction can also affect gas fluxes by influencing the environment inside the chamber.

Large C losses reported for soils under dairy pastures throughout New Zealand have been reported by Mudge et al. (2011) which is consistent to what observed at most sites, which show a positive carbon balance (losses to atmosphere), with only Skealoghan showing a net carbon sequestration (420 tonnes per year). This could be due to the fen peat that accumulates every year (even if grazing is present fen vegetation is not palatable to cattle, and swampy conditions makes it difficult for the animals to walk through).

Lough Coy shows significantly higher emissions than the other turloughs, including Blackrock, despite the fact that Blackrock belongs to the same hydrogeological system (the Gort lowlands). This could be due to differences in the soils and vegetation, or to the specific activities going on at Lough Coy (grazing regimes, potential nutrient enrichment) that should be further investigated.

The direct relationship found between CO_2 emissions from the flooded basins and TP (Figure 5.4) was also found in lakes by Del Sontro et al. (2018). Also in this respect, turloughs behave like lakes, so that TP can be taken as an indirect indicator of CO_2 emissions.

The inverse correlation of depth and CH_4 emissions (Figure 5.3, b) was also found by Li et al. (2020) who reviewed 744 lake emissions from published studies and found that 84% of total methane emissions came from lakes with an average depth of less than 5 m. Average depth can be therefore used as an indicator for the methane emissions of turloughs.

Grasslands and wetlands have both been shown to be greenhouse gas sinks in the long term, when not severely impacted by human activities, though this characteristic is shown only at Skealoghan, among the studied sites. This could be due to the fact that these ecosystems have been impacted by humans for millennia and therefore some of them have lost the capacity of sequestering carbon. Different land management might however restore carbon sequestration capacities, or at least reduce emissions of GHG. This is probably true for Lough Coy which shows significantly higher GHG emissions than all the other turloughs, which do not seem to be justified by differences in habitats and water level alone.

As found by Bastviken et al. (2004), TP, DOC and lake area are the most useful variables affecting methane emissions. Also, the probability of ebullition is highest in shallow water areas (the maximum ebullition being between 0.5 and 1 m of depth). Methane ebullition can therefore be modelled according to depth.

Since higher temperatures increase the production of methane (as long as anoxic conditions persist), an increase in average temperatures and a lengthening of the growing season due to climate change may increase the production of methane in bogs. Wet fluxes of methane are significantly higher than dry fluxes and this is due to the fact that anoxic conditions caused by water favours the formation of this greenhouse gas.

Nitrous oxide is also now possibly the most important gas damaging the ozone layer in the 21st century (Ravishankara et al., 2021). This phenomenon is expected to become more severe, unless concerted efforts are made to reduce emissions. (Ahove & Bankole, 2018). Emissions of nitrous oxide should therefore be minimised both to control climate change and ozone depletion.

6.4.2.3 Nutrient retention

The approach followed in this work has been to compare the results obtained for soil and water analyses with those carried out by Waldren et al. (2015) as they are about ten years apart. A nutrient balance has also carried out, even if it will only be useful for those turloughs that do not dry up completely in summer, so as to compare nutrient contents when the amount of water in the turlough is roughly the same. This balance is, however, of limited interpretation with respect to a long timescale, as it only represent one hydrological year, as already mentioned.

In Ireland the emissions of N in rivers are estimated to be 14.3 kg $ha^{-1}yr^{-1}$ compared to a sustainable removal of 2.10 Kg $ha^{-1}yr^{-1}$ (La Notte et al., 2012). Hence, as in most countries in Europe emissions of nitrogen to rivers in Ireland are unsustainable. This is confirmed by the fact that of the 7 turloughs studied, only L. Gealain (which is in a National Park) is oligotrophic.

It is very difficult to state definitively on whether turloughs are a source or sink of nutrients, as this will probably change through seasons and years, a point also highlighted by McCormack et al. (2016). From the present study most turloughs seem to be roughly in a balance between the nutrient retention capacity and the effective nutrients that are cycled through the turloughs and their catchments. Coolcam and Lough Gealain are the ones showing the highest disservices regarding nutrient retention (-154 € yr^{-1} and -73 € yr^{-1}). While in the case of Coolcam it could be due to inputs from agriculture and grazing, in the case of Lough Gealain it might come from further up in the catchment (or from recent grazing), therefore further investigations in this direction are very important, also in light of the habitat value of this turlough.

Nutrient retention should rank as one of the most important ES of inland wetlands according to Okruszko (2011). While turloughs have a specific and peculiar ecohydrology that influences the behaviour of nutrients, further data of groundwater quality needs to be gathered both upstream and downstream of turloughs at springs and in rivers to verify the findings from the present study. It is also necessary to compare nutrient concentrations in soils and waters, therefore at least seasonal measurements of nutrients concentrations in waters and soils should be performed.

6.4.2.4 Habitat preservation

The value of the habitats present at the turloughs studied is testified by the fact that all of them are part of an SAC and a few of them of an SPA. The main habitat present in Annex 1 of the EU Habitats directive is "3180 Turloughs", however other habitats can be present, notably Hardwater lake habitats (3140), Alkaline fen (7230), Chenopodion vegetation (3270) and Limestone pavement (8240) (NPWS, 2019). At least 90 examples of turloughs wider than 10 ha were previously present in Ireland, however following a survey in the '80s (Coxon, 1987) only 60 were found to be hydrologically active. It is therefore imperative to protect the remaining ones from drainage, pollution and climate change.

Relative values of habitat quality presented in Table 5.27 highlight how Lough Gealain is the most valuable site with a value of 11, followed by Caranavoodaun (6). This is not surprising, considering that Lough Gealain is the closest turlough to a pristine state and alterations by anthropogenic activities are minimal.

Biodiversity can be said to underpin most, if not all, ES provision. In contrast to provisioning services, regulating services are more difficult to quantify and monetise, although several different techniques have been used to date. Valuation of this ES must therefore be based on an understanding of the biophysical conditions underpinning it (Russi et al., 2012). Some debate has arisen on whether 'biodiversity' is a service; in the TEEB database this is categorised as a supporting service ('genepool') although some classifications (e.g. UK NEA, 2011) also consider wild species diversity to be an ES in its own right. Although this distinction seems subtle, it is important when aggregating multiple valuation estimates; where biodiversity is valued solely as a supporting service there is a risk of double counting by already valuing biodiversity in other provisioning, regulating and cultural services (Russi et al., 2012).

It has to be remembered that economic techniques never reveal the real or total value of biodiversity. Contingent valuation, for example has serious shortcomings in revealing non-use values like bequest and existence values (See Section 2 for a review of the different economic values) (Desaigues and Ami, 2001). For this reason, the economical valuations presented here must be considered a conservative estimate of the real value of the habitats of turloughs.

Ecological value, threats and integrity states are the three components that have to be considered to estimate habitat value. The ecological quality as well as the conservation status and the pressures and threats to the turloughs were based on Waldren et al. (2015), together with evidence from fieldwork, personal communication from Stephen Waldren and recent works (Bhatnaghar et al., 2021, O'Connor, 2017).

Though this analysis was done at habitat level, stable habitats that do not show deterioration (together with a functional hydrological regime), are able to support the plant and animal species (Stephen Waldren, personal communication) that are a reason for the turloughs being designated as SAC and/or SPA.

A monetary valuation of the habitat preservation service was carried out by considering the public spending for the preservation of protected areas in Ireland. This is to be considered a conservative value, as it does not consider further spending that might have been allocated and the intrinsic existence value of the habitats.

Threats to turloughs come from agriculture, septic tanks effluent, climate change, and industry (an abattoir is present beside Blackrock turlough, for example). While most of these are, at the moment, low to medium risk (the stocking rate of animals have been more or less constant in the last ten years and climate change effects are still of low impact) an exacerbation of climate change and local increase in agricultural pressure or, alternatively, the total abandonment of agriculture, could threaten some of the turloughs. The big urban waste water treatment plants are outside these turloughs' zones of contributions, however septic tanks for single houses are widespread and could impact water quality.

Though habitat quality and ecohydrology are considered stable based on expert judgement and some recent studies (Bhatnaghar et al., 2022), there are some reasons for concern. In particular, a recent survey by the NPWS (2022) showed that Caranavoodaun, Skealoghan and Lough Coy showed some signs of degradation. At Caranavoodaun several new dwellings with private sewage systems are proposed and overgrazing by horses has been reported in winter, so that vegetation cover is absent from some areas. Skealoghan showed the absence of some typical turlough water beetles and Lough Coy showed some vegetation changes. Habitat assessments should be therefore performed at regular intervals and all the classes of animals and plants previously surveyed should be included.

6.4.2.5 Cultural ES

As already mentioned in Section 2, cultural services *include* ecotourism, heritage value, scientific, aesthetic and spiritual values. While some of the values are difficult to estimate, ecotourism is valued in this Section using the travel cost method. An estimate of the relevance of the turloughs in a local, regional and international context is also given in Section 5.5.2.

As already mentioned, turloughs offer cultural value for being a part of the traditional fabric of Ireland, as well as inspiration for literature (as already mentioned in Section 2) and some of them also offer scenic beauty.

Blackrock and Lough Coy for example, are studied for their unique ecohydrology (e.g. in the Waldren et al., 2015 study). It has also been personally communicated that students on courses from the University of Galway and Trinity College Dublin visit these turloughs once per year, though the economic value is difficult to estimate.

Lastly, all of the turloughs offer amenity and “spiritual” value in having water at least some part of the year, most have them having farm animals and outcrops of scenic calcareous rocks. These aspects however, are difficult to quantify.

According to the Goodwillie ranking (Table 5.21) Coolcam is ranked as having international importance, while Caranavoodaun and Skealoghan have regional importance and Lough Aleenaun is of local importance. Lough Gealain, not mentioned here, is however just a few metres away from Knockaunroe, which is indicated as having international importance (and ranked higher than Coolcam). It is therefore reasonable to assume that Lough Gealain shares those characteristics too and in fact it attracts international tourists, as described in Section 5.5.1.

Lough Gealain is the only turlough where tourism attracting several thousand people per year has been documented. This is also partly due to the fact that Lough Gealain is part of the Burren National Park. For the other turloughs, the potential has been identified for their development as ecotouristic destinations, based on the value of their habitats.

De Groot et al. (2012) report an average value of \$4,203 ha^{-1} yr^{-1} (€ 4,677 ha^{-1} yr^{-1} in 2022) for inland wetlands, which is significantly lower than the value calculated for Lough Gealain (€ 43,664 ha^{-1} yr^{-1}) and shows how important this turlough is in an Irish and international context).

The value calculated for the other turloughs though (774 € ha^{-1} yr^{-1} to 4,412 € ha^{-1} yr^{-1}) only reflects the expenditure for two scientific studies and obviously does not reflect their whole value. The potential values proposed in Table 5.22 also means that there is a big potential for the appreciation of turloughs by the public.

6.5 The ecosystem services of turloughs in the context of the wider literature

The ES concept is still cause for controversy and can be best used as a tool to compare different scenarios rather than giving an absolute value to nature. This work constitutes the first attempt to use the ES framework to calculate and valuate the ES provided by turloughs.

The values calculated for Lough Aleenaun and Lough Gealain (see Table 5.23, from €35,556 ha^{-1} $yr^{-1}$to €122,150 $ha^{-1}yr^{-1}$, with an average of €70,222) are in line with what proposed by Costanza et al. (2014) as an average value for the world's wetlands (\$140,174 $ha^{-1}yr^{-1}$ or €154,782 $ha^{-1}yr^{-1}$), while the rest of the turloughs are valued at lower figures. Brander et al. (2013) however, estimated a much lower value for European wetlands (US\$17,326 $ha^{-1}yr^{-1}$. or €18,607 $ha^{-1}yr^{-1}$) and a median value of US\$3,706 (€3,980 $ha^{-1}yr^{-1}$) which are lower, even by an order of magnitude of the values calculated here.

The values proposed by the TEEB (Russi et al., 2013) for inland wetlands of up to US\$44,000 per hectare per year (€47,260 $ha^{-1}yr^{-1}$), are also in line with the values for some of the turloughs, with the exception of Lough Aleenaun and Lough Gealain which show values an order of magnitude higher. It must also be remembered that the value of the habitats of the turloughs was captured only in part in this ES valuation, therefore the values for the ES turloughs will surely be higher. Some limitations are that the total values calculated here do not consider non-use values.

6.6 Indicators of ES from hydrological, hydrochemical, soil, and biodiversity characteristics

Several indicators have been proposed to indirectly quantify the ES of the 7 turloughs for the provision of water and fodder for animals (number of grazing animals), for flood risk prevention (maximum volume of the turloughs), and for ecoutourism (number of visitors). Indicators are also important when limited field data are available. Being both terrestrial and wetland habitats, turloughs need indicators able to describe both phases.

Regarding climate regulation, TP has been found to be a good indicator of CO_2 emissions in the flooded stage. This is coherent with what found by Li et al. (2021) that state that eutrophic lakes emit nearly 50% more methane than oligotrophic ones. The size of the turlough basin is also indicative. It has been found that small lakes have a disproportionate contribution to GHG emissions (Del Sontro et al., 2018) and therefore there is a negative relationship between GHG emissions and flooded surface of the turloughs. The depth of the basin is also negatively correlated to the emission of methane. Chlorophyll α is a proxy for algal biomass, TP, and nitrogen loading and can serve as a substrate for denitrification and consequent N_2O production. It can therefore also be linked to GHG emissions and be determined remotely with satellite images if field data are not available, by using chlorophyll α absorption and emission characteristics (Chen et al., 2013).

For nutrient retention, soil texture is important because it influences the retention of some nutrients and speed with which they drain to groundwater. The hydrological regime is also important, because for quickly-draining turloughs the risk of nutrients draining to the groundwater is bigger, as degradation/transformation processes for some of the nutrients have less time to happen. The presence of cattle and of settlements is also indicative of possible nutrients enrichments.

For the preservation of habitats, land use and vegetation maps give information on the plant species. Surveys of animal and plant species are also suggested for species-level habitat assessments. The presence of a protected area, such as SACs and SPAs is also indicative of valuable habitats.

For the cultural ES, the variety of indicators is the highest (Egoh et al., 2012). For turloughs being included in an SACs or SPAs, ecotourism is the main leisure activity, given the amenity value of many of them. A perfect example of this is Lough Gealain, part of the Burren National park, with picturesque outcrops of limestones and oligotrophic waters. The presence of hiking trails, public roads and parking spaces, make the site more accessible and attractive. These elements are therefore indicators of ecotourism, at least potential.

6.7 Framework for the analysis of the ecosystem services of turloughs

A framework for the quantification and valuation of the ES of turloughs has been proposed. This describes the steps taken to quantify and value the ES of turloughs and also proposes alternatives, in the case that field data are not available.

Most ES quantification exercises are done at a regional/national scale hence the tools usually employed (e.g. InVEST) are of limited applicability. More accurate information is also needed (mainly from fieldwork) since turloughs have highly variable hydro-ecological characteristics.

Regarding the frequency of sampling, turloughs show variability within them during the year and also between each other. The variability throughout the year has been shown to not be captured well by a single sample near the maximum flooded stage. In fact, testing for differences between the single sample taken at the start of 2018 and the average of the monthly sampling between December 2018 and November 2019, 38 of 66 statistical tests showed significant differences (see Appendix F). It is therefore proposed that some physico-chemical, chemical and biological parameters are surveyed with at least a seasonal frequency, while others can be estimated through indirect indicators.

Further studies on the ES of turloughs can start from the models proposed here and values could be applied to other sites with similar characteristics (benefit transfer), but ideally still with some fieldwork carried out.

The framework proposed here constitutes the first attempt to carry out a field-scale assessment of the ES of turloughs. The frameworks proposed by other authors at larger scale (catchment to national scale or wider) had therefore to be adapted to reflect the amount of detail required. While for the seven turloughs studied in depth almost all of the ecohydrological relevant parameters were surveyed, this would not be possible if a nationwide study of turloughs was to be undertaken. Indicators were therefore proposed here to overcome this technical challenge. The study by Egoh et al. (2012) provided a good starting point that was adapted to the peculiarities of turloughs. In particular, chlorophyll α (also from remotely sensed images), land cover, soil type, and vegetation cover are all parameters linked to the provision of ES and that can be inferred from remotely sensed images.

The study of the socio-economical local situation would benefit future studies, as turloughs are deeply integrated in the local socio-economical structure and this factor is linked to the value of ES. Stakeholders could therefore be involved early in the process, to ensure that management changes can be implemented.

In synthesis, compared to the usual frameworks used for studies at a smaller geographical scale, more field-based measures are required, especially for the ecohydrological characteristics, with at least seasonal water sampling. Some soil sampling is also advised, as the variability in some of the turloughs is high. Some data are available from the GSI and the Irish EPA. Indicators for ES can also be inferred from remotely sensed images.

7 CONCLUSIONS AND RECOMMENDATIONS

The overarching aim of this thesis was to quantify the ES of a selection of turloughs as this had never been done before. A secondary aim was to analyse the values obtained in the context of the existing literature for similar types of habitats. Both aims have been achieved and the main conclusions from the study are presented here.

7.1 Water and soil chemistry, biodiversity, habitat condition

The majority of the 55 turloughs have mesotrophic waters (33), while 7 of them have oligotrophic waters, 11 have eutrophic waters and 4 hypertrophic. Among the oligotrophic turloughs, which are therefore the most sensitive to nutrient enrichment, Lough Gealain shows an enrichment in phosphorus compared to when it was previously studied by Waldren et al. (2015), which could threaten its habitats (which have some of the highest relative values). An enrichment in TP was also found for Caranavoodaun, while a lower average was found for Coolcam. Increases in sulphates should also be investigated.

Several of the surveyed turloughs have chemical characteristics that deviate from the average for all the turloughs for one or more parameters. Notable examples are Blackrock and Lough Coy with dark coloured waters which decrease the growth of algae, especially in the case of Blackrock. Lough Coy also presents peculiarities in water nutrients (P and chlorophyll α) and in high emissions of GHG.

Significant differences in the soil organic carbon content between the present study and the Waldren et al. (2015) study were only found for the soil type AlluvMin at Coolcam and FenPt at Caranavoodaun which might be due to differences in the sampling strategies. In general, however, carbon stocks are therefore judged as being relatively stable.

The condition of the habitats and their capacity to provide ES have been judged to be stable based on field observation and personal communication from experts. However, erosion, climate change end anthropogenic activities could threaten the habitats contained in the turloughs, as well as their hydrological functioning. In particular, Caranavoodaun, Skealoghan and Lough Coy showed some reasons for concerns in a recent survey by the NPWS.

7.2 Quantification and valuation of ecosystem services and tools used

Ad-hoc models were used for the quantification of the ES of turloughs as the existing tools that are typically applied at a smaller scale were found to be unsuitable. For the valuation of ES, market prices were used for the provision of water and forage and for carbon sequestration; the replacement cost method was used for flood risk and water purification; and the travel cost method was used for the valuation of ecotourism.

Turloughs play an important role in the regulation of water flows. This is the single most economically valuable ES (on average 95% of the total value calculated). The next most valuable services were ecotourism and habitat preservation. There is unrealised value in the turloughs in the form of water provision for human consumption and cultural services. The calculated monetary values range from €898,144 yr^{-1} (Lough coy) to €4,181,079 yr^{-1} (Lough Gealain), or €35,556 ha^{-1} yr^{-1} (Lough Coy) to €122,150 ha^{-1} yr^{-1} (Lough Aleenaun).

Only one site (Skealoghan) was shown to be a carbon sink of 420 t CO_2eq yr^{-1}, while Lough Coy showed the highest yearly GHG emissions of 1,026 t CO_2eq yr^{-1}. In addition, TP in the waters was found to be a good predictor of GHG emissions.

The balance of water nutrients over a hydrological year was roughly neutral for all turloughs, however further data on groundwater quality could be gathered both upstream and downstream of turloughs at springs and in rivers to verify the findings from the present study. It is also necessary to compare nutrient concentrations in soils and waters during the hydrological year, and therefore it is recommended that at least seasonal measurements of nutrients concentrations in waters and soils should be performed.

One site (Lough Gealain) is part of the National Burren Park (one of the most visited sites in Ireland), therefore providing significant ecotouristic value. A potential for ecotourism has also been indicated for the other turloughs which could also incentivise measures to protect turloughs.

Some ES have not been analysed, however they could provide a wider picture and a more exhaustive analysis. Some that could be relevant are pollination, pest control, maintenance of genetic diversity, medicinal resources, erosion prevention, habitat connectivity.

7.3 Indicators of ES from hydrological, hydrochemical, soil, and biodiversity characteristics

Several indicators have been proposed to indirectly quantify the ES of turloughs. This is important when limited field data are available. Some of the most important are land use, vegetation, and soil type.

Among water quality parameters, TP has been found to be a good indicator of CO_2 emissions in the flooded stage. Chlorophyll α is a good proxy for algal biomass, TP, and nitrogen loading and can serve as a substrate for denitrification and consequent N_2O production. It can therefore also be linked to GHG emissions and potentially be determined remotely with satellite images if field data are not available. Surface and depth of the turlough basins have also been linked to GHG emissions.

Numbers of tourists, presence of public accesses, roads and car parks are indicators for ecotourism. The presence of a protected area (SACs/SPAs) can also be linked to habitat and cultural value.

7.4 Framework for the quantification and valuation of turlough ecosystem services

A framework has been proposed for the quantification and valuation of the ES of turloughs which requires field data that can be integrated with literature data, depending on the availability and the level of depth of the studies. Compared to the usual frameworks used for studies at a smaller geographical scale, more field-based measures are therefore required, especially for the ecohydrological characteristics. Some soil sampling is also advised, as the variability in some of the turloughs is high. Some indicators can be linked to the provision of ES and be inferred from remotely sensed images.

Due to the variability of several physico-chemical and chemical parameters, a single sample taken near the maximum flooded stage has been shown not to be representative of the whole variability during a hydrological year. Samples with at least a seasonal frequency should therefore be taken.

The study of the socio-economical local situation would benefit future studies, as turloughs are deeply integrated in the local socio-economical structure and this factor is linked to the value of ES. Stakeholders should therefore be involved early in the process, to ensure that management changes can be implemented.

7.5 Comparison of the biophysical and monetary estimates of the ecosystem services with wider literature

Though no valuation of the ES of turloughs had been previously carried out, the ES values calculated (from €35,556 ha^{-1} yr^{-1} to €122,150 ha^{-1} yr^{-1}) are in line with some the literature on ES provision for similar habitats, but some of the turloughs show significantly higher values.

ES quantification/valuation of these ecosystems is in its infancy and therefore efforts should be put in developing and standardising quantification and valuation methods, with this thesis offering a contribution.

7.6 Implications and recommendations for future research

During this thesis a number of recommendations for further research in turlough ES were identified as follows:

- Future studies should better determine bulk densities, soil depths and collect more samples for a more thorough soil organic carbon determination and to compare future value to the ones calculated here;
- Soil and water nutrients should be studied with at least seasonal sampling, as some of the turloughs (the oligotrophic ones) are particularly sensitive to nutrient enrichment (especially Lough Gealain, which shows an enrichment in phosphorus). Several turloughs are characteristic for one or more parameters and should be investigated further because the unusually high values could point to pollution. Nutrient control measures should be taken at a catchment scale and the microbiological quality of the waters of turloughs should be evaluated to highlight any potential contamination from septic tanks.

- Waters could be analysed in swallow holes/estavelles regularly (possibly with continuous sampling) for the main nutrient species, so as to know the mass of elements leaving the turloughs and confirm the nutrient balances performed in this study;
- More frequent surveys for GHG employing the closed chamber method should be carried out, also possibly integrating with the eddy covariance method and ideally with surveying of soil temperature and humidity. Continuous surveys of environmental parameters (soil temperature and humidity, air temperature, PAR, water table depth) would allow for the development of more accurate models of NEE. Vegetation composition/growth should also be monitored;
- Models should be developed to estimate the amount of water and fodder that can be taken from turloughs (also potentially for human consumption) without significant impact on the habitats and on their hydro-ecology;
- Climate change might exacerbate flood risk at the turloughs and therefore modelling of their flooding at sensitive sites should be performed. Climate change is also expected to have an effect on greenhouse gas emissions;
- Different approaches and techniques (like contingent valuation) could be considered in the future for the valuation of the ES of turloughs and capture non-use values;
- There should be some stakeholder involvement to facilitate management changes;
- Some ES have not been analysed, however they could provide a wider picture and a more exhaustive analysis. Some that could be relevant are pollination, pest control, maintenance of genetic diversity, medicinal resources, erosion prevention, habitat connectivity.

In conclusion, this work provided a quantification and valuation of the ES of turloughs, which had never been done before. Turloughs show a range of hydrological and ecohydrological characteristics and contain important habitats that are being protected under EU law. The majority of the 55 turloughs surveyed have mesotrophic waters (33), while 7 of them have oligotrophic waters, 11 have eutrophic waters and 4 are hypertrophic. They provide valuable ES, which show values that are some times higher than estimates in previous studies for similar habitats. Though their ecohydrological condition has been assessed to be stable in general, compared to a previous study dating to about ten years ago, there are threats that could cause the degradation of their habitats and the ES they provide. The monitoring of their waters to detect any nutrient enrichment is especially important for the oligotrophic ones, which have a high biodiversity value. The regulation of water flows, the conservation of habitats and ecotourism are the most valuable ES they provide and there are opportunities to enhance these values and get to a better ecohydrological state, for example by lowering nutrient emissions in the zones of contribution of the turloughs. This could entail also the study of the local socio-economical environment, as turloughs are deeply integrated in the local socio-economical structure. Stakeholders could therefore be involved early in the process, to ensure that management changes can be implemented. The study of further turloughs with the methodology proposed in this thesis would help to have a more complete picture of the ES provided by these features at a national scale.

The main threat to turloughs in the past was drainage but in recent years eutrophication and the abandonment of small-scale agriculture are serious threats. These aspects should then be addressed at Policy level, through the Water Directive and the Common Agricultural Policy (CAP) (Skeffington & Gormally, 2007). The microbiological quality of the waters of turloughs should be evaluated to highlight any potential contamination from septic tanks.

Some sites with oligotrophic waters (like Lough Gealain) are also particularly sensitive to eutrophication and excessive grazing, therefore these sites should still be monitored regularly (at least seasonally).

Future ES valuations should focus on integrating different methodologies of valuation and giving a global picture of the ES of turloughs for Ireland, so as to integrate these values in Ireland’s total ES values. Single ES like climate regulation should be estimated for the whole of Ireland, as at the moment they are not included as a part of the budget at a European level.

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APPENDIX A. MAPS AND DATA FROM LITERATURE

Maps from Waldren et al. (2015).

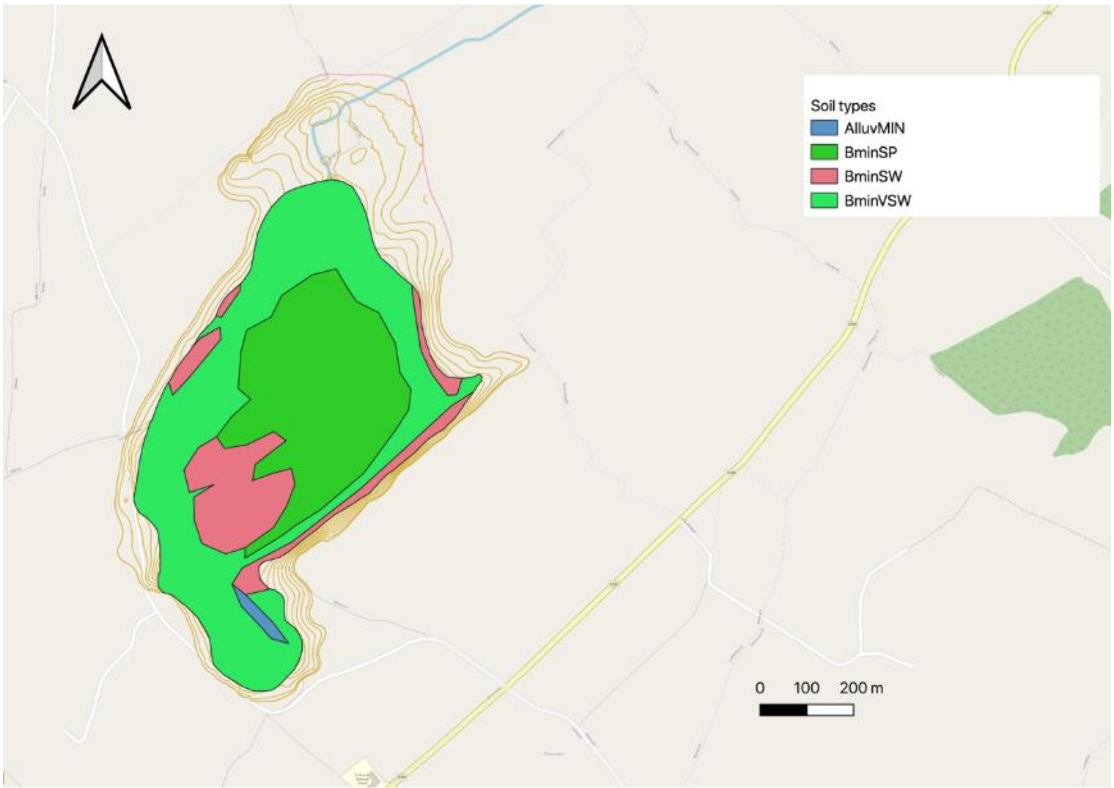

***Figure A.1**. Blackrock, soil map.*

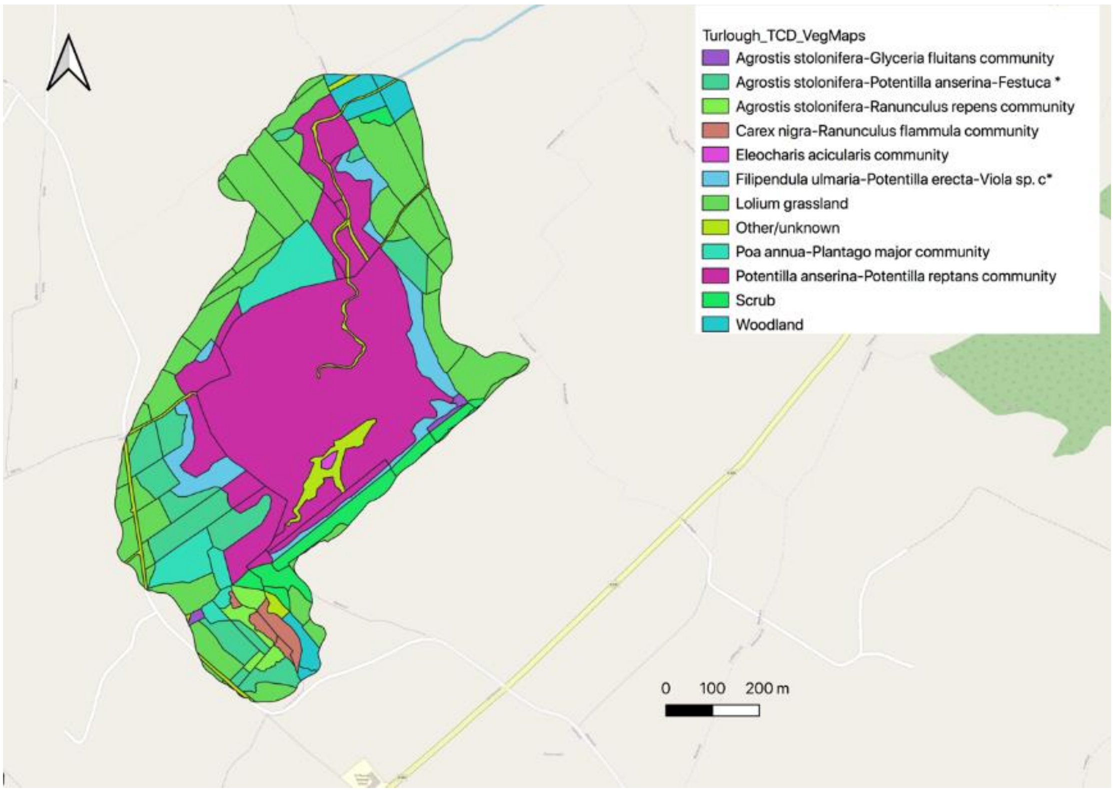

***Figure A.2**. Blackrock, vegetation cover.*

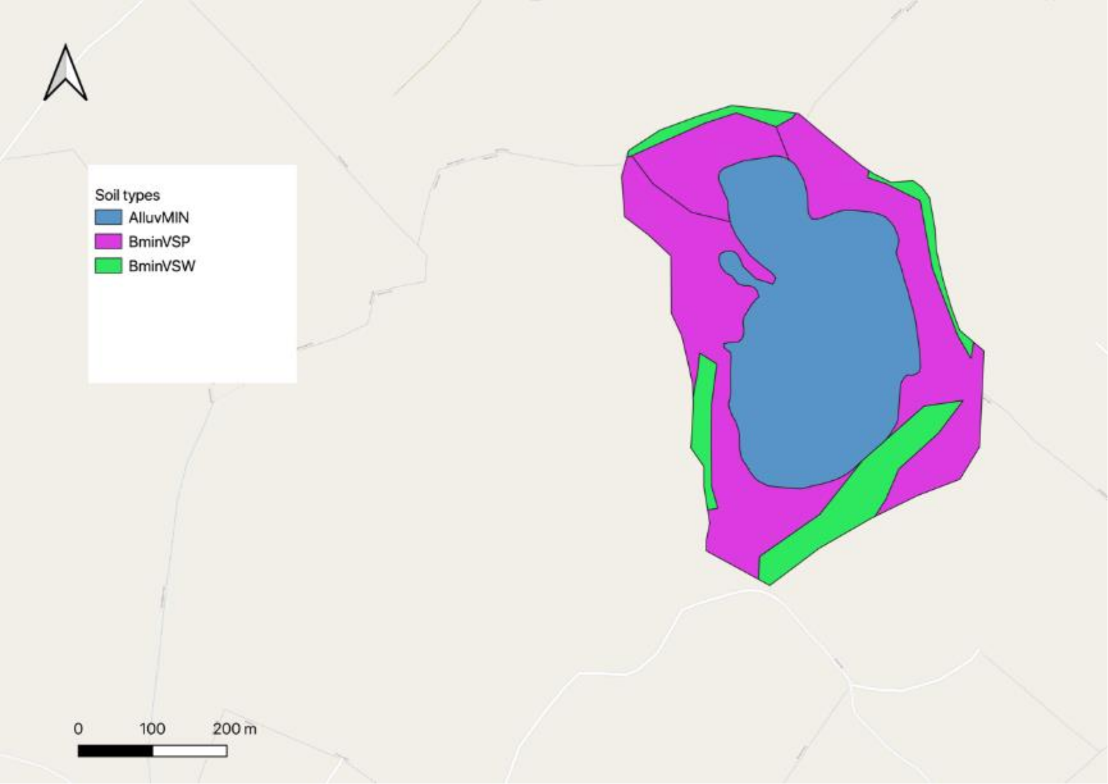

Figure A.3. *Blackrock, Lough Coy, soil map.*

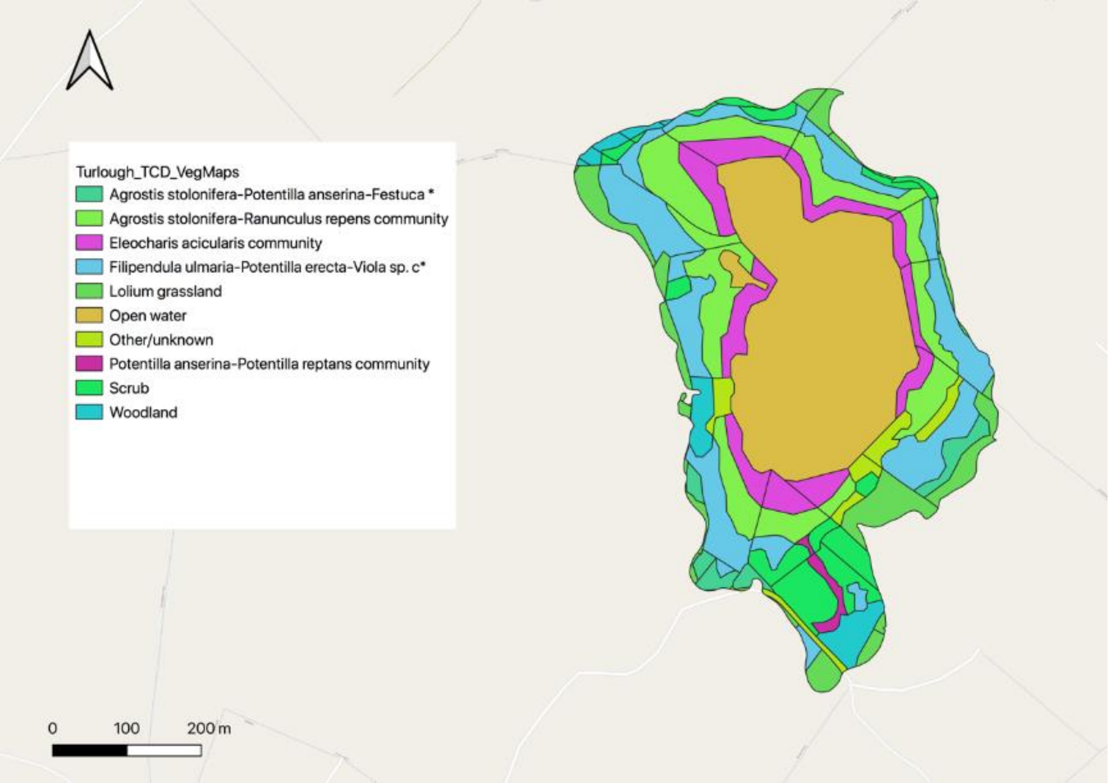

Figure A.4. *Lough Coy, vegetation cover.*

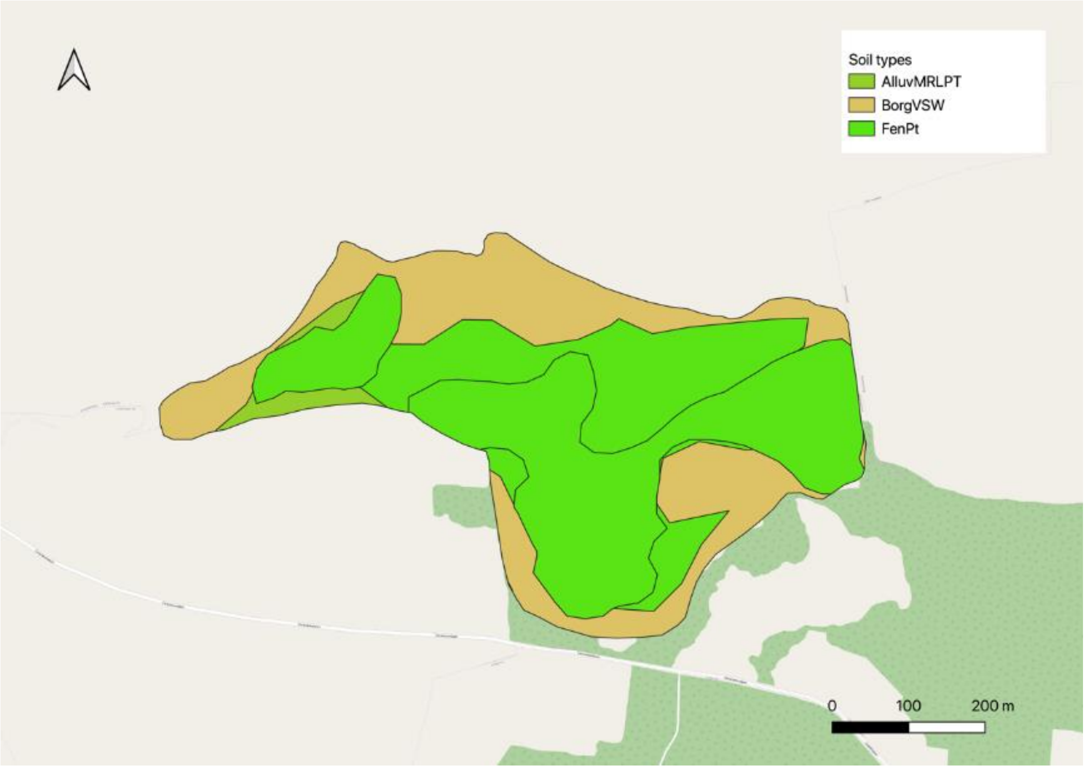

***Figure A.5**. Caranavoodaun, soil types.*

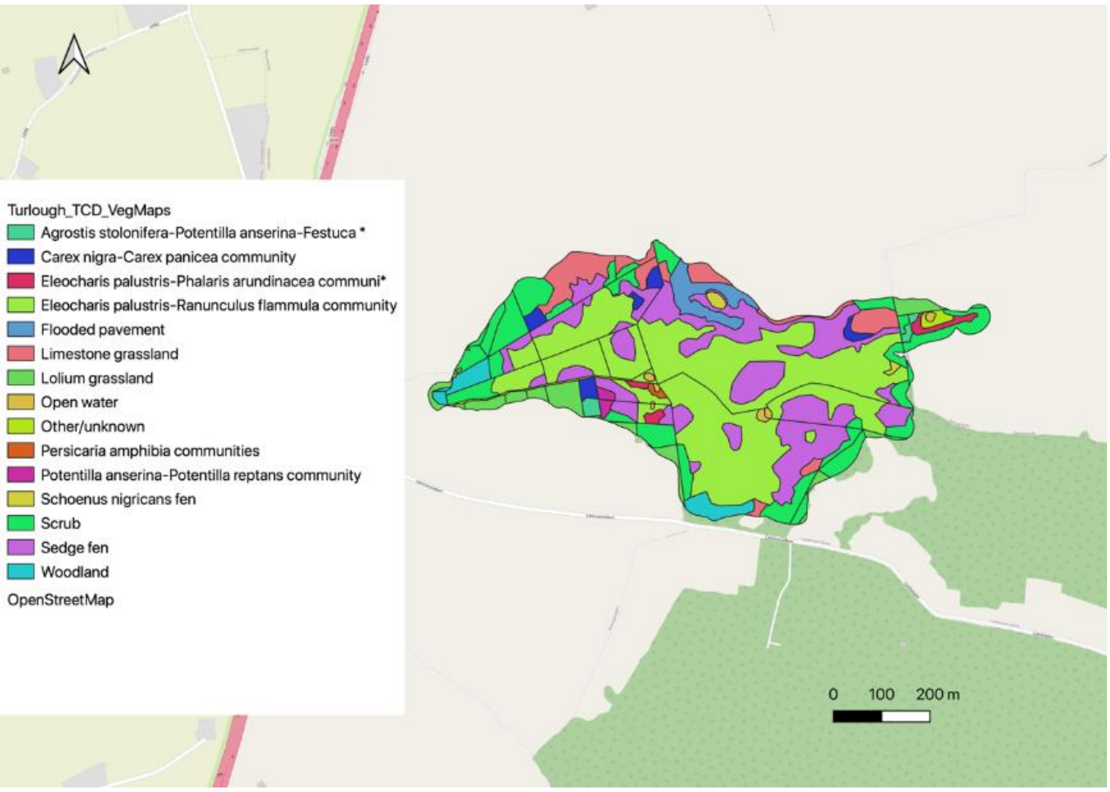

***Figure A.6**. Caranavoodaun, vegetation cover.*

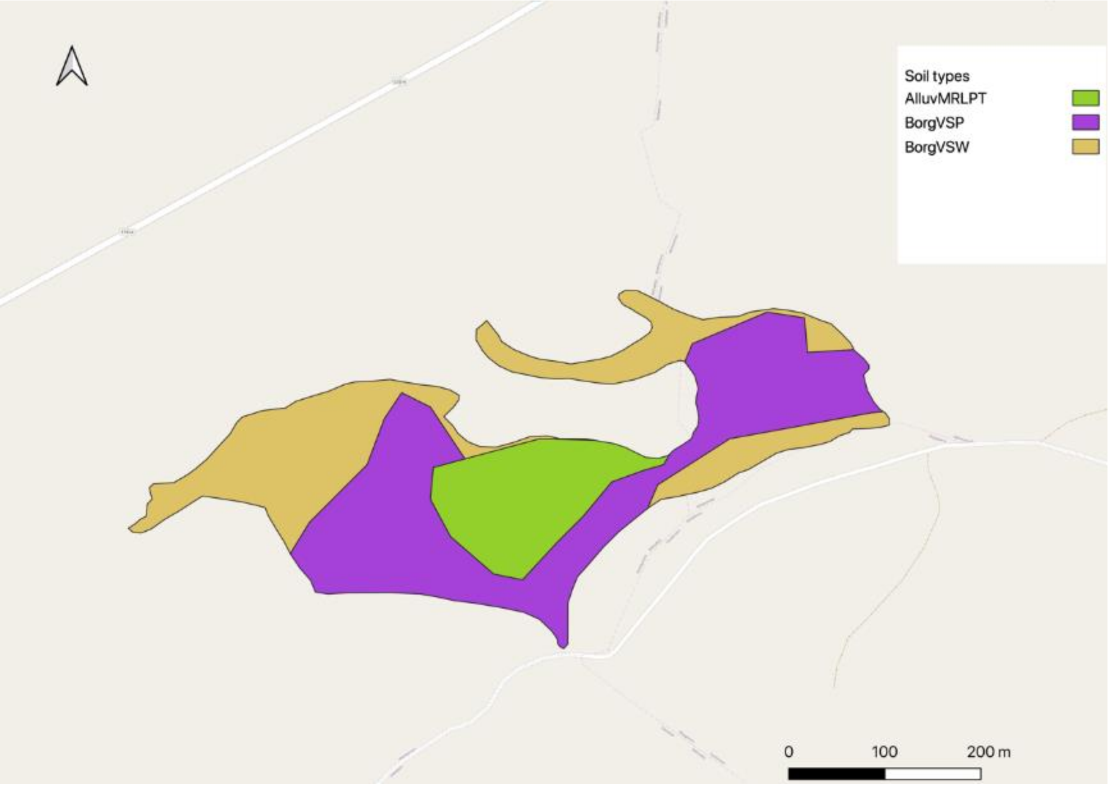

***Figure A.7**. Lough Aleenaun, soil types.*

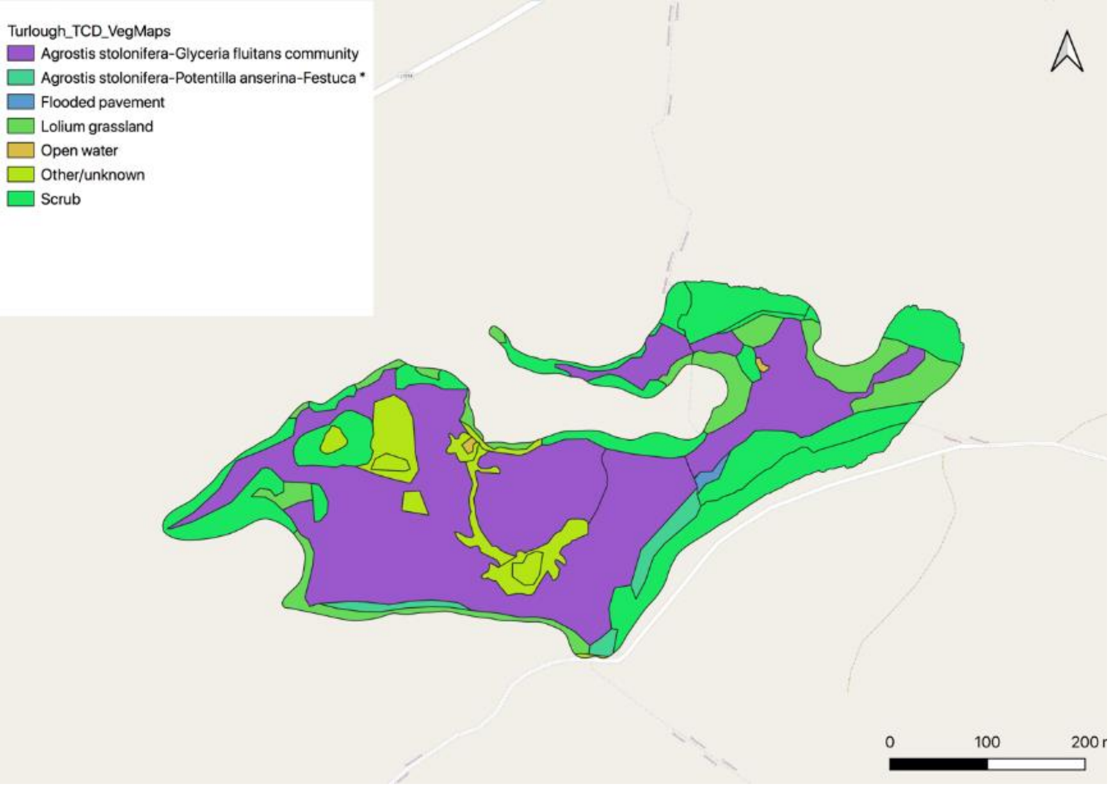

***Figure A.8**. Lough Aleenaun, vegetation cover.*

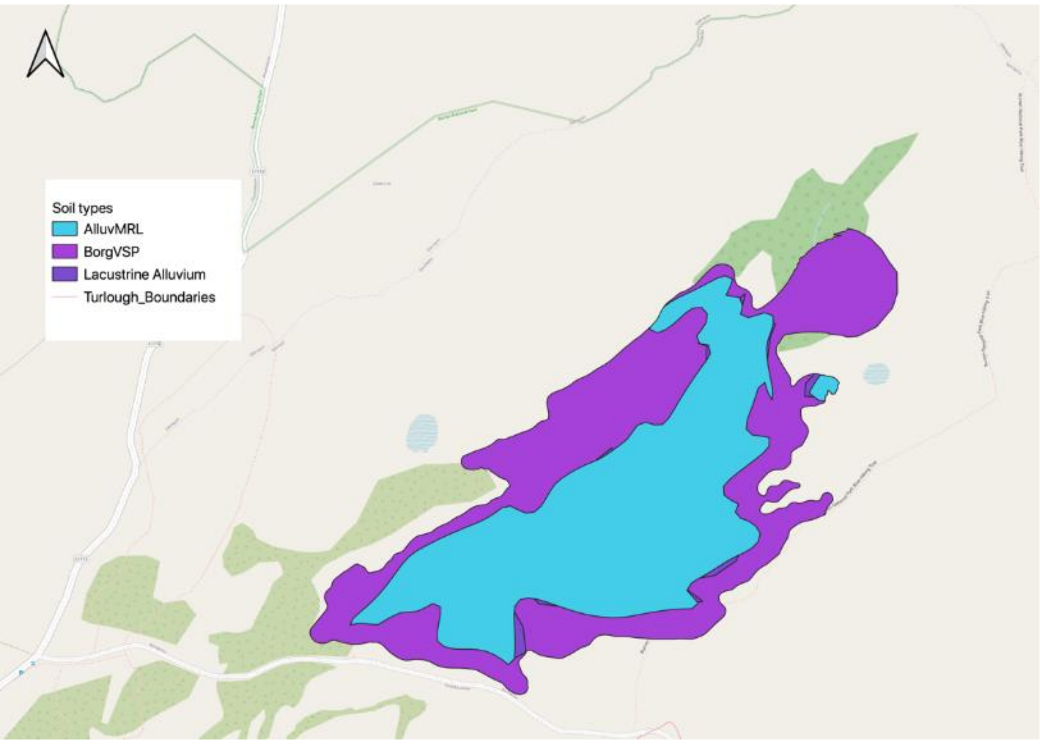

Figure A.9. *Lough Gealain, soil types.*

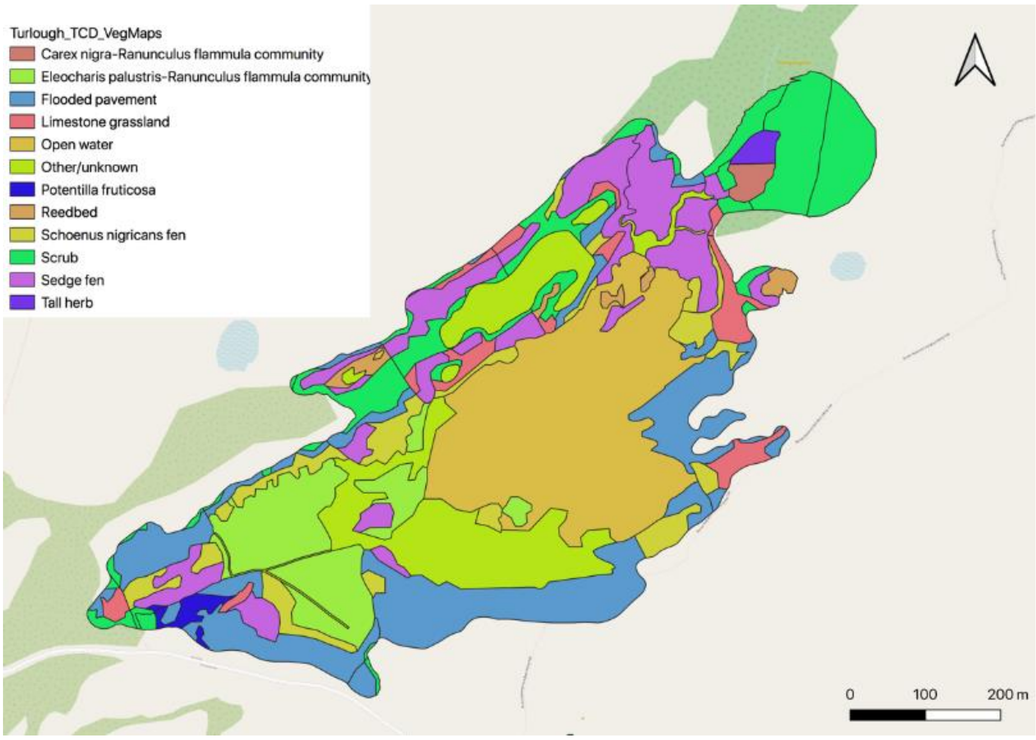

Figure A.10. *Lough Gealain, vegetation cover.*

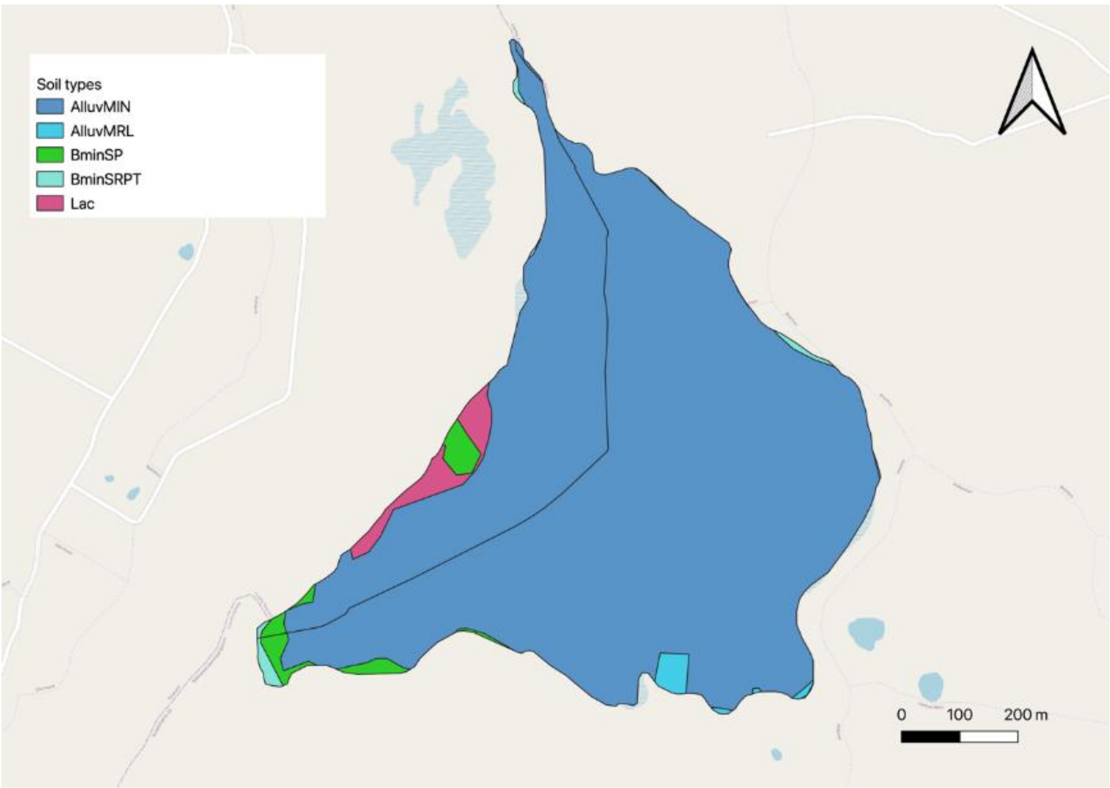

***Figure A.11**. Coolcam, soil types.*

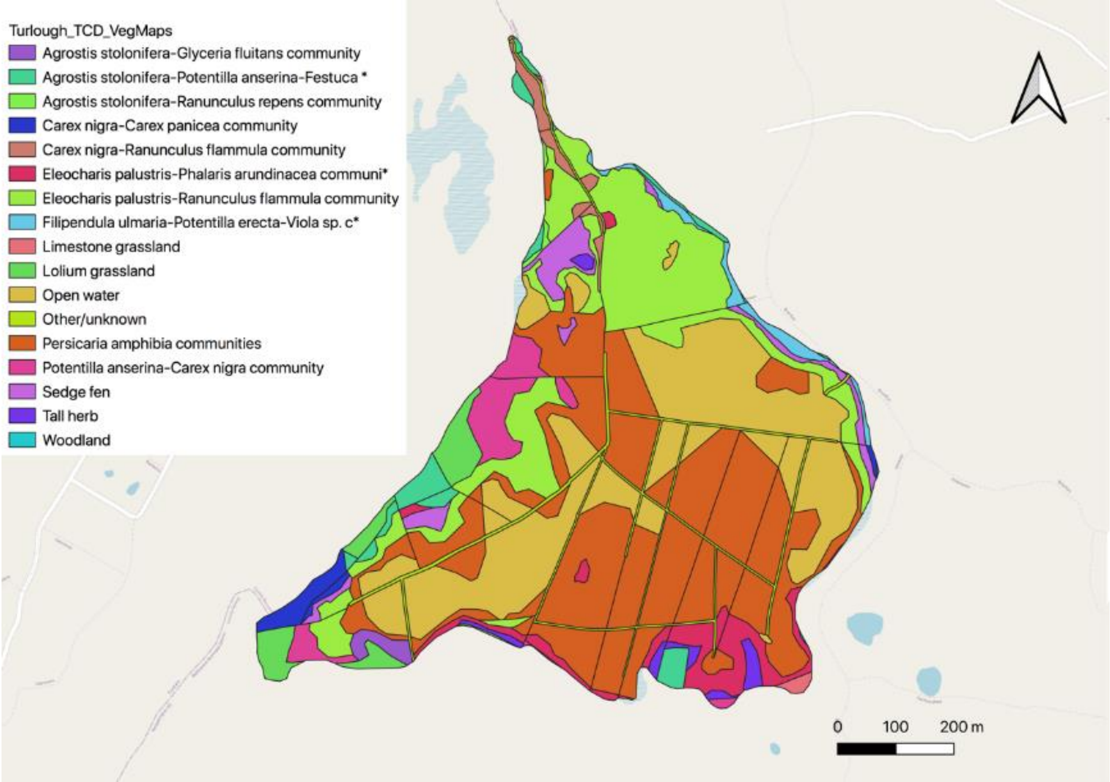

***Figure A.12**. Coolcam, vegetation cover.*

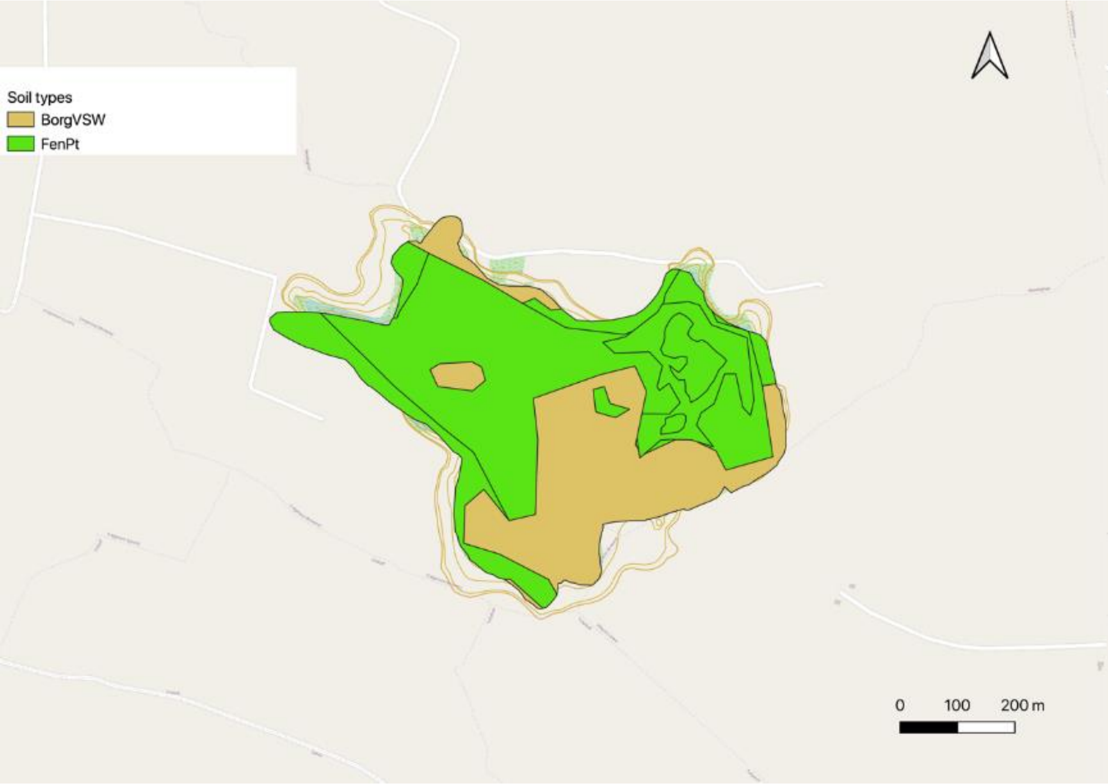

Figure A.13. *Skealoghan, soil types.*

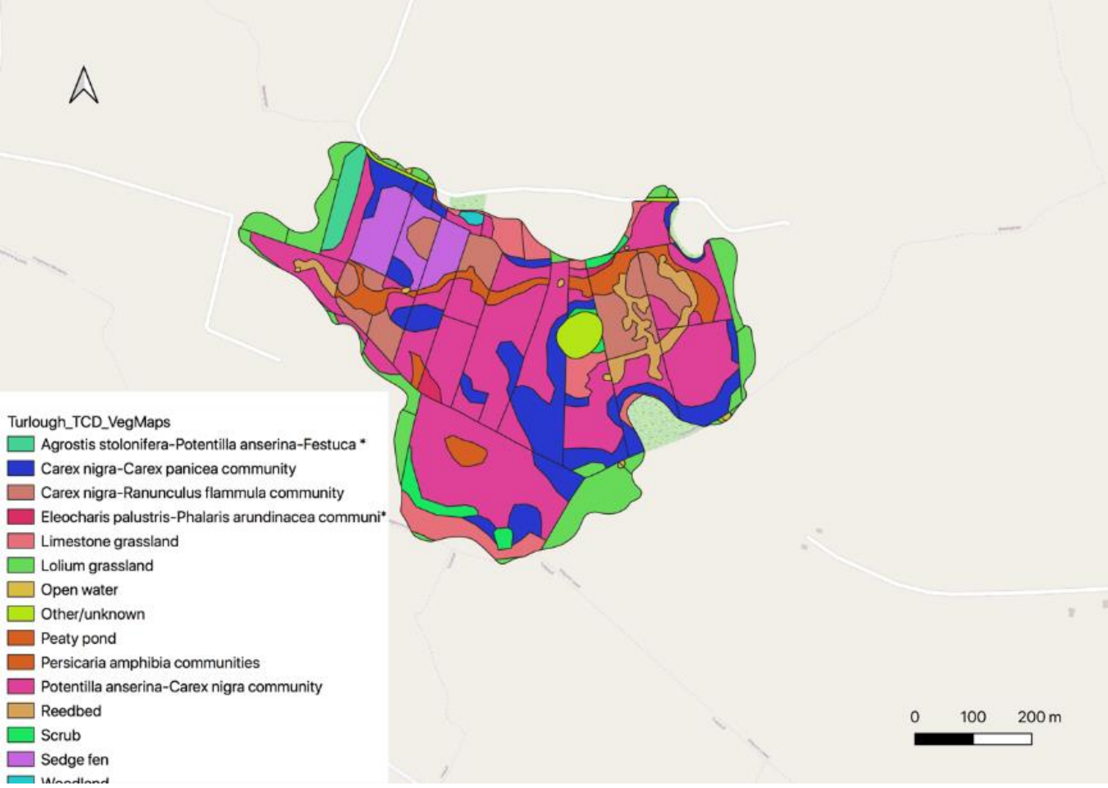

Figure A.14. *Skealoghan, vegetation cover.*

***Table A.1**. Mean values, standard deviations and ranges for total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), total oxidised nitrogen (TON), chlorophyll α (Chl α) and silicates, plus mean values for TN:TP ratio, pH, alkalinity, dissolved oxygen, colour and turbidity in the studied flooding season. Also shown are the trophic classifications of the turloughs according to the OECD (1982) (From Waldren et al., 2015).*

Turlough	TP (µg l^{-1})	SRP (µg l^{-1})	TN (mg l^{-1})	TON (mg l^{-1})	Chl α (µg l^{-1})	TN:TP ratio	Silicates (mg l-1 SiO2-Si)	pH	Dissolved O2 (mg l-1)	Colour (mg l^{-1}Pt/Co)	Turbidity (NTU)	Trophic status based on (OECD 1982) a	
												Mean TP	Mean Chl α
Ardkill	82±33	42±27	1.74±0.04	1.25±1.04	12.7±16.1	26	1.64	8.10	11.0	28	1.9	Eutrophic	Eutrophic
Ballindereen	12±9	1±0.4	0.73±0.04	0.15±0.21	3.0±2.7	73	0.43	8.21	11.8	17	1.1	Mesotrophic	Mesotrophic
Blackrock	52±16	27±10	1.72±0.04	1.21±0.37	1.3±0.7	35	1.27	7.89	10.7	72	2.7	Eutrophic	Oligotrophic
Brierfield	20±10	2±1	1.57±0.04	0.06±0.11	5.0±3.1	32	1.73	8.13	11.1	36	2.0	Mesotrophic	Mesotrophic
Caherglassan	43±12	19±7	1.22±0.04	0.85±0.52	3.3±4.3	30	0.87	7.95	11.2	85	3.0	Eutrophic	Mesotrophic
Caranavoodaun	11±4	2±1	2.30±0.04	1.86±1.42	2.8±2.8	258	1.63	8.16	11.0	25	2.2	Mesotrophic	Mesotrophic
Carrowreagh	43±8	8±8	0.92±0.04	0.36±0.41	12.1±9.5	21	1.23	8.23	12.0	48	3.4	Eutrophic	Eutrophic
Coolcam	34±21	4±4	1.27±0.04	0.92±0.59	18.1±11.6	45	0.90	8.17	11.4	23	3.4	Mesotrophic	Eutrophic
Croaghill	25±17	4±2	1.17±0.04	0.71±0.67	7.6±10.3	57	1.57	8.16	11.2	44	2.5	Mesotrophic	Mesotrophic
Garryland	25±7	11±4	1.08±0.04	0.57±0.22	1.1±0.6	46	1.08	7.71	10.0	80	1.9	Mesotrophic	Mesotrophic
Kilglassan	27±12	5±4	1.45±0.04	1.07±1.00	5.0±3.4	58	1.81	8.22	11.6	28	3.5	Mesotrophic	Mesotrophic
Knockaunroe	4±2	1±0.4	0.55±0.04	0.30±0.15	1.2±0.7	147	0.43	8.13	11.1	10	0.6	Mesotrophic	Mesotrophic
Lisduff	7±2	2±1	1.90±0.04	1.75±0.84	1.4±0.5	282	2.52	8.12	11.0	21	4.1	Oligotrophic	Oligotrophic
L. Aleenaun	31±14	9±6	1.25±0.04	1.01±0.28	9.2±12.8	48	0.32	8.04	11.8	14	5.5	Mesotrophic	Eutrophic
Lough Coy	43±16	21±10	1.41±0.04	1.00±0.25	5.2±5.6	36	1.18	7.86	10.6	72	2.5	Eutrophic	Mesotrophic
Lough Gealain	4±1	1±0.4	0.59±0.04	0.35±0.12	1.1±0.7	163	0.39	8.17	11.2	8	0.7	Oligotrophic	Oligotrophic
Rathnalulleagh	45±22	3±2	1.25±0.04	0.66±0.49	33.5±36.5	34	1.01	8.09	11.9	28	5.4	Eutrophic	Mesotrophic
Roo West	10±4	1±1	0.59±0.04	0.25±0.24	2.1±1.1	65	0.41	8.27	11.6	14	1.6	Oligotrophic	Oligotrophic
Skealoghan	20±6	6±6	0.92±0.04	0.50±0.65	6.9±4.2	37	1.92	8.07	9.8	26	1.7	Mesotrophic	Mesotrophic
Termon	15±8	2±1	0.62±0.04	0.28±0.32	6.9±4.2	49	2.30	8.09	10.4	21	1.3	Mesotrophic	Mesotrophic
Tullynafrankagh	33±18	3±2	2.14±0.04	1.49±1.33	18.4±20.0	93	2.93	8.92	11.6	36	2.7	Mesotrophic	Eutrophic
Turloughmore	19±11	3±2	0.63±0.04	0.33±0.37	4.8±4.6	46	0.36	8.12	12.0	11	0.8	Mesotrophic	Mesotrophic

Table A.2. *Soil types areal extension.*

Soil type (% area occupied)	turloughs						
	ALE	BLA	CARA	COOL	COY	GEA	SKE
BMinVSW		50.3			12.2		
BMinSW		15.6					
BMinDW							
BMinVSP					46.1		
BMinSP		33.2		1.9			
BMinDP							
BMinSRPT			33.4	0.6			
BOrgVSW	35.5						35.1
BOrgSW							
BOrgVSP	47.0					48.7	
FenPt			64.1				64.9
Lac				2.0			
PtMRL							
AlluvMRLPT	17.5		2.5				
AlluvMRL				0.7		50.5	
AlluvMIN		0.8		94.8	41.7		
Water (during summer sampling)						0.8	

***Table A.3**. Subsoils (percent coverage)*.

Site	KaRck	TLs	TDSs	FenPt	Cut	BasEsk	GLs	A	Mrl	L	Water	Grazing (% area)
Blackrock	15.6	50.3			33.2			0.8				100
Caranavoodaun	33.4	2.5								19.9	41.4	100
Coolcam						0.6	1.9		0.7	2.0	94.8	100
Lough Aleenaun	35.5	47.0	17.5									100
Lough Coy	12.2	38.9								7.2	41.7	100
Lough Gealain	48.7									0.8	50.5	0
Skealoghan	13.4	35.1			43.6						7.9	87

Abbreviations: KaRck=Karstified limestone bedrock at surface; TLs=Limestone till (Carboniferous); TDSs=Sandstone till (Devonian); FenPt=Fen peat; Cut=Cutover peat; BasEsk=Esker sands and gravels; GLs=Limestone sands and gravels (Carboniferous); A=Alluvium undifferentiated; Mrl=Marl(Shell); L=Lake sediments undifferentiated; Water = Water (Waldren et al., 2015).

***Table A.4**. Description of the soil units present at the 7 turloughs (from Waldren et al., 2015)*.

Soil type	**Acronym**	**Description**
Well drained mineral		
Very shallow well drained mineral	BminVSW	Soil depth <25cm; well drained mineral soils derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Shallow well drained mineral	BminSW	Soil depth 25-76cm well drained mineral soils; derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Deep well drained mineral	BminDW	Soil depth >76cm; well drained; mineral soils; derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Poorly drained mineral		
Very shallow poorly drained mineral	BminVSP	Soil depth < 25 cm; poorly drained mineral soils derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Shallow poorly drained mineral	BminSP	Soil depth 25-76cm; poorly drained mineral soils derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Deep poorly drained mineral	BminDP	Soil depth >76cm; poorly drained mineral soils derived principally from calcareous parent materials. Generally have medium textures (sandy loam, loam, sandy clay loam) with semi-fibrous organic material.
Shallow poorly drained mineral soils with peaty topsoil	BminSPPT	Soil depth 25-76cm; poorly drained mineral soils derived principally from calcareous parent materials. Distinct peaty topsoil present with organic texture and dark (10 YR 3/1, 3/2, 3/3, 2/1or 2/2) colouration. Lower horizons generally have silty clay, clay loam textures with semi-fibrous organic material.
Deep poorly drained mineral soils with peaty topsoil	BminDPPT	Soil depth >76cm; poorly drained mineral soils derived principally from calcareous parent materials. Distinct peaty topsoil present with organic texture and dark (10 YR 3/1, 3/2, 3/3, 2/1or 2/2) colouration. Lower horizons generally have silty clay, clay loam textures with semi-fibrous organic material.
Well drained organic		
Very shallow well drained organic	BorgVSW	Soil depth <25cm; well drained organic soils derived principally from calcareous parent materials. Generally have organic or loamy textures with fibrous organic material.
Shallow well drained organic	BorgSW	Soil depth 25-76cm; well drained organic soils derived principally from calcareous parent materials. Generally have organic or loamy textures with fibrous organic material.
Poorly drained organic		
Very shallow poorly drained organic	BorgVSP	Soil depth <25cm; poorly drained organic soils derived principally from calcareous parent materials. Generally have organic or loamy textures with fibrous organic material. M/SM not significant.
Fen Peat	FenPt	Soil depth >30cm; poorly drained organic soils derived principally from calcareous parent materials. Generally have organic or organic silty clay textures with fibrous organic material. Dark (10 YR 3/1, 3/2, 3/3, 2/1or 2/2) or Dusky red (10 R 3/2, 3/3or 3/4) colouration. 0-20% marl or shell marl may or may not be present.

Alluviums		
Peat-marl	PtMRL	Mid-point of the continuum from marl to peat and has a characteristic calcium carbonate content of 55-70% and an organic matter content of 10-25% (Coxon, 1986). Dark (10 YR 3/1, 3/2, 3/3, 2/1, 2/2) or greyish brown (10 YR 5/2) soil matrix with abundant flecks of snail shell marl and/or marl deposition. Profile generally undifferentiated into horizons. Depths range from very shallow to deep.
Marl with peaty topsoil	AlluvMRL PT	Profile generally has two distinct horizons consisting of peaty topsoil with organic texture and dark colouration (10 YR 3/1, 3/2, 3/3, 2/1, 2/2) and a grey (10 YR 5/1, 6/1, 7/1 or 8/1) marl horizon with a clay, silty clay or silty clay loam texture. Distinct mottling is often present.
Marl alluvium	AlluvMRL	Generally grey (10 YR 5/1) or greyish brown (10 YR 5/2), very shallow or shallow, often stony soils. Abundant marl and/or shell marl evident. Semi-fibrous organic matter. Deeper lacustrine type soils
Mineral alluvium	AlluvMIN	Generally dark, very shallow, often stony soils with silty textures and semi-fibrous organic material. Marl and/or shell marl often common but not abundant

Table A.5. *Vegetation communities areal extension.*

Vegetation community	**ALE**	**BLA**	**CARA**	**COOL**	**COY**	**GEA**	**SKE**
Agrostis stolonifera-Glyceria fluitans	7.48	0.21		0.34			
Agrostis stolonifera-Potentilla anserina-Festuca rubra		0.78		0.10	4.12		
Agrostis stolonifera-Ranunculus repens	0.33	5.69	0.22	1.40	0.61		0.60
Carex nigra-Carex panicea			0.57	0.68			4.62
Carex nigra-Equisetum fluviatile							1.02
Carex nigra-Ranunculus flammula		0.72		0.63		0.23	2.72
Eleocharis acicularis		0.08			2.55		
Eleocharis palustris-Phalaris arundinacea			0.34	2.27			0.17
Eleocharis palustris-Ranunculus flammula			13.52	9.61		3.41	
Filipendula ulmaria-Potentilla erecta-Viola		3.24		0.69	4.38		
Flooded Pavement	0.04		0.95			6.56	
Limestone grassland			2.24			1.37	1.88
Lolium grassland	1.50	15.87	1.50	1.70	2.19		3.43
Molinia caerulea-Carex panicea			7.77	1.56		4.52	1.86
Open water	0.02		0.16	13.55	8.00	8.11	0.08
Other/unknown	1.03	2.12	0.28	1.49	0.74	4.83	0.06
Polygonum amphibium			0.05	18.99			0.82
Poa annua-plantago major		3.43					
Potentilla anserina-Carex nigra				1.97			13.57
Potentilla anserina-P. reptans		24.14	0.15		0.18		
Reedbed						0.41	1.08
Schoenus nigricans fen			0.14			2.37	
Tall herb				0.60		0.20	
Woodland/scrub	3.85	4.08	6.12	0.01	2.68	4.79	0.70

Table A.6*. Communities of conservation importance (from Waldren et al., 2015).*

Community	***Area mapped (ha)***	***Locations***
Filipendula ulmaria-Potentilla erecta-Viola sp.	*36.73*	*9*
Schoenus nigricans fen	*45.24*	*7*
Carex nigra-Leontodon autumnalis	*56.30*	*9*
Carex nigra-Carex viridula community	*?*	*2*
Eleocharis acicularis community	*4.45*	*4*
Flooded pavement	*32.33*	*7*
Eleocharis palustris-Ranunculus flammula community	*221.8*	*9*

Table A.7. *Potential plant indicators (from Waldren et al., 2015).*

Species/community	***Parameter***
Eleocharis palustris-Ranunculus flammula commu	*Long duration flooding, low P*
Baldellia ranunculoides	
Carex elata	
Littorella uniflora	
Teucrium scordium	
Flooded pavement community	
Schoenus nigricans fen	
Danthonia decumbens	*Short duration flooding, low P*
Parnassia palustris	
Potentilla fruticosa	
Schoenus nigricans	
Molinia caerulea-Carex nigra community	*Low P*
Carex hostiana	
Carex viridula agg.	
Cirsium dissectum	
Eleocharis acicularis community	
Polygonum amphibium communities	*Long duration flooding, medium to high P*
Eleocharis acicularis	
Oenanthe aquatica	
Polygonum amphibium	*Short-medium duration flooding, medium high P*
Rorippa amphibia	
Bellis perennis	
Cardamine pratensis	
Carex hirta	
Filipenula ulmaria	
Rumex crispus	
Trifolium repens	
Eleocharis palustris	*Long duration flooding*
Equisetum fluviatile	
Glyceria fluitans	
Lolium grassland communities	*Short duration flooding*
Limestone grassland community	
Woodland & Scrub communities	
Herb-dominated communities	*Medium-High P*
Poa annua/Plantago major community	*Over grazing and especially trampling and poaching by stock*
Tall herb community	*Possibly reduced grazing pressure, moderate P*

Table A.8. *Economic valuation methods of the different ecosystem services (ES). CV: Contingent Valuation/Choice Modelling; DE: Defensive Expenditures/Averting Behaviour/Avoided Costs; HPM: Hedonic Pricing Method; MA: Market Analysis; PF: Production Function; RC: Replacement/Restoration Costs; TC: Travel Cost. Adapted with permission from (Georgiou & Turner, 2012).*

ES	***Valuation methods***
Provisioning	
Water for residential use, livestock watering, and food manufacture processing	MA; PF; RC; CV; DE, HP
Water for landscape, turf, and agricultural irrigation	MA; PF; RC; DE; CV
Food, reeds, grass/hay or timber harvesting, pharmaceuticals, and other products used in industry	MA; PF; CV
Regulating	
Habitat preservation	MA; PF; RC; CV; TC; DE, HP
Climate regulation	MA; PF; RC; CV; DE; HP
Waste removal	MA; PF; RC; CV; DE; HP
Nutrient and toxicant retention	MA; PF; RC; CV; DE; HP
Saltwater intrusion	MA; PF; RC; DE; CV
Erosion prevention, flood and storm protection, and shoreline stabilisation	MA; PF; RC; DE; CV; HP
Cultural	
Recreational fishing, boating, hunting, trapping, and plant gathering	MA, PF, RC, CV, TC, DE, HP
Cultural, historic and aesthetic value provision	CV

Table A.9. *Software tools for the quantification and valuation of the different ES*.

Valuation tool	**Tool description**	**Ecosystem service applicability**
InVEST	Suite of models for quantifying ES in biophysical or monetary units	CB; CP; CS; CU; F; HP; P; W; WP
Artificial Intelligence for Ecosystem Services (ARIES)	ES modelling platform integrating socio-economic and environmental modelling. Using artificial intelligence an Bayesian analysis.	CB; CU; FP; P; W;
Multiscale Integrated Models of Ecosystems, Services (MIMES)	Analytical framework integrating different ecological and economics models.	CU; CP; FP; P; W; WP
Toolkit for Ecosystem Service Site-based Assessment (TESSA)	PDF manual that provides guidance on how to assess ES. Requires stakeholders participation.	CS; EV; CU; CP; E; F; FP; P; T; WP
Social Values for Ecosystem Services (SOLVES)	ArcGIS dependent application that allows to quantify the social value that people attribute to cultural ES.	CU
WaterWorld	Web-based tools to quantify hydrological services associated with specific activities. Allows to analyse current conditions and future scenarios.	W; E; FP; WP
Ecosystem Services Toolkit (EST)	Guidance document with steps for conducting qualitative and quantitative ES assessments	CU; CP; FP; P; W; WP
Protected Areas Benefit Assessment Tool (PA-BAT)	Rapid, workshop-driven method that requires stakeholder participation.	CP; CU; E; F; FP; G; HP; P; T; W; WP
Co$ting Nature	Web-based tool that allows the mapping of ES and the analysis of the impacts of human intervention. It also provides an index that can be used for ES quantification or conservation prioritisation.	CS; E; F; FP; HP; CU; CP; P; T; W; WP
Land Utilisation Capability Indicator (LUCI)	Spatially-explicit GIS toolbox to quantify ES and compare development scenarios with the status quo. It can be used from local to national scale and applies to sustainable development, conservation, sustainable tourism, restoration, and policy-making.	E; CS; FP; HP; WP

EcoServ	GIS toolbox to map ES from county to regional scale. Maps both demand of ES and capacity of habitats to provide them. It also incorporates socio-economic factors. https://ecosystemsknowledge.net/ecoserv-gis	CU; Regulating services
(IMAGE)	IMAGE can be used to identify problems of global environmental change, and to advise on possible response strategies	CS; E; F; FP; HP; CU; CP; P; T; W; WP
Spatial assessment and Optimization for Regional Ecosystem Services (SAORES)	SAORES provides a platform for exploratory scenario analysis and optimal planning design, rather than ES assessment. SAORES is formed with four modules: the scenario development module, the integrated ecosystem service model base, the ecosystem service trade-off analysis module, and the multi-objective spatial optimization module based on NSGA-II	CS; E; F; FP; HP; CU; CP; P; T; W; WP

Table A.10*. Structure and function status, threats and pressures and summary of ecological conditions for Lough Aleenaun (modified from Waldren et al., 2015)*.

Indicator	**Comments**
Hydrological Function: Good	
Water Quality: Intermediate	30 µg/l TP, 15 µg/l SRP (69 µg/l TP, 11 µg/l SRP in the NPWS study)
Biological Responses: Bad (-3)	
Algal communities: -2	Extensive algal mats regularly recorded, high max chlorophyll α
Vegetation Communities: -1	High cover of negative indicator communities, moderate cover of positive indicators
Rumex cover: -1	60.9% frequency
Important plants: 1	*Rorippa islandica*
Important aquatic invertebrates: 0	None present

Pressures		
Code	**Impact**	**Notes**
A04.01.01 Intensive cattle grazing (turlough)	M	Moderate grazing impact over the whole of the turlough
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	
Threats		
Code	**Impact**	**Notes**
A02.01 Agricultural intensification (ZOC)	M	Likely increase in ZOC
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Continuing medium impact pressure
A04.01.01 Intensive cattle grazing (turlough)	M	Continuing medium impact pressure
A10.02 Removal of stone walls and embankments (in turlough)	L	
M01.03 Flooding and rising precipitations	L	
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	

Summary	
Structure and Function	Inadequate/Bad
Future Prospects	Inadequate
Site Conservation Condition	Bad

Table A.11*. Structure and function status, threats and pressures and summary of ecological conditions for Blackrock (modified from Waldren et al., 2015)*.

Indicator	**Comments**
Hydrological Function: *Good*	Some drainage work is known in the ZOC but not considered to significantly impact on the functioning of the turlough
Water Quality: *Bad*	Average of 35 µg/l TP and 17 µg/l SRP (52.4 µg/l TP and 27 µg/l SRP).
Biological Responses: *Intermediate (0)*	Rather mixed responses across categories
Algal communities: 0	No algal mats were recorded, low maximum chlorophyll α; probably due to the highly coloured water due to runoff from the Slieve Aughty forestry activity
Vegetation communities: 0	Moderate cover of both positive and negative indicator communities

Rumex cover: -1	81.1% frequency
Important plants: 1	*Viola persicifolia*
Important aquatic invertebrates: 0	No important species
Overall Structure & Function: *Inadequate*	
Pressures	
Code	**Impact**
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	H
A04.01.01 Intensive cattle grazing (turlough)	M
E02.01 Factory (adjacent to or within turlough)	M
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L
B01 Forest planting on open ground (ZOC)	L
Threats	
Code	**Impact**
A02.01 Agricultural intensification (ZOC)	M
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	H
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L
A04.01.01 Intensive cattle grazing (turlough)	M
Summary	
Structure & Function	
Future Prospects	
Site Conservation Condition	

Table A.12**. Structure and function status, threats and pressures and summary of ecological conditions for Caranavoodaun (modified from Waldren et al., 2015).

Indicator	**Comments**
Hydrological Function: *Good*	Drainage has lowered the flood level in the past but is not considered to be currently impacting the ecological function
Water Quality: *Good*	13 µg/l TP and 9 µg/l SRP (11 µg/l TP and 2 µg/l SRP in the NPWS study)
Biological Responses: *Very Good (6)*	
Algal communities: 0	No algal mats recorded (negligible quantities in 2008), low max chlorophyll a from the NPWS study (2.84 µg/l), higher in the present study (150 µg/l)
Vegetation communities: 2	High cover of positive indicator communities typical of oligotrophic turloughs
Rumex cover: 1	Absent
Important plants: 1	*Frangula alnus, Plantago maritima*
Important aquatic invertebrates: 2	*Alona rustica, Alonella excisa, Berosus signaticollis, Lestes dryas, Sympetrum sanguineum, Eurycercus glacialis*
Overall Structure & Function: *Good*	

Pressures		
Code	**Impact**	**Notes**
A04.01.01 Intensive cattle grazing (turlough)	M	Moderate cattle grazing within the turlough
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	M	There are a reasonably high number of dwellings in the ZOC, some very close to the

		turlough; likely contribution to slight nutrient enrichment
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	L(ZOC)	
B01 Forest planting on open ground (ZOC)	L(ZOC)	
E01.03 Dispersed habitation (ZOC)	L(ZOC)	There are a reasonably high number of dwellings in the ZOC, some very close to the turlough, the major impact of these is likely through groundwater pollution
Code	**Impact**	**Notes**
A02.01 Agricultural intensification (ZOC)	H	Likely to increase due to prevalence of pasture in ZOC
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Likely to increase due to prevalence of pasture in ZOC
A04.01.01 Intensive cattle grazing (turlough)	M	Continuing pressure
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	Continuing pressure
A10.02 Removal of stone walls and embankments (in turlough)	L	
M01.03 Flooding and rising precipitations	L	
J02.07.02 Groundwater abstractions for public water supply (ZOC)	L	Possible threat due to demand caused by density of dispersed dwellings in vicinity of turlough
Summary		
Structure & Function	**Favourable**	
Future Prospects	**Inadequate/Favourable**	
Site Conservation Condition	**Inadequate/Favourable**	

Table A.13**. Structure and function status, threats and pressures and summary of ecological conditions for Coolcam (modified from Waldren et al., 2015).

Indicator	**Comments**
Hydrological Function: *Good*	
Water Quality: *Intermediate*	21 µg/l TP (34 µg/l TP in the NPWS study) and 8 µg/l SRP (7 . µg/l in the NPWS study)
Biological Responses: *Intermediate (1)*	
Algal communities: -1	No algal mats have been recorded, but max Chlorophyll a is high (18.7 mg/l in the NPWS study and 45.4 mg/l in the present study)
Vegetation communities: 1	Moderate cover of positive indicators, low cover of negative indicators
Rumex cover: 1	3.7%
Important plants: 0	None recorded
Important aquatic invertebrates: 0	None recorded
Overall Structure & Function: *Inadequate*	Some good aspects to the vegetation despite overall inadequate status

Pressures		
Code	**Impact**	**Notes**
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	
A08 Fertilisation (within turlough)	M	Some evidence of fertiliser input within turlough
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	Relatively modest number of dwellings in the ZOC
C01.07 Mining and extraction activities not referred to above (marl, limestone; in turlough)	L	Quarry adjacent to the turlough, likely to have some local impact
A04.01.01 Intensive cattle grazing (turlough)	L	Low grazing impact, slightly less than half of the turlough grazed
Threats		
Code	***Impact***	***Notes***
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Pressure likely to continue due to prevalence of pasture in ZOC
A02.01 Agricultural intensification (ZOC)	L	Likely to increase moderately due to prevalence of pasture in ZOC
A10.02 Removal of stone walls and embankments (in turlough)	L	
M01.03 Flooding and rising precipitations	L	
A04.01.01 Intensive cattle grazing (turlough)	L	
A02.03 Grassland removal for arable land (ZOC)	L	
Summary		
Structure & Function	**Inadequate**	
Future Prospects	**Inadequate/Favourable**	
Site Conservation Condition	**Inadequate**	

Table A.14*. Structure and function status, threats and pressures and summary of ecological conditions for Lough Coy (modified from Waldren et al., 2015)*.

Indicator	**Comments**
Hydrological Function: *Good*	Some drainage work evident in the ZOC but unlikely to have significant impact on the turlough hydrology
Water Quality: *Bad*	56 µg/l TP (43.3 µg/l in the NPWSS study) and 27 µg/l SRP (24 µg/l in the NPWS study).
Biological Responses: *intermediate (2)*	
Algal communities: -1	No algal mats recorded, likely due to the highly coloured water due to runoff from the Slieve Aughty forestry activity; however, high max Chlorophyll a (450 mg/l) and a mean of 76 mg/l

Vegetation communities: 1	Moderately high cover of positive indicator communities, low cover of negative indicators
Rumex cover: 0	27.3% frequency
Important plants: 1	*Viola persicifolia*
Important aquatic invertebrates: 1	*Alonella excisa*
Overall Structure & Function: Inadequate	

Pressures		
Code	**Impact**	**Notes**
A04.01.01 Intensive cattle grazing (turlough)	H	All of the turlough grazed, and some land parcels with very high stocking levels
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Agricultural runoff and runoff from forestry in the Slieve Aughty mountains
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	Relatively low dwelling number in areas of high and extreme pathway susceptibility
B01 Forest planting on open ground (ZOC)	L	But major impact will be on groundwater nutrient enrichment
Threats		
Code	**Impact**	**Notes**
A02.01 Agricultural intensification (ZOC)	M	Agricultural intensification in ZOC likely
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Continuing pressure
A04.01.01 Intensive cattle grazing (turlough)	M	Continuing pressure
A02.03 Grassland removal for arable land (ZOC)	L	Some evidence of shift to maize production locally
A10.02 Removal of stone walls and embankments (in turlough)	L	
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	
M01.03 Flooding and rising precipitations	L	
A04.03 Abandonment of pastoral systems, lack of grazing (ZOC)	L	Possible pressure, given productivity of site

Summary	
Structure & Function	**Inadequate**
Future Prospects	**Inadequate**
Site Conservation Condition	**Inadequate**

Table A.15*. Structure and function status, threats and pressures and summary of ecological conditions for Lough Gealain (modified from Waldren et al., 2015).*

Indicator	**Comments**
Hydrological Function: *Good*	
Water Quality: *Very Good*	9 µg/l TP and 6 µg/l SRP (4 µg/l TP and 1 µg/l SRP in the Waldren study). Extremely low mean water TP
Biological Responses: *Very Good (7)*	
Algal communities: 0	No algal mats recorded, low max CHL

Vegetation communities: 2		Exceptionally high cover of positive indicators (over 96%), no negative indicators
Rumex cover: 1		Absent
Important plants: 2		*Potentilla fruticosa, Frangula alnus, Plantago maritima*
Important aquatic invertebrates: 2		*Alonella excisa, Alanopsis elongata, Graptodytes bilineatus*
Overall Structure & Function: *Good*		
Pressures		
Code	***Impact***	***Notes***
A04.01.01 Intensive cattle grazing (turlough)	L	Historically reported as ungrazed. Some grazing has been reported by NPWS personnel
Threats		
Code	**Impact**	**Notes**
A04.01.01 Intensive cattle grazing (turlough)	L Continuing pressure	Possible threat. Has to be monitored
A02.01 Agricultural intensification (ZOC)	L	possible threat in ZOC, but likely to be very limited
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	L	Likely low impact pressure
M01.03 Flooding and rising precipitations	L	
H02.07 Diffuse groundwater pollution due to non-sewered population (ZOC)	L	Likely low impact pressure

Summary	
Structure & Function	**Favourable**
Future Prospects	**Favourable**
Site Conservation Condition	**Favourable**

Table A.16*. Structure and function status, threats and pressures and summary of ecological conditions for Skealoghan (modified from Waldren et al., 2015).*

Indicator		**Comments**
Hydrological Function: *Good*		
Water Quality: *Intermediate*		30 µg/l TP and 11 µg/l SRP (20 µg/l TP and 6 µg/l SRP in the NPWS study)
Biological Responses: *Intermediate (1)*		Mixed – algal communities reflecting enrichment, but otherwise contains important species
Algal communities: -2		Extensive algal mats were recorded, and max CHL is high
Vegetation communities: 0		Relatively low cover of both positive and negative indicators
Rumex cover: 1		6.9%
Important plants: 1		*Plantago maritima*
Important aquatic invertebrates: 1		*Alonella excisa, Eurycercus glacialis*
Overall Structure & Function: *Inadequate*		Rather mixed
Pressures		
Code	**Impact**	**Notes**

H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Moderate to high nutrient levels in groundwater likely due to agricultural inputs
A04.01.01 Intensive cattle grazing (turlough)	M	Moderate grazing levels over the majority of the turlough
A05.02 Stock feeding (within and adjacent to turlough)	L	Some evidence of stock feeding adjacent to the turlough
A08 Fertilisation (within turlough)	L	Some evidence of fertilizer inputs directly into the turlough
Threats		
Code	***Impact***	***Notes***
H02.06 Diffuse groundwater pollution due to agricultural and forestry activities (ZOC)	M	Ongoing pressure, which might increase due to agricultural intensification
A04.01.01 Intensive cattle grazing (turlough)	M	Ongoing pressure
A02.03 Grassland removal for arable land (ZOC)	M	Likely threat as the ZOC contains large amount of pasture
A02.01 Agricultural intensification (ZOC)	L	Potential agricultural intensification in ZOC; major impacts likely to be via groundwater nutrient levels. May counter any attempts to address nutrients within the turlough
M01.03 Flooding and rising precipitations		L
A10.02 Removal of stone walls and embankments (in turlough)		L
Summary		
Structure & Function		**Inadequate**
Future Prospects		**Inadequate**
Site Conservation Condition		**Inadequate**

Table A.17*. Summary of structure and function assessment for the 7 turloughs and summary for national assessment. Green=Good (and very good), Orange=Inadequate and Red =Bad (from Waldren et al., 2015). B=bad, I=intermediate, V.G.=very good.*

Turlough	**Soil type**	**Hydrological Functions Assessment**	**Water Quality Assessment**	**Biological Responses Assessment**	**Overall S&F Assessment**	**Biological response index**
BLA	MIN	🟩	🟥	🟧	🟧	0 (I)
COOL	MIN	🟩	🟧	🟧	🟧	1 (I)
COY	MIN	🟩	🟧	🟧	🟧	2 (I)
CARA	ORG	🟩	🟩	🟩	🟩	6 (V.G.)
ALE	ORG	🟩	🟧	🟥	🟧	-3 (B)
SKE	ORG	🟩	🟧	🟧	🟧	1 (I)
GEA	MAR	🟩	🟩	🟩	🟩	7 (V.G.)

APPENDIX B. LOCATION AND DATES OF WATER, SOIL AND GREENHOUSE GAS SAMPLING AND MEASURING

Table B.1. *Date of water sampling at the 55 turloughs.*

Turlough	Date of sampling	Turlough	Date of sampling	Turlough	Date of sampling
Ardacong S.	15/4/18	Coolcam	21/2/18	Moate	19/3/18
Ardkill	15/4/18	Coole (Park)	21/2/18	Newtown (Coole)	21/2/18
Ardmullan	19/3/18	Correal Cross	21/2/18	Polldowagh	21/2/18
Balla	19/3/18	Croaghill	21/2/18	Rahasane	21/2/18
Ballindereen	20/2/18	Cuillan South	21/2/18	Rathbaun	21/2/18
Ballinduff	20/2/18	Droomadoon	19/3/18	Roo West	21/2/18
Ballinturley	20/2/18	Fort William	19/3/18	Shrule	21/2/18
Ballyboy	20/2/18	Four Roads	19/3/18	Skealoghan	21/2/18
Belclare	21/2/18	Garryland West	19/3/18	Termon North	19/3/18
Bell Harbour	21/2/18	Glenamaddy	19/3/18	Termon South	19/3/18
Blackrock	20/2/18	Hawkhill	19/3/18	Tullynafrankagh	19/3/18
Breandrum	19/3/18	Kilglassan	19/3/18	Turloughmore	19/3/18
Brierfield	19/3/18	Knockaunroe	19/3/18	Turloughnagullaum	21/2/18
Caherglassaun	19/3/18	Labane	19/3/18		
Cahermore	20/2/18	Lisduff	19/3/18		
Caranavoodaun	20/2/18	L. Aleenaun	19/3/18		
Carran North	19/3/18	L. Coy	19/3/18		
Carran South	19/3/18	L. Funshinagh	19/3/18		
Carrowkeel	19/3/18	L. Gealain	20/2/18		
Castle Plunket	19/3/18	L. Loum	19/3/18		
Cockstown	19/3/18	Managh	19/3/18		

Table B.2. Dates of water sampling in the 7 turloughs studied in depth.

Turl.	Dates of sampling											
ALE	2/12/18	8/1/19	29/1/19	27/2/19	1/4/19	4/5/19	25/5/19	7/7/19	31/7/19	9/9/19	8/10/19	3/11/19
BLA	2/12/18	8/1/19	29/1/19	27/2/19	1/4/19	4/5/19	25/5/19	7/7/19	31/7/19	9/9/19	8/10/19	3/11/19
CARA	2/12/18	8/1/19	29/1/19	27/2/19	1/4/19	4/5/19	25/5/19	7/7/19	31/7/19	4/9/19	8/10/19	3/11/19
COOL	3/12/18	9/1/19	30/1/19	28/2/19	2/4/19	5/5/19	26/5/19	8/7/19	2/8/19	4/9/19	9/10/19	4/11/19
COY	2/12/18	8/1/19	29/1/19	27/2/19	1/4/19	4/5/19	25/5/19	7/7/19	1/8/19	9/9/19	9/10/19	4/11/19
GEA	2/12/18	8/1/19	29/1/19	28/2/19	1/4/19	4/5/19	25/5/19	7/7/19	1/8/19	9/9/19	9/10/19	4/11/19
SKE	3/12/18	9/1/19	30/1/19	27/2/19	2/4/19	5/5/19	26/5/19	8/7/19	2/8/19	4/9/19	9/10/19	4/11/19

Table B.3. *Date and location of the soil samples taken at the 7 turloughs.*

SAMPLE	EASTING	NORTHING	SAMPLE	EASTING	NORTHING
Ale1-1	124963.2	195331.2	BL11	150116.6856	208055.0432
Ale2-2	124941.6	195317.3	BL12	149996.1258	208087.2167
Ale3-1	124931.3	195349.3	BL13	150009.6168	207954.132
Ale3-3	124927.7	195332.1	BL14	149953.2104	207895.9779
Ale4-1	124904.9	195346.4	BL15	149935.659	208002.727
Ale5-1	124637.5	195452.8	BL17	149688.73	207742.528
Ale5-2	124687.3	195439.8	BL18	149709.068	207810.988
Ale6	124636.9	195513.3	BL19	149767.974	207821.834
Ale7-1	124689.9	195370.4	BL20	149709.2857	207870.7055
Ale10	124751.3	195361.8	BL21	149762.076	207910.827
Ale11	124813.6	195355.3	BL22	149838.011	207942.976
Ale12-1	124864.6	195352.6	BL23	149866.943	207821.912
Ale18-1	124973.4	195301	BL25	149749.5734	207987.7684
Ale18-2	124945.4	195342.8	BL26	149723.836	208050.578
Ale18-3	124963.6	195426.6	BL27	149846.653	208052.185
Ale18-4	124793.4	195438	BL28	149687.728	207934.09
Ale18-5	124675.9	195388.8	Cara1	145362.013	215289.132
Ale18-6	125187	195587.8	Cara2	145224.535	215276.013
Ale18-7	124836	195502	Cara3-1	145381.1	215210.9
Ale18-8	124598	195483	Cara3-3	145205	215397
BL01	149695.9874	208198.5677	Cara4	145231	215321
BL02	149628.619	208209.516	COOL3	157334.4994	270853.9478
BL03	149683.6189	208260.532	COOL4	157419.7476	270741.864
BL04	149681.9634	208102.8714	COOL5	157314.7694	270702.6218
BL05	149739.7117	208111.5407	COOL6	157138.2402	270466.1501
BL06	149775.4871	208330.678	COOL7	157195.5891	270515.0981
BL07	149956.1934	208359.7049	COOL8	157255.7352	270468.1711
BL08	150077.3581	208386.2667	COOL9	157349.6786	270504.4202
BL09	150071.865	208280.339	COOL10	157551.6011	270505.6826
BL10	150193.595	208139.277	COOL11	157668.2308	270411.8716
COOL 15	157969.2708	270412.2595	Gea8	131457.595	194921.22
COOL16	158039.8187	270501.2947	Gea9	131593.927	195092.698
COOL17	158066.5361	270615.4577	GEA18_1	131202	194559
COOL18	158151.522	270743.374	GEA18_2	131246	194604

COOL19	158168.0973	270889.7342	GEA18_3	131229.273	194675.703
COOL21	157925.8098	271092.8752	GEA18_4	131350	194766
COOL22	157437.88	271527.0536	GEA18_5	131509	194917
COOL25	157500.5533	271152.3604	GEA18_6	131603.394	194993.389
COY17	148903.3	207254.5	Ske1	124445.8	263015
COY18	148934	207514	Ske2	124382	262965
COY19	148889	207516	Ske3	124453	262943
COY20	148879	207601	Ske4	124651	262797
COY21	149139.909	207572.24	Ske5	124589.675	262716.107
COY22	149010.859	207659.536	Ske6	124550.501	262647.047
COY23	148809.669	207719.224	Ske9	124851.65	262625.198
COY24	148879	207601	Ske10	124536	262511
COY25	148833.557	207610.894	Ske11	124396.794	262582.382
COY26	148837	207506	Ske14	124312.174	262911.368
Gea1	131348.021	194544.142	Ske15	124211.423	262957.073
Gea10	131482.307	195058.112	Ske18	124943.282	262808.2
Gea11	131357.496	194979.08	Ske19	124928.363	262777.712
Gea12	131227.37	194866.846	Ske22	124676	262901
Gea13	130931.565	194632.102	Ske23	124304	263010
Gea15	131105.094	194726.342	Ske24	124562	263007
Gea16	131205.187	194752.404	Ske25	124871	262913
Gea18	131731.359	194722.208	Ske26	124869	262811
Gea19	131727.203	194926.294	Ske27	124833	262711
Gea2	131375.683	194521.456	Ske28	124767	262814
Gea20	131736.445	195024.003			
Gea3	131465.525	194544.33			
Gea4	131594.523	194562.865			
Gea5	130941.967	194542.684			
Gea6	131280.997	194803.859			
Gea7	131364.523	194850.308			

Table B.4. *Dates of greenhouse gas measuring and sampling in the 7 turloughs*.

Turl.	**Summer ‘18**	**Autumn ‘18**	**Spring ‘19**	**Summer ‘19**	**Autumn ‘19**	**Winter ’19-‘20**	**Summer ‘20**
ALE			13 Mar, coll. 2 (d)	7 Jul., coll. 4 (w), 27 Jul., coll. 1-3 (d)	9 Sep. coll. 2, (d)	4 Nov , coll 3 (w), 4 Feb, coll. 1 (d), 4 (b)	13 Sep., coll. 2 (d)
BLA	11, 29 July, coll. 5-6 (d),	5 Sep., coll. 5 (d)		19 Jun, coll. 5-6 (d) , 31 Jul., 5-8 (d)	9 Sep., coll. 5-6 (d), 28 Sep., coll. 6 (d)	3 Nov. coll. 7-8 (w), 20 Nov. coll. 5-6 (d), 7-8 (b)	
CARA				4 Aug., coll. 9-10 (d)	5 Sep. coll. 9 (d)-10 (w)	4 Nov., coll. 11(w), 4 Feb, coll. 12 (b)	
COOL			14 Mar, coll. 13 (d)	5 Aug., coll. 14 (d), 15 (w)	4 Sep., coll.13 (d), 14 (w)	11 Dec., coll. 13 (d)-16 (w), 27 Feb., 13 (d), 14-16 (b),	
COY				7 Jul, coll. 19 (d), 18 (w), 31 Jul. coll. 20 (d), 19 (w) 4 Aug., coll. 19, 20 (d)	4 Nov., coll. 18 (w)	4 Dec., 17-19 (b), 20 (d)	12 Sep., coll. 20 (d)
GEA	9-10 July, coll. 21-26 (d)			7 July, coll. 21 (d), 22 (d), 23 (d), 1 Aug. coll. 21 (d), 22 (d), 26 (d)	9 Sep. coll. 26 (d), 4 Nov., coll. 22 (w)	4-5 Dec. coll. 24 (d), 26 (d), 23 (b), 22 (b)	
SKE				4 Aug., coll. 30 (d)-28 (d)	4 Sep. coll. 30 (d), 29 Sep., coll. 30 (d)	4 Nov., coll. 30 (w), 11 Dec., coll. 27 (d)-28 (w), 27 Feb., coll., 29 (b), 28 (b), 30 (d)	

APPENDIX C. WATER ANALYTICAL RESULTS

Table C.1. *Analytical results and trophic status after water sampling at the 55 turloughs.*

Turlough	**Date of sampling**	**pH**	**E.C. (μS cm^{-1})**	**D.O. (%)**	**D.O. (mg l^{-1})**	**TDS (mg l^{-1})**	**ORP (mV)**	**Turb. (NTU)**	**Colour (mg l^{-1} Pt/Co)**	**Alkal. (mg l^{-1})**	**TN (ppm)**	**TOC (ppm)**	**SRP**	**TP (μg l^{-1})**	**Trophic status (OECD, 1992)**
Ardacong S.	15/4/18	8.58	325	73.3	7.82	220	225	2.8	25	110.8	0.4	6.2	3	24	Mesotrophic
Ardkill	15/4/18	8.4	354	77.4	8.33	169	134.8	2.1	22	95	0.46	7.35	3	32	Mesotrophic
Ardmullan	19/3/18	8.77	268	73.6	7.71	180	169	0.5	25	152.4	0.36	7.8	6.6	69	Eutrophic
Balla	19/3/18	7.55	269	72	9.57	200	133.5	15.3	11	129	0.53	9.2	3	151	Hypertrophic
Ballindereen	20/2/18	8.11	303	70.04	8.85	231	117.5	0.9	5	211	0.393	7.2	5	24	Mesotrophic
Ballinduff	20/2/18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	299.6	n.a.	n.a.	n.a.	n.a.	n.a.
Ballinturley	20/2/18	7.81	203	66.3	6.94	135	175	2.8	27	215	0.76	11.09	39	189	Hypertrophic
Ballyboy	20/2/18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	<2	37	Mesotrophic
Belclare	21/2/18	8.43	225	70.1	7.5	161	231.3	2.5	61	365.3	0.07	0.9	6	26	Mesotrophic
Bell Harbour	21/2/18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	16	137.3	0.33	2.6	n.a.	n.a.	n.a.
Blackrock	20/2/18	8.35	238	66.5	7.27	167	183.9	8.6	73	138.2	1.25	9.4	10	35	Mesotrophic
Breandrum	19/3/18	8.7	358	69	7.04	238	197.5	1.9	211	232	0.46	8.4	13	256	Hypertrophic
Brierfield	19/3/18	8.62	320	71.9	7.75	219	100.3	1.1	16	203	0.31	5.1	7	12	Mesotrophic
Caherglassaun	19/3/18	7.1	205	67.2	8.11	158	161.5	2.3	28	114.9	0.69	6.4	2	20	Mesotrophic
Cahermore	20/2/18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	264.4	n.a.	n.a.	6.6	33	Mesotrophic
Caranavoodaun	20/2/18	8.21	339	66.4	8.01	266	86.1	7.2	10	262.9	1.67	n.a.	13	48	Eutrophic
Carran North	19/3/18	8.42	238	71.4	7.48	163	118.8	0.2	25	109.4	0.32	6.1	<2	5	Oligotrophic
Carran South	19/3/18	8.53	215	61.2	6.62	150	127.2	0.1	25	101.1	0.28	4.9	<2	13	Mesotrophic?
Carrowkeel	19/3/18	7.54	163	66.1	9.85	120	133.3	1.8	9	210.2	0.47	8.77	4	23	Mesotrophic
Castle Plunket	19/3/18	8.67	235	74.1	7.69	165	191.7	3.1	28	233.3	0.3	6	<2	21	Mesotrophic

Cockstown	19/3/18	7.36	229	34.2	3.73	163	216.7	4.2	11	123.9	0.74	11.7	4	37	Eutrophic
Coolcam	21/2/18	8.37	201	74.7	8.06	147	240.4	2.3	18	224.4	0.33	4.5	2	34	Mesotrophic
Coole (Park)	21/2/18	8.37	267	53.2	5.68	184	74.4	2.2	40	138.9	0.48	9.6	2	226	Mesotrophic
Correal Cross	21/2/18	8.72	323	77.7	7.92	219	167.1	2.9	30	162.3	0.37	9	3	20	Mesotrophic
Croaghill	21/2/18	8.22	265	77.5	8.76	184	251.9	1.2	61	125.8	0.75	7.5	<2	10	Mesotrophic
Cuillan South	21/2/18	8.79	221	71.6	7.66	158	225.3	3.5	23	228.7	0.33	5.6	<2	20	Mesotrophic
Droomadoon	19/3/18	8.68	292	78.9	8.75	207	133.9	1.8	21	145	0.47	9.9	4	105	Hypertrophic
Fort William	19/3/18	8.63	324	84.3	8.68	215	98.1	0.1	18	243.6	0.41	6.3	87.1	78	Eutrophic
Four Roads	19/3/18	8.6	225	80.6	10.75	11	132.8	7.8	40	83	0.5	11.4	<2	180	Hypertrophic
Garryland West	19/3/18	8.57	252	63.5	6.82	175	99.7	0.2	49	105.5	0.39	6.9	<2	15	Mesotrophic
Glenamaddy	19/3/18	8.38	245	75.5	8.51	173	236.3	3.1	52	98.1	0.41	10.1	<2	10	Mesotrophic
Hawkhill	19/3/18	7.95	311	46.4	5.26	228	122.8	0.7	20	170.5	0.21	2.8	<2	20	Mesotrophic
Kilglassan	19/3/18	8.05	369	79.4	10.88	175	134.5	1.3	3	107	0.37	6.62	<2	26	Mesotrophic
Knockaunroe	19/3/18	8.52	240	69.5	7.52	166	135.7	0.15	20	109.8	0.27	3	<2	5	Oligotrophic
Labane	19/3/18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	32	215.7	0.79	11.4	5	37	Mesotrophic
Lisduff	19/3/18	8.47	273	74.2	7.7	180	153.7	0.6	18	137.4	0.3	4.3	7	62	Eutrophic
L. Aleenaun	19/3/18	8.31	225	86.3	10.3	187	149.5	0.4	10	160.6	0.69	6.21	7	18	Mesotrophic
L. Coy	19/3/18	8.41	270	68.3	7.35	190	191.2	3.4	28	138.2	0.37	6.3	5	17	Mesotrophic
L. Funshinagh	19/3/18	8.55	305	71.3	n.a.	208	166.8	4.2	25	201.6	0.39	6.8	6	57	Eutrophic
L. Gealain	20/2/18	8.56	228	66.2	7.3	160	136.8	0.1	11	127.5	0.39	2.3	<2	6	Oligotrophic
L. Loum	19/3/18	8.26	405	63.8	6.82	274	116.3	0.2	18	313	0.36	6.1	3	17	Mesotrophic
Managh	19/3/18	8.32	308	63.6	6.85	211	111.8	0.2	13	180	0.24	3.5	8	36	Eutrophic
Moate	19/3/18	8.21	417	65.3	7.05	287	11.2	2.9	30	390	0.67	12.3	<2	8	Oligotrophic
Newtown (Coole)	21/2/18	8.43	387	68	7.38	257	88.2	0.4	23	286.2	0.47	5.4	n.a.	21	Mesotrophic

Polldowagh	21/2/18	8.80	504	74.2	8.06	342	127.6	4.9	3	353	1.15	3.1	34	127	Hypertrophic
Rahasane	21/2/18	n.a.	647	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rathbaun	21/2/18	8.79	n.a.	71.6	7.66		225.3	2.9	42	285.8	0.53	10	2	19	Mesotrophic
Roo West	21/2/18	8.83	237	77.8	8.25	160	99	1.6	13	97	0.21	4.2		13	Mesotrophic
Shrule	21/2/18	8.51	254	80.4	9.2	184	n.a.	2.1	9	105	0.44	6.18	<0.2	46.67	Mesotrophic
Skealoghan	21/2/18	8.5	287	69.2	8.1	213	155.2	0.6	16	205.1	0.3	4.6	3	9	Oligotrophic
Termon North	19/3/18	8.75	296	72.3	7.74	203	113.7	3	13	130.5	0.33	5.3	2	13	Mesotrophic
Termon South	19/3/18	8.64	314	68.5	7.34	215	119.9	1.2	16	178.7	0.29	4.7	3	15	Mesotrophic
Tullynafrankagh	19/3/18	8.55	401	58.2	6.19	274	39.4	0.8	28	257.1	1.43	7.9	4	40	Eutrophic
Turloughmore	19/3/18	8.22	294	80.5	8.84	202	132.8	0.2	15	151	0.49	9.1	7	10	Mesotrophic
Turloughnagullaum	21/2/18	8.6	271	91.7	9.89	185	119.7	0.2	8	148.3	0.37	8.9	<2	16	Mesotrophic

Trophic status (OECD, 1992), TP levels: <4: ultraoligotrophic; <10: oligotrophic; 10-35: mesotrophic; 35-100: eutrophic; >100 hypertrophic.

Table C.2. *Major cations of the 55 turloughs.*

Turl.	**Ca**	**Fe**	**K**	**Mg**	**Mn**	**Na**
Ardacong South	54.769	0.071	3.606	4.335	0.004	19.853
Ardmullan	52.117	0.223	3.166	4.268	0.024	6.048
Ardmullan2	52.725	0.243	3.137	4.332	0.024	6.101
Balla	55.841	0.081	3.023	3.514	0.015	10.629
Ballinturley	67.661	0.142	4.355	4.417	0.141	6.761
Ballyboy	70.977	0.029	3.77	5.049	0.004	9.881
Belclare	83.15	0.174	2.201	4.4	0.019	9.786
Blackrock	50.911	0.161	2.199	3.822	0.027	10.036
Breandrum	67.275	0.366	4.524	2.666	0.006	7.88
Brierfield	63.036	0.032	2.475	2.618	0.004	6.898
Coolcam	62.692	0.042	1.975	5.043	0.004	8.655
Croaghill	81.471	0.11	3.256	6.04	0.068	8.574
Cahermore	64.464	0.045	4.466	7.351	0.005	11.284
Carran North	52.01	0.047	0.966	1.819	0.005	8.563
Carran South	47.036	0.023	0.982	1.838	0.006	8.339
Carrowkeel	32.946	0.043	5.51	4.395	0.007	8.457
Castle Plunket	67.903	0.039	2.183	2.965	0.003	8.596
Cockstown	51.21	0.06	0.716	2.698	0.024	7.315
Coole	47.613	0.089	1.974	3.694	0.016	10.669
Coole2	50.989	0.275	2.549	4.875	0.057	12.101
Correal Cross	52.604	0.188	4.965	4.62	0.006	8.218
Cuillan South	57.229	0.0426	3.206	3.431	0.004	8.677
Droomadoon	59.458	0.284	2.782	3.932	0.025	12.777
Fort William	54.354	0.045	4.244	11.493	0.005	8.459
Four Roads	50.062	0.019	1.237	3.659	0.003	8.278
Four roads2	54.636	0.04	1.439	3.686	0.004	8.034
Garryland W.	47.752	0.116	2.084	3.998	0.014	11.016
Glenamaddy	46.186	0.111	1.646	2.397	0.008	8.196
Hawkhill	54.851	0.021	1.866	3.726	0.006	9.77
Hawkhill2	62.765	0.036	2.467	4.656	0.005	11.074
Kilglassaun	51.436	0.074	4.377	4.354	0.004	9.209
Knockaunroe	51.822	0.024	1.091	2.217	0.003	9.036
L. Coy	54.691	0.05	2.344	3.801	0.006	10.237
L. Funshinagh	63.233	0.048	2.819	3.146	0.008	7.769
L. Gealain	50.445	0.023	0.801	2.174	0.004	8.877
Labane	61.173	0.031	2.764	4.467	0.006	10.893
Labane 2	66.86	0.238	4.918	7.09	0.419	17.802
Lisduff	52.34	0.022	3.121	5.115	0.004	8.101
Lough Loum	69.265	0.028	3.554	7.59	0.007	12.268
Managh	58.768	0.024	1.905	4.048	0.006	10.461
Moate	78.596	0.227	3.476	4.279	0.028	10.655
Newtown	70.244	0.056	2.547	5.976	0.011	14.403
Polldowagh	75.345	0.024	3.432	6.668	0.005	11.811
Rath	72.822	0.049	3.103	3.936	0.005	9.212
Roo West	48.557	0.026	2.016	2.535	0.005	9.356
Shrule	53.169	0.028	2.742	4.259	0.003	10.657
Termon N.	51.772	0.023	3.27	6.316	0.004	14.97
Termon S.	58.851	0.054	2.696	6.488	0.023	12.019
Tullynafranknagh	67.605	0.117	10.464	6.824	0.011	17.736
Turloughmore	57.435	0.076	0.435	6.23	0.017	9.103

Table C.3. *Monthly turbidity values (NTU). n.a.: dry turlough.*

Turl.	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19
Ale	3.28	4.31	3.88	8.11	6.94	23.6	3.56	n.a.	1.07	2.6	3.6	4.8
Bla	3.59	5.02	4.29	3.23	n.a.	8.3	n.a.	n.a.	2.32	8.06	10.5	3.4
Cara	5.8	2.19	8.95	31	30.4	12	5.75	10.5	2.13	3.2	12.6	7.9
Cool	0.75	2.08	2.23	8.62	17.4	15.2	1.96	2.67	0.7	10.6	1.4	0.99
Coy	2.98	5.91	3.3	6.2	7.55	17.5	2.94	2.17	2.21	2.2	2	2.9
Gea	0.7	0.54	4.01	9	14.1	3.45	1.01	4.58	1.3	1.2	2	1.1
Ske	0.87	1.49	1.22	5.02	3.6	2.01	n.a.	n.a.	0.93	1.7	1.8	0.68

Table C.4. *Monthly colour measurements (units Pt/Co). n.a.: dry turlough.*

Turl.	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19
Ale	11	11	12	11	13	23	49		17	68	12	29
Bla	99	108	66	66					156	120	149	65
Cara	22	17	11	31	22	36	47	116	36	22	17	22
Cool	23	11	21	15	30	23	97	16	20	7	11	20
Coy	82	61	65	41	34	63	86	99	132	67	31	62
Gea	10	11	9	9	9	10	26	23	55	14	5	4
Ske	15	25	15	17	62	32			50	44	24	37

***Table C.5**. Monthly pH measurements. n.a.: dry turlough*

Turl.	Dec 18	Jan 19	Feb 19	Mar 19	Apr 19	May 19	Jun 19	Jul 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	7.69	8.1	8.52	7.28	8.16	8.71	8.53	n.a.	7.15	7.12	8.05	8.37
Bla	7.79	7.73	7.89	7.81	n.a.	n.a.	n.a.	7.78	7.76	8.09	8.26	8.3
Cara	7.49	8.16	6.98	8.02	7.41	7.92	8.05	8.22	7.42	7.31	8.4	8.32
Cool	7.18	7.79	7.12	7.15	7.74	6.93	7.21	7.97	7.82	7.12	8.03	8.11
Coy	7.6	7.82	8.17	7.6	7.62	8.64	8.84	8.82	8.22	8.05	7.71	8.25
Gea	7.94	8.17	8.19	7.23	7.83	7.83	7.58	8.11	7.94	7.1	8.26	8.29
Ske	7.06	7.14	6.89	6.96	8.2	n.a.	n.a.	n.a.	8.21	8.1	8.4	8.2

Table C.6. Electrical Conductivity (µS cm^{-1})

Turl.	Dec 18	Jan 19	Feb 19	Mar 19	Apr 19	May 19	Jun 19	Jul 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	335	292	285	220	195	146	170	n.a.	n.a.	344	322	300
Bla	325	220	302	252	n.a.	n.a.	n.a.	n.a.	346	329	261	282
Cara	415	263	421	289	252	284	255	257	352	333	242	326
Cool	385	262	248	352	217	289	257	374	527	485	483	482
Coy	352	248	385	262	260	224	267	216	281	319	258	336
Gea	244	240	302	220	242	237	244	248	275	290	257	235
Ske	359	224	215	201	178	n.a.	n.a.	n.a.	497	333	247	359

***Table C.7**. Alkalinity (mg l^{-1} $CaCO_3$).*

Turl.	Dec 18	Jan 19	Feb 19	Mar 19	Apr 19	May 19	Jun 19	Jul 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	161.3	162.72	162.12	144.3	193.2	185.2	193.0	n.a.	270	139.0	172	189.4
Bla	125.6	143.36	163.2	154.8	n.a.	n.a.	n.a.	n.a.	244	114.4	112.4	181.52
Cara	241.7	236.2	165.4	141.6	153.0	168	218	182.3	289	134.9	195.6	208.6
Cool	204.4	202.84	210.8	192.7	242.4	237.0	n.a.	211.8	245	204.1	287.2	228.76
Coy	133.3	141.88	171.2	152.9	242.2	257.9	166.32	179.9	152	131.5	130.48	165.82
Gea	138.5	141.88	162.44	132.2	134.8	137.4	152.44	128.0	160	134.8	149.4	148.4
Ske	171.0	166.44	208.4	170.4	194.3	n.a.	n.a.	n.a.	267	145.3	204.52	164.68

***Table C.8**. Colour (Units Pt/Co).*

Turl.	**Dec 18**	**Jan 19**	**Feb 19**	**Mar 19**	**Apr 19**	**May 19**	**Jun 19**	**Jul 19**	**Aug 19**	**Sep 19**	**Oct 19**	**Nov 19**
Ale	11	11	12	11	13	23	49	n.a.	17	68	12	29
Bla	99	108	66	66	n.a.	n.a.	n.a.	n.a.	156	120	149	65
Cara	22	17	11	31	22	36	47	116	36	22	17	22
Cool	23	11	21	15	30	23	97	16	20	7	11	20
Coy	82	61	65	41	34	63	86	99	132	67	31	62
Gea	10	11	9	9	9	10	26	23	55	14	5	4
Ske	15	25	15	17	62	32	n.a.	n.a.	50	44	24	37

***Table C.9**. Carbon (mg l^{-1}).*

Turl.	**Dec 18**	**Jan 19**	**Feb 19**	**Mar 19**	**Apr 19**	**May 19**	**Jun 19**	**Jul 19**	**Aug 19**	**Sep 19**	**Oct 19**	**Nov 19**
Ale	17.73	14.43	3.15	16.92	4.94	7.92	8.24	7.67	4.29	6.45	49.11	45.63
Bla	27.08	31.40	20.14	27.89	n.a.	n.a.	n.a.	n.a.	18.49	20.14	46.55	38.43
Cara	37.89	42.63	9.89	24.95	11.48	16.49	13.73	21.16	11.16	9.7	46.51	42.33
Cool	47.85	28.44	5.99	21.93	12.01	14.16	4.90	6.78	29.42	5.5	79.33	41.55
Coy	26.06	32.89	9.79	28.89	9.29	14.16	18.58	23.96	4.85	13.35	59.05	35.21
Gea	26.70	31.94	2.92	15.42	4.61	3.85	4.35	7.24	5.15	4.03	41.36	28.42
Ske	42.55	18.29	4.34	16.62	16.21	n.a.	n.a.	n.a.	10.81	11.22	62.90	25.36

***Table C.10**. Total nitrogen and Total Oxised Nitrogen (mg l^{-1}).*

	Dec-18		Jan-19		Feb-19		Mar-19		Apr-19		May-19		Jun-19		Jul-19		Aug-19	
Turl.	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**	**TON**	**TN**
Ale	1.15	0.89	0.86	0.64	0.80	4.59	0.53	0.78	0.54	0.33	0.36	0.33	0.89	1.08	1.45	1.57	0.28	0.43
Bla	0.96	0.87	0.78	1.03	1.27	0.98	0.53	1.50	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.81	1.89
Cara	2.32	2.02	1.33	1.60	3.06	5.81	2.10	2.41	0.91	0.94	0.01	0.94	0.92	1.10	1.91	1.96	1.05	1.20
Cool	1.01	1.95	0.88	0.09	5.95	1.09	0.76	1.05	0.63	0.74	0.25	0.36	<0.01	<0.01	0.27	0.52	1.08	1.11
Coy	1.00	0.95	0.85	1.15	1.55	1.11	1.03	1.76	0.49	0.87	0.13	0.15	0.99	1.16	1.17	1.32	2.44	2.45
Gea	0.64	0.97	0.32	0.57	0.71	0.79	0.40	0.68	0.32	0.47	0.16	0.17	0.07	0.34	0.30	0.55	0.42	0.66
Ske	0.15	0.30	0.19	0.22	0.38	0.51	0.40	0.45	0.21	1.18	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.13

Table C.11. *Chlorides (mg l-1).*

Turl.	Jun 19	July 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	16.71	n.a.	7.67	14.32	16	27
Bla	n.a.	n.a.	16.81	11.39	14	17.3
Cara	29.50	25.30	21.04	22.63	18.2	45.5
Cool	17.57	16.76	14.59	16.51	14.1	13.9
Coy	16.20	18.49	29.99	13.48	23	13.4
Gea	13.18	13.95	17.03	7.77	11.4	16.2
Ske	n.a.	n.a.	12.78	7.71	12.5	17.3

Table C.12. *Sulphates (mg l-1).*

	Sulphates					
Turl.	**Jun 19**	**July 19**	**Aug 19**	**Sep 19**	**Oct 19**	**Nov 19**
Ale	1.18	n.a.	0.97	8.80	2.40	3.30
Bla	n.a.	n.a.	7.49	5.23	4.50	6.30
Cara	1.40	0.70	1.32	1.88	1.80	3.90
Cool	0.78	1.48	4.70	3.82	4.20	3.90
Coy	5.38	6.91	16.08	8.63	3.00	5.40
Gea	1.66	2.64	1.84	1.37	1.80	1.50
Ske	n.a.	n.a.	3.95	0.84	1.20	1.50

Table C.13. *Nitrates (mg l-1).*

	Nitrates					
Turl.	Jun 19	July 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	<0.04	n.a.	<0.04	0.67	3.63	5.76
Bla	n.a.	n.a.	2.06	1.18	1.59	1.59
Cara	<0.04	0.12	0.10	0.10	1.02	4.65
Cool	<0.04	<0.04	1.49	0.45	3.59	2.26
Coy	<0.04	0.08	1.76	0.59	1.11	2.90
Gea	0.17	<0.04	0.43	0.32	0.89	1.68
Ske	n.a.	n.a.	0.21	n.a.	0.18	n.a.

Table C.14. *Monthly SRP and TP data for the 7 turloughs (mg l^{-1}).*

	Dec-18		**Jan-19**		**Feb-19**		**Mar-19**		**Apr-19**		**May-19**	
Turl.	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**
Ale	0.023	0.035	0.021	0.037	0.005	0.027	0.001	0.005	0.004	0.012	0.015	0.044
Bla	0.01	0.033	0.019	0.026	0.007	0.025	0.003	0.014	n.a.	n.a.	n.a.	n.a.
Cara	0.008	0.074	0.002	0.035	0.011	0.005	0.028	0.077	0.011	0.064	0.006	0.069
Cool	0.001	0.016	0.003	0.007	0.004	0.006	0.001	0.007	0.007	0.073	0.006	0.021
Coy	0.017	0.011	0.112	0.083	0.005	0.131	0.008	0.013	0.004	0.013	0.014	0.056
Gea	0.003	0.017	0.007	0.012	0.006	0.011	0.001	0.002	0.004	0.004	0.007	0.006
Ske	0.018	0.02	0.005	0.1	0.004	0.009	0	0.006	0.026	0.065	n.a.	n.a.

Turl.	**Jun-19**		**Jul-19**		**Aug-19**		**Sep-19**		**Oct-19**		**Nov-19**	
	SRP	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**	**SRP**	**TP**
Ale	0.026	0.059	0.014	n.a.	0.025	0.03	0.007	0.015	0.024	0.047	0.01	0.024
Bla	n.a.	n.a.	n.a.	n.a.	0.04	0.05	0.023	0.08	0.026	0.037	0.006	0.018
Cara	0.022	0.028	0.011	0.076	0.011	0.019	0.008	0.035	0.006	0.025	0.028	0.067
Cool	0.018	0.016	0.017	0.043	0.022	0.028	0.007	0.008	0.008	0.013	0.002	0.013
Coy	0.042	0.121	0.03	0.083	0.036	0.025	0.009	0.029	0.03	0.071	0.017	0.034
Gea	0.003	0.006	0.006	0.006	0.021	0.018	0.011	0.014	0.005	0.009	0.003	0.008
Ske	n.a.	n.a.	n.a.	n.a.	0.025	0.033	0.008	0.014	0.008	0.012	0.003	0.014

Table C.15. *Monthly chlorophyll α data for the 7 turloughs (mg l^{-1}). n.a.: dry turlough.*

Turl.	Dec-18	Jan-19	Feb-19	Mar-19	Apr-19	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19
Ale	2.2	4.4	1.53	19.92	7.78	54.67	50.5	n.a.	47.5	33.4	36.1	10.6
Bla	2.3	2.3	2	9.38	n.a.	n.a.	n.a.	n.a.	12.2	21.7	6.3	1.7
Cara	n.a.	310	152.2	244.18	186.26	198.31	10.19	111.66	63.4	48.9	4.2	320.3
Cool	10.8	73.2	28.4	70.43	178.54	27.34	17.61	50.04	13.6	26.7	10	37.8
Coy	8.3	20.4	6.53	18.07	54.67	69.5	62.55	55.83	73.4	94	449.7	2.2
Gea	2.5	3.1	1.22	11.82	21.31	11.12	4.73	12.51	58.4	3.9	6.7	2.2
Ske	39	8.8	3.4	15.29	1.67	n.a.	n.a.	n.a.	22.5	3.3	6.7	7.5

Table C.16. *Dissolved inorganic carbon (mgl^{-1}), as calculated with the CO2SYS Excel add-on.*

Turl.	Dec 18	Jan 19	Feb 19	Mar 19	Apr 19	May 19	Jun 19	Jul 19	Aug 19	Sep 19	Oct 19	Nov 19
Ale	19.35	19.52	19.45	17.31	23.18	22.22	23.16	27.76	32.40	16.68	20.64	22.73
Bla	15.07	17.20	19.58	18.57	20.71	22.86	25.00	27.14	29.28	13.73	13.49	21.78
Cara	29.00	28.34	19.85	16.99	18.36	20.16	26.16	21.87	34.68	16.19	23.47	25.03
Cool	24.53	24.34	25.29	23.12	29.09	28.44	0.00	25.41	29.40	24.49	34.46	27.45
Coy	15.99	17.02	20.54	18.35	29.06	30.95	19.96	21.59	18.24	15.78	15.66	19.90
Gea	16.62	17.02	19.49	15.86	16.17	16.49	18.29	15.36	19.20	16.17	17.93	17.81
Ske	20.52	19.97	25.01	20.45	23.31	25.49	27.67	29.85	32.04	17.43	24.54	19.76

APPENDIX D. SOIL ANALYTICAL RESULTS

Table D1. *Analytical results of the soil samples with date of sampling.*

Date of sampling	Turl.	sample	pH	OM (%)	SOC (%)	total P (mg kg^{-1})	Soil type	$CaCO_3$ (%)	Inorg (%)	Depth (m)	Ston. (% vol.)	BD (g cm^{-3})
26/8/17	ALE	Ale5-2	7.3	28.2	16.3	2060	BorgVSP	5.4	66.4	0.125	4.9	0.43
26/8/17	ALE	Ale7-1	7.19	12.5	7.2	713	BorgVSP	0.8	86.8	0.25	1.5	0.52
26/8/17	ALE	Ale10	7.79	16.9	9.8	1483	BorgVSP	2.4	80.8	0.05	1.4	0.49
26/8/17	ALE	Ale11	7.34	11.5	6.7	1231	BorgVSP	8.8	79.7	0.03	1.4	0.53
26/8/17	ALE	Ale12-1	7.59	12.4	7.2	943	BorgVSP	13.2	74.4	0.2	1.8	0.52
26/6/18	ALE	Ale18-1	7	21.9	12.7	660	BorgVSP	21.5	56.5	0.125	4.2	0.46
26/6/18	ALE	Ale18-2	7.7	17.2	10.0	760	BorgVSP	20.9	61.8	0.125	5.2	0.49
26/6/18	ALE	Ale18-3	7.4	23.3	13.5	443	BorgVSP	26.5	50.2	0.125	0.1	0.45
26/6/18	ALE	Ale18-4	7.3	25.0	14.5	593	BorgVSP	36.2	38.8	0.125	0.2	0.44
26/6/18	ALE	Ale18-5	6.8	19.5	11.3	653	BorgVSP	7.0	73.5	0.125	0.2	0.47
26/6/18	ALE	Ale18-6	6.2	15.6	9.0	1733	BorgVSP	15.8	68.7	0.125	2.9	0.50
26/6/18	ALE	Ale18-7	7	21.0	12.2	2157	BorgVSP	34.5	44.4	0.125	0.1	0.46
26/8/17	ALE	Ale1-1	7.58	21.8	12.7	1200	BorgVSW	22.3	55.8	0.125	3.3	0.46
26/8/17	ALE	Ale2-2	7.53	17.7	10.3	729	BorgVSW	22.7	59.5	0.05	8.6	0.49
26/8/17	ALE	Ale3-1	7.03	13.7	7.9	2060	BorgVSW	24.3	62.0	0.05	1.8	0.51
26/8/17	ALE	Ale3-3	7.54	10.0	5.8	776	BorgVSW	15.1	75.0	0.125	2.3	0.54
26/8/17	ALE	Ale4-1	7.56	9.3	5.4	855	BorgVSW	26.4	64.3	0.03	1.8	0.55
26/8/17	ALE	Ale5-1	7.21	23.4	13.6	1428	BorgVSW	9.1	67.5	0.04	1.3	0.45
26/8/17	ALE	Ale6	7.09	19.1	11.1	784	BorgVSW	0.7	80.2	0.125	1.7	0.48
26/8/17	ALE	Ale18-8	7.4	15.0	8.7	2414	BorgVSW	10.4	74.5	0.125	0.0	0.50
2/7/18	BLA	BL05	7.29	15.8	9.2	787	BMinSP	4.4	79.8	0.3	0.6	0.67
2/7/18	BLA	BL07	6.78	5.3	3.1	726	BMinSP	3.1	91.6	0.3	0.2	1.03
2/7/18	BLA	BL11	4.83	17.2	10.0	548	BMinSP	3.0	79.8	0.3	0.2	0.64
2/7/18	BLA	BL12	5.74	10.7	6.2	1005	BMinSP	7.1	82.1	0.3	0.1	0.82

2/7/18	BLA	BL13	6.76	16.3	9.4	8440	623	BMinSP	8.8	74.9	0.3	1.1	0.66
2/7/18	BLA	BL14	7	15.5	9.0	16200	761	BMinSP	6.7	77.8	0.3	22.2	0.68
2/7/18	BLA	BL15	5.6	8.6	5.0	5620	1100	BMinSP	4.5	86.9	0.3	0.4	0.89
2/7/18	BLA	BL19	6.2	19.3	11.2	8020	937	BMinSP	4.7	75.9	0.3	1.0	0.58
2/7/18	BLA	BL22	5.3	18.1	10.5	6720	513	BMinSP	8.3	73.6	0.3	5.7	0.61
2/7/18	BLA	BL23	6.5	18.6	10.8	8750	814	BMinSP	5.6	75.7	0.3	3.6	0.60
2/7/18	BLA	BL26	7	17.4	10.1	4360	896	BMinSP	4.9	77.7	0.3	0.6	0.63
2/7/18	BLA	BL27	6.5	15.4	8.9	5340	984	BMinSP	4.1	80.5	0.3	0.4	0.69
2/7/18	BLA	BL20	6	12.0	7.0	8240	1270	BMinSW	6.6	81.4	0.3	0.1	0.78
2/7/18	BLA	BL21	6	12.2	7.1	6700	1123	BMinSW	9.4	78.4	0.3	0.0	0.78
2/7/18	BLA	BL25	6.5	17.9	10.4	7020	717	BMinSW	4.5	77.5	0.3	0.1	0.62
2/7/18	BLA	BL28	5.6	12.6	7.3	4610	858	BMinSW	5.8	81.6	0.3	0.1	0.76
2/7/18	BLA	BL01	6.84	12.3	7.1	7730	654	BMinVSW	3.1	84.6	0.1	0.6	0.77
2/7/18	BLA	BL02	6.69	15.6	9.1	8150	703	BMinVSW	4.9	79.5	0.1	8.1	0.68
2/7/18	BLA	BL03	6.41	14.2	8.3	6360	537	BMinVSW	5.3	80.5	0.1	0.6	0.72
2/7/18	BLA	BL04	5.79	13.8	8.0	4910	517	BMinVSW	7.6	78.6	0.1	9.2	0.73
2/7/18	BLA	BL06	6.89	15.8	9.2	5530	618	BMinVSW	3.1	81.1	0.1	4.6	0.67
2/7/18	BLA	BL08	6.03	8.6	5.0	5310	752	BMinVSW	6.5	84.9	0.1	0.3	0.90
2/7/18	BLA	BL09	7.2	15.7	9.1	5510	834	BMinVSW	4.4	79.9	0.1	0.6	0.68
2/7/18	BLA	BL10	5.83	14.0	8.1	4650	443	BMinVSW	5.8	80.2	0.1	0.7	0.72
2/7/18	BLA	BL17	5.84	12.5	7.2	26210	927	BMinVSW	6.9	80.6	0.1	1.0	0.77
2/7/18	BLA	BL18	5.67	8.2	4.8	5820	715	BMinVSW	4.8	86.9	0.1	9.1	0.91
2/7/18	CARA	Cara1	6.58	21.8	12.6	10320	831	BOrgVSW	12.3	65.9	0.1	1.5	0.46
2/7/18	CARA	Cara2	6.4	42.9	24.9	9521	699	BOrgVSW	15.5	41.6	0.25	2.3	0.36
2/7/18	CARA	Cara3-1	6.21	18.2	10.5	6140	816	BOrgVSW	3.3	78.5	0.2	0.7	0.48
2/7/18	CARA	Cara3-3	7.2	11.2	6.5	7380	1094	BOrgVSW	19.1	69.7	0.2	6.7	0.53
2/7/18	CARA	Cara4	6.97	23.1	13.4	10020	953	BOrgVSW	1.3	75.6	0.2	0.1	0.45
7/7/18	COO	COOL4	7	10.9	6.3	3590	153	AlluvMIN	5.7	83.4	0.24	1.3	0.82
7/7/18	COO	COOL5	6.9	11.1	6.5	4390	232	AlluvMIN	8.6	80.3	0.08	1.4	0.81

7/7/18	COO	COOL6	5.8	10.5	6.1	15120	521	AlluvMIN	7.6	81.9	0.05	2.8	0.83
7/7/18	COO	COOL7	6.8	18.5	10.7	13090	437	AlluvMIN	16.9	64.6	0.17	0.2	0.60
7/7/18	COO	COOL9	7.2	13.5	7.9	5340	242	AlluvMIN	15.1	71.3	0.15	2.8	0.74
7/7/18	COO	COOL10	7	14.5	8.4	4990	308	AlluvMIN	8.0	77.5	0.2	9.9	0.71
7/7/18	COO	COOL11	7.2	19.5	11.3	7700	297	AlluvMIN	12.2	68.3	0.15	2.1	0.58
7/7/18	COO	COOL15	7	12.0	7.0	6200	251	AlluvMIN	0.6	87.4	0.4	3.9	0.78
7/7/18	COO	COOL16	7.4	22.4	13.0	8780	242	AlluvMIN	15.3	62.3	0.1	1.7	0.51
7/7/18	COO	COOL17	7.4	8.0	4.6	4230	340	AlluvMIN	7.9	84.1	0.08	23.5	0.92
7/7/18	COO	COOL18	7.5	20.5	11.9	7700	280	AlluvMIN	13.1	66.4	0.05	6.8	0.56
7/7/18	COO	COOL19	7.1	21.0	12.2	12000	330	AlluvMIN	7.5	71.4	0.08	24.8	0.54
7/7/18	COO	COOL21	7.2	14.2	8.2	7100	366	AlluvMIN	2.3	83.5	0.3	16.4	0.72
7/7/18	COO	COOL22	7.2	22.1	12.8	7540	135	AlluvMIN	5.8	72.1	0.15	5.9	0.52
7/7/18	COO	COOL25	6.8	15.4	8.9	4210	259	AlluvMIN	4.5	80.2	0.1	5.5	0.69
7/7/18	COO	COOL8	7.3	8.4	4.9	3410	247	BMinSP	9.6	82.1	0.3	5.3	0.90
7/7/18	COY	COY17	7.2	9.3	5.4	5970	516	BMinVSP	4.9	85.8	0.1	3.4	0.87
7/7/18	COY	COY18	7.5	8.2	4.7	5832	386	BMinVSP	3.9	87.9	0.1	12.7	0.91
7/7/18	COY	COY19	7.3	17.3	10.0	6140	1590	BMinVSP	3.6	79.1	0.1	5.6	0.63
7/7/18	COY	COY20	6.9	11.1	6.4	8300	1317	BMinVSP	6.1	82.8	0.1	0.2	0.81
7/7/18	COY	COY21	7.2	16.2	9.4	6810	596	BMinVSP	5.7	78.1	0.1	0.7	0.66
7/7/18	COY	COY22	6.3	12.3	7.1	11580	946	BMinVSP	5.6	82.0	0.1	3.0	0.77
7/7/18	COY	COY24	6.2	18.2	10.6	10900	846	BMinVSP	1.9	79.9	0.1	6.1	0.61
7/7/18	COY	COY25	6.5	21.8	12.6	11180	886	BMinVSP	0.5	77.7	0.1	5.0	0.53
7/7/18	COY	COY26	8	6.3	3.7	10346	923	BMinVSP	3.6	90.1	0.1	3.1	0.99
7/7/18	COY	COY23	5.8	26.2	15.2	12700	351	BMinVSW	6.6	67.2	0.1	11.8	0.43
25/8/17	GEA	Gea1	7.02	51.2	29.7	15280	312	BorgVSP	1.2	47.6	0.1	10.4	0.32
25/8/17	GEA	Gea2	7.34	25.2	14.6	7910	421	BorgVSP	0.9	73.9	0.1	17.9	0.44
25/8/17	GEA	Gea3	6.75	65.2	37.8	12389	540	BorgVSP	1.6	33.2	0.1	7.4	0.27
25/8/17	GEA	Gea4	7.46	25.5	14.8	5690	278	BorgVSP	1.0	73.6	0.15	1.7	0.44

25/8/17	GEA	Gea4	7.46	25.5	14.8	5690	278	BorgVSP	1.0	73.6	0.15	1.7	0.44
25/8/17	GEA	Gea5	7.18	56.5	32.8	17260	513	BorgVSP	6.0	37.5	0.23	13.9	0.30
25/8/17	GEA	Gea6	6.64	32.2	18.7	11290	693	BorgVSP	15.5	52.3	0.1	7.7	0.41
25/8/17	GEA	Gea7	6.4	49.5	28.7	16500	582	BorgVSP	13.0	37.5	0.1	10.1	0.33
25/8/17	GEA	Gea8	6.9	43.1	25.0	3892	498	BorgVSP	19.6	37.3	0.04	10.1	0.36
25/8/17	GEA	Gea9	6.33	46.5	27.0	12830	471	BorgVSP	23.4	30.1	0.12	17.3	0.34
25/8/17	GEA	Gea10	6.1	26.8	15.5	6170	282	BorgVSP	1.3	71.9	0.1	7.9	0.43
25/8/17	GEA	Gea11	6.65	53.6	31.1	15500	510	BorgVSP	0.9	45.5	0.1	12.0	0.32
25/8/17	GEA	Gea12	6.19	34.3	19.9	13530	518	BorgVSP	1.3	64.4	0.08	6.0	0.40
25/8/17	GEA	Gea13	7.12	39.3	22.8	11900	371	BorgVSP	3.4	57.3	0.1	6.5	0.37
25/8/17	GEA	Gea15	7.28	46.5	27.0	14820	459	BorgVSP	0.9	52.6	0.1	8.4	0.34
25/8/17	GEA	Gea16	6.05	39.6	23.0	11820	492	BorgVSP	1.0	59.4	0.1	11.8	0.37
25/8/17	GEA	Gea18	6.49	58.4	33.9	17270	382	BorgVSP	0.8	40.8	0.1	9.2	0.30
25/8/17	GEA	Gea19	6.54	36.6	21.2	15493	353	BorgVSP	0.8	62.6	0.1	1.2	0.38
25/8/17	GEA	Gea20	6.55	40.6	23.5	12950	589	BorgVSP	1.1	58.3	0.1	5.8	0.37
26/6/18	GEA	GEA181	7.6	5.5	3.2	10150	56	AlluvMRL	14.5	80.0	0.35	14.4	1.02
26/6/18	GEA	GEA182	7.5	42.2	24.5	15930	81	AlluvMRL	8.5	49.4	0.35	8.3	0.13
26/6/18	GEA	GEA183	7.2	14.7	8.5	2280	85	AlluvMRL	34.2	51.1	0.35	0.1	0.70
26/6/18	GEA	GEA185	7.6	22.8	13.2	2900	538	BorgVSP	25.6	51.6	0.1	4.7	0.45
26/6/18	GEA	GEA186	7	37.4	21.7	10900	178	AlluvMRL	33.1	29.5	0.35	1.1	0.22
25/9/17	SKE	Ske1	7.36	9.0	5.2	3280	851	BorgVSW	0.5	40.6	0.1	3.7	0.30
25/9/17	SKE	Ske2	6.71	73.9	37.0	9090	663	FenPt	2.7	23.4	1	2.9	0.15
25/9/17	SKE	Ske3	7.08	71.3	35.6	24400	754	FenPt	3.5	25.2	1	1.8	0.15
25/9/17	SKE	Ske4	5.48	13.7	8.0	17230	779	BorgVSW	4.6	31.5	0.1	2.5	0.28
25/9/17	SKE	Ske5	7.33	12.8	7.4	4070	341	BorgVSW	12.8	67.6	0.2	2.9	0.47
25/9/17	SKE	Ske6	7.4	21.6	12.5	8730	559	BorgVSW	10.0	68.4	0.2	9.5	0.46
25/9/17	SKE	Ske9	5.41	12.0	6.9	5490	486	BorgVSW	7.1	81.0	0.1	0.8	0.53

25/9/17	SKE	Ske10	7.31	27.5	15.9	6834	489	BorgVSW	9.3	63.2	0.1	4.3	0.43
25/9/17	SKE	Ske18	6.52	6.5	3.8	2860	513	BorgVSW	18.8	27.9	0.15	3.6	0.32
25/9/17	SKE	Ske24	5.9	8.8	5.1	4990	508	BorgVSW	8.8	40.2	0.1	1.0	0.32
25/9/17	SKE	Ske11	7.41	62.1	31.1	7182	518	FenPt	7.5	30.3	1	2.3	0.15
25/9/17	SKE	Ske14	7.47	70.1	35.1	11690	484	FenPt	0.5	29.4	1	1.7	0.15
25/9/17	SKE	Ske15	7.25	73.3	36.6	10392	659	FenPt	3.4	23.3	1	0.6	0.15
25/9/17	SKE	Ske19	7.05	71.2	35.6	6870	397	FenPt	0.5	28.3	1	1.6	0.15
4/7/18	SKE	Ske22	7.33	65.0	32.5	7870	542	FenPt	3.4	31.5	1	0.8	0.15
4/7/18	SKE	Ske23	7.3	66.3	33.2	18350	1329	FenPt	6.9	26.8	1	1.3	0.15
4/7/18	SKE	Ske25	7	67.1	33.6	5450	713	FenPt	2.0	30.9	1	1.2	0.15
4/7/18	SKE	Ske26	7.1	69.0	34.5	19180	641	FenPt	23.9	7.1	1	1.0	0.15
4/7/18	SKE	Ske27	7.3	62.1	31.1	4400	330	FenPt	12.4	25.5	1	0.0	0.15
4/7/18	SKE	Ske28	7.1	62.7	31.3	26360	741	FenPt	1.9	35.4	1	0.3	0.15

APPENDIX E. GREENHOUSE GAS FLUXES

Table E.1. *Average CO_2 fluxes (nmol mol^{-1} m^{-2} s^{-1}) at the 7 turloughs. d=dry, w=wet. F=full light, P=partially shaded, D=dark.*

Turl.		**Summer 2018**			**Spring 2019**			**Summer 2019**			**Autumn 2019**			**Winter 2019**		
		F	P	D	F	P	D	F	P	D	F	P	D	F	P	D
ALE	d	-382.78	1,222.50		-3,609.17	597.22	4,309.44	-3,476.39	1,924.17	5,270.28	-1,951.39	505.56	4,098.89			
	w				-1,311.67	196.94	1,444.17	-2,304.72	897.78	2,174.17	-221.67	23.89	1,364.72			
BLA	d	-1,202.78	544.72	3,213.89	-1,061.39	544.44	1,794.44	-5,326.94	160.56	6,759.17	743.61	422.50	907.78			
	w							-1,350.28	1,945.56	4,160.00	135.56	561.94	643.33			
CARA	d	-1,005.00	556.11	1,316.11	-1,258.33	518.33	1,063.06	-1,402.50	1,802.22	2691.11	-1,740.28	454.17	2,009.72			
	w				-410.28	186.94	349.72	-570.56	-165.56	646.11	-570.56	148.89	658.89			
COOL	d				-907.78	538.89	1,011.11	-14,056.94	5,246.39	11,680.83	-1,628.61	825.56	3,279.72	-753.61	173.89	2,028.89
	w				-74.44	174.72	330.83	-1,454.72	1,055.00	1,891.39	-225.00	497.22	1,219.44	95.83	448.33	800.83
COY	d				225.56	2,935.56	5,165.56	-988.33	8,937.22	6,888.89	-356.94	4,643.06	7,004.17	245.28	1,831.67	3,251.39
	w				-426.94	24.44	319.44	542.50	4,645.28	6,553.61	-191.94	1,238.61	2,669.17	889.44	1,152.78	1,486.67
GEA	d	-344.17	1,024.44	1,137.78	173.06	507.22	1,491.67	-14,696.11	112.50	112.78	-296.94	550.56	1,398.06			
	w	-152.22	215.83	319.44	-149.17	108.33	158.89	-146.67	222.50	223.06	-143.89	96.11	161.67	-141.39	7.78	158.61

SKE	d	-1,373.06	1,288.06	2,433.33	-763.89	3,483.33	7,730.56	-6,516.39	-2,355.28	1,805.83	-1,169.17	86.39	1,364.17
	w	71.67	250.56	429.44	-1,029.17	81.94	1,193.06	-886.67	-25.56	835.56	93.33	117.22	141.39

Table E.2. Average CH_4 fluxes (nmol mol^{-1} m^{-2} s^{-1}) at the 7 turloughs. d=dry, w=wet

		Summer 2018	**Spring 2019**	**Summer 2019**	**Autumn 2019**	**Winter 2019**
ALE	d		1.11	1.78	1.94	0.75
	w				1.83	
BLA	d		0.36	0.64	0.64	
	w					1.22
CARA	d		0.92		1.08	
	w			1.33		1.47
COOL	d		0.64	1.36	1.11	2.56
	w					
COY	d		0.61	-0.58	0.22	2.33
	w			0.33		0.11
GEA	d	0.39	0.08	1.75	0.33	
	w		0.00	0.33	0.00	5.22
SKE	d		0.75	2.36	1.69	2.03
	w		1.11	1.78	1.94	0.75

Table E.3. Average N_2O fluxes (nmol mol^{-1} m^{-2} s^{-1}) at the 7 turloughs. d=dry, w=wet.

Turl.	wetness	Summer 2018	Spring 2019	Summer 2019	Autumn 2019	Winter 2019
ALE	d		0.05	1.32	0.02	
	w		0.02	0.02		0.01
BLA	d		0.04	0.19	0.19	
	w		0.01			0.45
CARA	d			0.83	0.39	1.31
	w					
COOL	d		0.03	0.51	0.06	2.55
	w					
COY	d		0.03	0.44	0.03	0.21
	w			0.06		0.10
GEA	d	0.0	0.03	0.16	0.03	
	w		0.01	0.05		1.92
SKE	d		0.03	0.03	0.04	
				0.01		

APPENDIX F. STATISTICAL TESTS

Table F.1*. Shapiro-Wilk normality tests for the soil parameters for new data (from this thesis) and old data (from Waldren et al., 2015). In red, groups that do not show a normal distribution. Tests performed with R 4.1 (α =0.05).*

Lough Aleenaun

ALE SOM new data

Shapiro-Wilk normality test

W = 7.63 E-01, p-value = 3.89 E-02

ALE SOM old data

Shapiro-Wilk normality test

W = 8.24 E-01, p-value = 1.26 E-01

ALE TN new data

Shapiro-Wilk normality test

W = 9.68 E-01, p-value = 8.61 E-01

ALE TN old data

Shapiro-Wilk normality test

W = 9.71 E-01, p-value = 8.84 E-01

ALE TP new data

Shapiro-Wilk normality test

W = 8.91 E-01, p-value = 3.65 E-02

ALE TP old data

Shapiro-Wilk normality test

W = 8.95 E-01, p-value = 3.84 E-01

Blackrock

BLA SOM new data

Shapiro-Wilk normality test

W = 8.50 E-01, p-value = 1.94 E-01
BLA SOM old data

Shapiro-Wilk normality test

W = 7.88 E-01, p-value = 6.43 E-02

BLA TN new data

Shapiro-Wilk normality test

W = 9.57 E-01, p-value = 7.87 E-01

BLA TN old data

Shapiro-Wilk normality test

W = 8.31 E-01, p-value = 1.41 E-01

BLA TP new data

Shapiro-Wilk normality test

W = 8.42 E-01, p-value = 1.71 E-01

BLA TP old data

Shapiro-Wilk normality test

W = 8.95 E-01, p-value = 3.84 E-01

Caranavoodaun

CARA SOM new data

Shapiro-Wilk normality test

W = 8.86 E-01, p-value = 3.38 E-01

CARA SOM old data

Shapiro-Wilk normality test

W = 8.75 E-01, p-value = 2.87 E-01

CARA TN new data

Shapiro-Wilk normality test

W = 9.67 E-01, p-value = 8.55 E-01

CARA TN old data

Shapiro-Wilk normality test

W = 9.01 E0, p-value = 4.17 E-01

CARA TP new data

Shapiro-Wilk normality test

W = 6.92 E-01, p-value = 7.86 E-03

CARA TP old data

Shapiro-Wilk normality test

W = 9.62 E-01, p-value = 8.18 E-02

Coolcam

COOL SOM new data

Shapiro-Wilk normality test

W = 0.79023, p-value = 0.06729

COOL SOM old data

Shapiro-Wilk normality test

W = 8.24 E-01, p-value = 1.25 E-01

COOL TN new data

Shapiro-Wilk normality test

W = 9.03 E-01, p-value = 4.27 E-01

COOL TN old data

Shapiro-Wilk normality test

W = 7.36 E-01, p-value = 2.21 E-02

COOL TP new data

Shapiro-Wilk normality test

W = 8.45 E-01, p-value = 1.79 E-01

COOL TP old data

Shapiro-Wilk normality test

W = 8.81 E-01, p-value = 3.12 E-01

Lough Coy

COY SOM new data

Shapiro-Wilk normality test

W = 8.83 E-01, p-value = 3.23 E-01

COY SOM old data

Shapiro-Wilk normality test

W = 8.22 E-01, p-value = 1.21 E-01

COY TN new data

Shapiro-Wilk normality test

W = 8.57 E-01, p-value = 2.17 E-01

COY TN old data

Shapiro-Wilk normality test

W = 7.80 E-01, p-value = 5.52 E-02

COY TP new data

Shapiro-Wilk normality test

W = 8.04 E-01, p-value = 8.68 E-02

COY TP old data

Shapiro-Wilk normality test

W = 9.49 E-01, p-value = 7.30 E-01

Lough Gealain

GEA SOM new data

Shapiro-Wilk normality test

W = 8.59 E-01, p-value = 2.26 E-01

GEA SOM old data

Shapiro-Wilk normality test

W = 9.47 E-01, p-value = 7.15 E-01

GEA TN new data

Shapiro-Wilk normality test

W = 9.08 E-01, p-value = 4.53 E-01

GEA TN old data

Shapiro-Wilk normality test

W = 9.17 E-01, p-value = 5.12 E-01

GEA TP new data

Shapiro-Wilk normality test

W = 0.85721, p-value = 0.2184

GEA TP old data
Shapiro-Wilk normality test

W = 9.19 E-01, p-value = 5.26 E-01

Skealoghan

SKE SOM new data

Shapiro-Wilk normality test

W = 7.87 E-01, p-value = 6.38 E-02

SKE SOM old data

Shapiro-Wilk normality test

W = 9.04 E-01, p-value = 4.33 E-01

SKE TN new data

Shapiro-Wilk normality test

W = 0.84323, p-value = 0.174

SKE TN old data

Shapiro-Wilk normality test

W = 9.03 E-01, p-value = 4.29 E-01

SKE TP new data

Shapiro-Wilk normality test

W = 9.27 E-01, p-value = 5.75 E-01

SKE TP old data

Shapiro-Wilk normality test

W = 9.77 E-01, p-value = 9.21 E-01

Blackrock

t-Test: Two-Sample Assuming Unequal Variances

SOM	*new values*	*Waldren et al. (2015) values*
Mean	1.40E+01	1.46E+01
Variance	1.27E+01	6.66E+00
Observations	2.60E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.00E+01	
t Stat	-4.77E-01	
P(T<=t) one-tail	3.22E-01	
t Critical one-tail	1.81E+00	
P(T<=t) two-tail	6.44E-01	
t Critical two-tail	2.23E+00	

t-Test: Two-Sample Assuming Unequal Variances

TN	*new values*	*Waldren et al. (2015) values*
Mean	7.41E+03	7.05E+03
Variance	2.10E+07	1.93E+06
Observations	2.60E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	2.70E+01	
t Stat	3.42E-01	
P(T<=t) one-tail	3.68E-01	
t Critical one-tail	1.70E+00	
P(T<=t) two-tail	7.35E-01	
t Critical two-tail	2.05E+00	

t-Test: Two-Sample Assuming Unequal Variances

TP	*new values*	*Waldren et al. (2015) values*
Mean	7.83E+02	1.12E+03
Variance	4.30E+04	3.82E+05
Observations	2.60E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	5.00E+00	
t Stat	-1.33E+00	
P(T<=t) one-tail	1.21E-01	
t Critical one-tail	2.02E+00	
P(T<=t) two-tail	2.41E-01	
t Critical two-tail	2.57E+00	

Caranavoodaun

t-Test: Two-Sample Assuming Unequal Variances

SOM	*new values*	*Waldren et al. (2015) values*
Mean	2.34E+01	3.80E+01
Variance	1.40E+02	3.42E+02
Observations	5.00E+00	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	9.00E+00	
t Stat	-1.58E+00	
P(T<=t) one-tail	7.48E-02	
t Critical one-tail	1.83E+00	
P(T<=t) two-tail	1.50E-01	
t Critical two-tail	2.26E+00	

t-Test: Two-Sample Assuming Unequal Variances

	TN_new	*TN_old*
Mean	8.68E+03	1.59E+04
Variance	3.33E+06	5.68E+07
Observations	5.00E+00	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	6.00E+00	
t Stat	-2.27E+00	
P(T<=t) one-tail	3.20E-02	
t Critical one-tail	1.94E+00	
P(T<=t) two-tail	6.40E-02	
t Critical two-tail	2.45E+00	

Wilcoxon rank sum exact test for TP
W = 14, p-value = 0.9307. Alternative hypothesis: true location shift is not equal to 0

Coolcam

Wilcoxon rank sum exact test

SOM	*new values*	*Waldren et al. (2015) values*
Mean	1.52E+01	1.02E+01
Variance	2.40E+01	1.10E+01
Observations	1.60E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.40E+01	
W	2.90E+01	
p two-tail	9.31E-02	
t Critical two-tail	2.14E+00	

Wilcoxon rank sum test with continuity correction: TN

W = 6.45 E+01, p-value = 3.6 E-01
alternative hypothesis: true location shift is not equal to 0

t-Test: Two-Sample Assuming Unequal Variances

TP	*new values*	*Waldren et al. (2015) values*
Mean	2.90E+02	2.45E+02
Variance	9.36E+03	1.31E+03
Observations	1.60E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	2.00E+01	
t Stat	1.60E+00	
P(T<=t) one-tail	6.30E-02	
t Critical one-tail	1.72E+00	
P(T<=t) two-tail	1.26E-01	
t Critical two-tail	2.09E+00	

Lough Coy

t-Test: Two-Sample Assuming Unequal Variances

SOM	*new values*	*Waldren et al. (2015) values*
Mean	1.47E+01	1.45E+01
Variance	4.05E+01	2.08E+01
Observations	1.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.30E+01	
t Stat	5.47E-02	
P(T<=t) one-tail	4.79E-01	
t Critical one-tail	1.77E+00	
P(T<=t) two-tail	9.57E-01	
t Critical two-tail	2.16E+00	

t-Test: Two-Sample Assuming Unequal Variances

TN	*new values*	*Waldren et al. (2015) values*
Mean	8.98E+03	7.07E+03
Variance	7.02E+06	4.99E+06
Observations	1.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.20E+01	
t Stat	1.54E+00	
P(T<=t) one-tail	7.48E-02	
t Critical one-tail	1.78E+00	
P(T<=t) two-tail	1.50E-01	
t Critical two-tail	2.18E+00	

t-Test: Two-Sample Assuming Unequal Variances

TP	*new values*	*Waldren et al. (2015) values*
Mean	8.36E+02	1.16E+03
Variance	1.58E+05	1.62E+05
Observations	1.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.10E+01	
t Stat	-1.58E+00	
P(T<=t) one-tail	7.07E-02	
t Critical one-tail	1.80E+00	
P(T<=t) two-tail	1.41E-01	
t Critical two-tail	2.20E+00	

Lough Gealain

t-Test: Two-Sample Assuming Unequal Variances

SOM	*new values*	*Waldren et al. (2015) values*
Mean	3.88E+01	3.81E+01
Variance	2.07E+02	3.37E+02
Observations	2.30E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	7.00E+00	
t Stat	8.71E-02	
P(T<=t) one-tail	4.67E-01	
t Critical one-tail	1.89E+00	
P(T<=t) two-tail	9.33E-01	
t Critical two-tail	2.36E+00	

t-Test: Two-Sample Assuming Unequal Variances

TN	*new values*	*Waldren et al. (2015) values*
Mean	1.15E+04	2.19E+04
Variance	2.14E+07	7.45E+07
Observations	2.30E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	6.00E+00	
t Stat	-2.85E+00	
P(T<=t) one-tail	1.46E-02	
t Critical one-tail	1.94E+00	
P(T<=t) two-tail	2.92E-02	
t Critical two-tail	2.45E+00	

SIGNIFICANTLY DIFFERENT MEANS

t-Test: Two-Sample Assuming Unequal Variances

TP	*new values*	*Waldren et al. (2015) values*
Mean	4.00E+02	5.78E+02
Variance	3.03E+04	4.83E+04
Observations	2.30E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	7.00E+00	
t Stat	-1.83E+00	
P(T<=t) one-tail	5.46E-02	
t Critical one-tail	1.89E+00	
P(T<=t) two-tail	1.09E-01	
t Critical two-tail	2.36E+00	

Skealoghan

t-Test: Two-Sample Assuming Unequal Variances

SOM	*new values*	*Waldren et al. (2015) values*
Mean	5.61E+01	5.34E+01
Variance	3.82E+02	6.47E+02
Observations	2.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	7.00E+00	
t Stat	2.40E-01	
P(T<=t) one-tail	4.09E-01	
t Critical one-tail	1.89E+00	
P(T<=t) two-tail	8.17E-01	
t Critical two-tail	2.36E+00	

t-Test: Two-Sample Assuming Unequal Variances

TN	*new values*	*Waldren et al. (2015) values*
Mean	1.02E+04	2.24E+04
Variance	4.98E+07	1.15E+08
Observations	2.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	6.00E+00	
t Stat	-2.61E+00	
P(T<=t) one-tail	2.00E-02	
t Critical one-tail	1.94E+00	
P(T<=t) two-tail	4.01E-02	
t Critical two-tail	2.45E+00	

SIGNIFICANTLY DIFFERENT MEANS

t-Test: Two-Sample Assuming Unequal Variances

TP	*new values*	*Waldren et al. (2015) values*
Mean	6.15E+02	1.06E+03
Variance	4.92E+04	8.27E+04
Observations	2.00E+01	6.00E+00
Hypothesized Mean Difference	0.00E+00	
df	7.00E+00	
t Stat	-3.49E+00	
P(T<=t) one-tail	5.09E-03	
t Critical one-tail	1.89E+00	
P(T<=t) two-tail	1.02E-02	
t Critical two-tail	2.36E+00	

SIGNIFICANTLY DIFFERENT MEANS

Table F.3. *Shapiro tests for normality for the soil units in the different turloughs. Groups with one or two observation could not be tested. New=samples from this thesis. Old= samples from Waldren et al. (2015) (α =0.05).*

SOILTYPES	turlough	varname	batch	W	p.value
AlluvMIN	Cool	$CaCO_3$	new	9.48E-01	4.64E-01
AlluvMIN	Cool	OM	new	9.34E-01	2.77E-01
AlluvMIN	Cool	pH	new	7.70E-01	**1.11E-03**
AlluvMIN	Cool	TOTAL_P	new	9.42E-01	3.78E-01
BminSP	Bla	CaCO3	old	9.95E-01	8.65E-01
BminSP	Bla	OM	old	9.92E-01	8.30E-01
BminSP	Bla	pH	old	9.39E-01	5.25E-01
BminSP	Bla	TOTAL_P	old	9.01E-01	3.89E-01
BMinSP	Bla	$CaCO_3$	new	9.26E-01	3.43E-01
BMinSP	Bla	OM	new	8.46E-01	**3.28E-02**
BMinSP	Bla	pH	new	9.35E-01	4.41E-01
BMinSP	Bla	TOTAL_P	new	9.69E-01	8.95E-01
BMinSW	Bla	CaCO3	new	9.45E-01	6.83E-01
BMinSW	Bla	OM	new	7.45E-01	**3.45E-02**
BMinSW	Bla	pH	new	9.39E-01	6.47E-01
BMinSW	Bla	TOTAL_P	new	9.57E-01	7.60E-01
BMinVSP	Coy	$CaCO_3$	new	9.25E-01	4.39E-01
BMinVSP	Coy	OM	new	9.62E-01	8.23E-01
BMinVSP	Coy	pH	new	9.53E-01	7.19E-01
BMinVSP	Coy	TOTAL_P	new	9.43E-01	6.11E-01
BMinVSW	Bla	$CaCO_3$	new	9.63E-01	8.25E-01
BMinVSW	Bla	OM	new	7.79E-01	**1.19E-02**
BMinVSW	Bla	pH	new	8.78E-01	1.48E-01
BMinVSW	Bla	TOTAL_P	new	9.75E-01	9.36E-01
BorgVSP	Ale	$CaCO_3$	new	9.25E-01	3.32E-01
BorgVSP	Ale	OM	new	9.52E-01	6.67E-01
BorgVSP	Ale	pH	new	9.29E-01	3.70E-01

BorgVSP	Ale	TOTAL_P	new	8.75E-01	7.49E-02
BorgVSP	Gea	$CaCO_3$	new	6.83E-01	**3.53E-05**
BorgVSP	Gea	OM	new	9.71E-01	7.98E-01
BorgVSP	Gea	pH	new	9.61E-01	5.97E-01
BorgVSP	Gea	TOTAL_P	new	9.64E-01	6.45E-01
BorgVSW	Ale	$CaCO_3$	new	8.83E-01	2.01E-01
BorgVSW	Ale	OM	new	9.46E-01	6.76E-01
BorgVSW	Ale	pH	new	8.41E-01	7.74E-02
BorgVSW	Ale	TOTAL_P	new	8.35E-01	6.67E-02
BorgVSW	Ske	$CaCO_3$	new	4.39E-01	**1.89E-06**
BorgVSW	Ske	OM	new	9.07E-01	3.37E-01
BorgVSW	Ske	pH	new	8.09E-01	**3.55E-02**
BorgVSW	Ske	TOTAL_P	new	8.75E-01	1.68E-01
BOrgVSW	Cara	$CaCO_3$	new	8.69E-01	2.95E-01
BOrgVSW	Cara	OM	new	9.20E-01	5.38E-01
BOrgVSW	Cara	pH	new	9.20E-01	5.39E-01
BOrgVSW	Cara	TOTAL_P	new	9.89E-01	9.52E-01
FenPt	Ske	$CaCO_3$	new	5.01E-01	**1.79E-05**
FenPt	Ske	$CaCO_3$	old	9.69E-01	6.64E-01
FenPt	Ske	OM	new	9.37E-01	4.55E-01
FenPt	Ske	OM	old	7.91E-01	9.41E-02
FenPt	Ske	pH	new	9.41E-01	5.07E-01
FenPt	Ske	pH	old	7.69E-01	**4.33E-02**
FenPt	Ske	TOTAL_P	new	8.35E-01	**2.40E-02**
FenPt	Ske	TOTAL_P	old	1.00E+00	9.90E-01

***Table F.4**. Comparison of soil types for each turloughs between this project and Waldren et al. (2015) for pH, SOM, CaCO3, TOTAL_P, TOTAL_N. T-tests performed in R version 4.1.1. Rows in bold show significant differences (α =0.05).*

turlough	SOILTYPES	varname	t_test_statistic	t_test_parameter	t_test_pvalue	t_test_confidence_interval_lower	t_test_confidence_interval_upper	t_test_stderr
Ale	BorgVSW	pH	7.43E-01	1.07E+00	5.86E-01	-4.31E+00	4.95E+00	4.27E-01
Ale	BorgVSW	OM	-3.14E+00	1.22E+00	1.60E-01	-6.87E+01	3.15E+01	5.95E+00
Ale	**BorgVSW**	**$CaCO_3$**	**2.92E+00**	**7.70E+00**	**2.00E-02**	**1.81E+00**	**1.59E+01**	**3.02E+00**
Ale	BorgVSW	TOTAL_N	-2.28E+00					
Ale	BorgVSW	TOTAL_P	-1.94E+00	1.50E+00	2.33E-01	-4.20E+03	2.15E+03	5.28E+02
Bla	BMinSW	pH	-2.85E+00	3.00E+00	6.50E-02	5.44E+00	6.61E+00	1.84E-01
Bla	BMinSW	CaCO3	2.55E+00	3.00E+00	8.40E-02	3.27E+00	9.89E+00	1.04E+00
Bla	BMinSW	TOTAL_P	2.85E+00	3.00E+00	6.50E-02	5.94E+02	1.39E+03	1.25E+02
Cool	**AlluvMIN**	**OM**	**4.56E+00**	**1.50E+01**	**0.00E+00**	**1.21E+01**	**1.77E+01**	**1.31E+00**
Cool	AlluvMIN	$CaCO_3$	2.09E+00	1.50E+01	5.50E-02	6.03E+00	1.11E+01	1.19E+00
Cool	AlluvMIN	TOTAL_P	1.68E+00	1.50E+01	1.13E-01	2.39E+02	3.42E+02	2.41E+01
Gea	BorgVSP	pH	-7.50E-02	1.06E+00	9.52E-01	-6.96E+00	6.87E+00	6.24E-01
Gea	BorgVSP	OM	1.34E+00	1.22E+00	3.77E-01	-6.45E+01	8.89E+01	9.13E+00
Gea	BorgVSP	TOTAL_P	-2.37E-01	1.14E+00	8.48E-01	-9.99E+02	9.51E+02	1.02E+02
Ske	BorgVSW	pH	1.80E+00	7.00E+00	1.16E-01	5.85E+00	7.32E+00	3.11E-01
Ske	BorgVSW	OM	-2.50E-02	7.00E+00	9.81E-01	8.90E+00	2.10E+01	2.55E+00
Ske	BorgVSW	TOTAL_P	-1.18E+00	7.00E+00	2.76E-01	4.26E+02	7.06E+02	5.92E+01
Ske	**FenPt**	**OM**	**-4.82E+00**	**1.00E+01**	**1.00E-03**	**-1.06E+01**	**-3.90E+00**	**1.51E+00**
Ske	**FenPt**	**TOTAL_P**	**-6.17E+00**	**7.04E+00**	**0.00E+00**	**-8.70E+02**	**-3.88E+02**	**1.02E+02**

Lough Aleenaun

t-Test: Two-Sample Assuming Unequal Variances

BorgVSW	*TOTAL_N new*	*TOTAL_N old*
Mean	6.29E+03	1.67E+04
Variance	6.46E+06	3.96E+07
Observations	8.00E+00	2.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.00E+00	
t Stat	-2.28E+00	
P(T<=t) one-tail	1.31E-01	
t Critical one-tail	6.31E+00	
P(T<=t) two-tail	2.63E-01	
t Critical two-tail	1.27E+01	

t-Test: Two-Sample Assuming Unequal Variances

BorgVSP	*TOTAL_N new*	*TOTAL_N old*
Mean	9.07E+03	1.21E+04
Variance	4.17E+07	3.18E+07
Observations	1.20E+01	5.00E+00
Hypothesized Mean Difference	0.00E+00	
df	9.00E+00	
t Stat	-9.52E-01	
P(T<=t) one-tail	1.83E-01	
t Critical one-tail	1.83E+00	
P(T<=t) two-tail	3.66E-01	
t Critical two-tail	2.26E+00	

Blackrock

BMinSP	*TOTAL_N new*	*TOTAL_N old*
Mean	6.69E+03	8.27E+03
Variance	1.25E+07	4.33E+04
Observations	1.20E+01	3.00E+00
Hypothesized Mean Difference	0.00E+00	
df	1.10E+01	
t Stat	-1.54E+00	
P(T<=t) one-tail	7.60E-02	
t Critical one-tail	1.80E+00	
P(T<=t) two-tail	1.52E-01	
t Critical two-tail	2.20E+00	

Wilcoxon tests for non-normally distributed groups of soil types
Wilcoxon rank sum exact test
BMinSP Bla Total P
W = 0.00E+00
, p-value = 4.40 E-03
alternative hypothesis: true location shift is not equal to 0

SIGNIFICANT DIFFERENCES
Wilcoxon rank sum exact test
BMinSW Bla OM
W = 4.00 E+00, p-value = 4.00 E-01
alternative hypothesis: true location shift is not equal to 0

Wilcoxon rank sum test with continuity correction
BMinVSW Bla OM
W = 7.00E+00, p-value = 4.85 E-01
alternative hypothesis: true location shift is not equal to 0

Wilcoxon rank sum test with continuity correction
AlluvMin Cool pH
W = 0.00E+00, p-value = 1.22 E-01
alternative hypothesis: true location shift is not equal to 0

Wilcoxon rank sum test with continuity correction
BOrgVSP Gea $CaCO_3$
W = 12.00E+00, p-value = 4.35 E-01
alternative hypothesis: true location shift is not equal to 0

Wilcoxon rank sum exact test
BOrgVSW Ske $CaCO_3$
W = 8.00E+00, p-value = 2.22 E-01
alternative hypothesis: true location shift is not equal to 0
Wilcoxon rank sum exact test

FenPt Ske TP
W = 2.00E+00, p-value = 1.76 E-01
alternative hypothesis: true location shift is not equal to 0

SIGNIFICANT DIFFERENCES
Wilcoxon rank sum exact test
FenPT Ske $CaCO_3$
W = 19.00E+00, p-value = 9.45 E-01
alternative hypothesis: true location shift is not equal to 0

Wilcoxon rank sum test with continuity correction
FEnPt Ske pH
W = 14.00E+00, p-value = 6.13 E-01
alternative hypothesis: true location shift is not equal to 0

Table F.5. *Shapiro-Wilk tests of normality for the water chemistry parameters from this thesis and from Waldren et al. (2015). In bold groups that did not pass the normality test (α =0.05).*

new Ale_alka	**8.33E-01**	**2.57E-02**
new Ale_chlorides	9.33E-01	6.18E-01
new Ale_chloro	8.80E-01	1.04E-01
new Ale_colour...22	**7.19E-01**	**8.34E-04**
new Ale_colour...8	**7.19E-01**	**8.34E-04**
new Ale_EC	9.02E-01	2.30E-01
new Ale_nitrates	8.33E-01	1.47E-01
new Ale_pH	9.01E-01	1.93E-01
new Ale_SRP	9.06E-01	1.87E-01
new Ale_sulfates	7.97E-01	7.69E-02
new Ale_TN	**6.54E-01**	**4.14E-04**
new Ale_TOC	**7.27E-01**	**1.55E-03**
new Ale_TON	9.54E-01	7.34E-01
new Ale_TP	9.50E-01	6.41E-01
new Ale_turb	**6.34E-01**	**6.77E-05**
new Bla_alka	8.88E-01	2.25E-01
new Bla_chlorides	9.10E-01	4.84E-01
new Bla_chloro	**8.15E-01**	**4.11E-02**
new Bla_colour...23	8.83E-01	2.02E-01
new Bla_colour...9	8.83E-01	2.02E-01
new Bla_EC	9.61E-01	8.17E-01
new Bla_nitrates	9.42E-01	6.69E-01
new Bla_pH	**8.12E-01**	**2.79E-02**
new Bla_SRP	9.38E-01	5.92E-01
new Bla_sulfates	9.78E-01	8.93E-01
new Bla_TN	8.75E-01	2.87E-01
new Bla_TOC	0.91E-01	3.56E-01
new Bla_TON	9.63E-01	8.26E-01
new Bla_TP	9.01E-01	2.96E-01
new Bla_turb	8.79E-01	1.52E-01
new Cara_alka	9.57E-01	7.34E-01
new Cara_chlorides	8.41E-01	1.33E-01
new Cara_chloro	9.37E-01	4.83E-01
new Cara_colour...10	**6.55E-01**	**3.18E-04**
new Cara_colour...24	**6.55E-01**	**3.18E-04**
new Cara_EC	8.67E-01	5.99E-02
new Cara_nitrates	**6.32E-01**	**1.09E-03**
new Cara_pH	9.20E-01	2.88E-01
new Cara_SRP	**7.46E-01**	**2.40E-03**
new Cara_sulfates	8.42E-01	1.36E-01
new Cara_TN	**6.98E-01**	**1.35E-03**
new Cara_TOC	**8.39E-01**	**2.69E-02**
new Cara_TON	9.74E-01	9.30E-01
new Cara_TP	9.07E-01	1.98E-01
new Cara_turb	**7.81E-01**	**5.75E-03**
new Cool_alka	8.86E-01	1.23E-01
new Cool_chlorides	8.79E-01	2.64E-01
new Cool_chloro	**7.20E-01**	**1.32E-03**
new Cool_colour...11	**5.85E-01**	**8.13E-05**
new Cool_colour...25	**5.85E-01**	**8.13E-05**
new Cool_EC	9.03E-01	1.76E-01
new Cool_nitrates	8.94E-01	3.38E-01
new Cool_pH	8.64E-01	5.45E-02
new Cool_SRP	**8.02E-01**	**1.00E-02**

new Cool_sulfates	8.38E-01	1.26E-01
new Cool_TN	9.41E-01	5.97E-01
new Cool_TOC.	**8.46E-01**	**3.25E-02**
new Cool_TON	**5.88E-01**	**6.87E-05**
new Cool_TP	**7.10E-01**	**1.06E-03**
new Cool_turb	**7.64E-01**	**3.79E-03**
new Coy_alka	**8.14E-01**	**1.36E-02**
new Coy_chlorides	8.87E-01	3.04E-01
new Coy_chloro	**5.60E-01**	**5.04E-05**
new Coy_colour...12	9.32E-01	4.03E-01
new Coy_colour...26	9.32E-01	4.03E-01
new Coy_EC	9.26E-01	3.38E-01
new Coy_nitrates	9.11E-01	4.44E-01
new Coy_pH	8.91E-01	1.20E-01
new Coy_SRP	**7.33E-01**	**1.81E-03**
new Coy_sulfates	8.57E-01	1.78E-01
new Coy_TN	9.32E-01	5.05E-01
new Coy_TOC	9.10E-01	2.11E-01
new Coy_TON	9.23E-01	4.15E-01
new Coy_TP	8.92E-01	1.27E-01
new Coy_turb	**6.58E-01**	**3.44E-04**
new Gea_alka	9.40E-01	5.01E-01
new Gea_chlorides	9.54E-01	7.71E-01
new Gea_chloro	**6.41E-01**	**2.41E-04**
new Gea_colour...13	**7.04E-01**	**9.21E-04**
new Gea_colour...27	**7.04E-01**	**9.21E-04**
new Gea_EC	8.85E-01	1.01E-01
new Gea_nitrates	8.78E-01	2.61E-01
new Gea_pH	8.83E-01	9.46E-02
new Gea_SRP	**7.84E-01**	**6.26E-03**
new Gea_sulfates	8.53E-01	1.66E-01
new Gea_TN	9.91E-01	9.98E-01
new Gea_TOC	**8.02E-01**	**9.93E-03**
new Gea_TON	9.46E-01	6.50E-01
new Gea_TP	**7.74E-01**	**4.87E-03**
new Gea_turb	**7.42E-01**	**2.20E-03**
new Ske_alka	8.79E-01	1.55E-01
new Ske_chlorides	9.57E-01	7.59E-01
new Ske_chloro	**8.12E-01**	**2.80E-02**
new Ske_colour...14	9.22E-01	3.75E-01
new Ske_colour...28	9.22E-01	3.75E-01
new Ske_EC	8.93E-01	2.13E-01
new Ske_pH	**7.88E-01**	**1.48E-02**
new Ske_SRP	8.51E-01	7.57E-02
new Ske_sulfates	8.01E-01	1.04E-01
new Ske_TN	8.35E-01	1.19E-01
new Ske_TOC	8.38E-01	5.42E-02
new Ske_TON	8.43E-01	1.74E-01
new Ske_TP	**6.96E-01**	**1.27E-03**
new Ske_turb	**8.15E-01**	**2.18E-02**
Waldren Ale_alka	8.41E-01	5.87E-02
Waldren Ale_Ca	9.25E-01	4.69E-01
Waldren Ale_chloride	**7.88E-01**	**1.48E-02**
Waldren Ale chloro	**4.73E-01**	**3.11E-06**

Waldren Ale_colour	9.70E-01	9.00E-01
Waldren Ale_DO	5.72E-01	4.47E-05
Waldren Ale_K	8.31E-01	6.01E-02
Waldren Ale_Mg	9.14E-01	3.86E-01
Waldren Ale_Na	8.92E-01	2.44E-01
Waldren Ale_nitrates	9.58E-01	7.74E-01
Waldren Ale_pH	8.93E-01	2.14E-01
Waldren Ale_silic	**8.08E-01**	**2.53E-02**
Waldren Ale_SRP	9.17E-01	3.67E-01
Waldren Ale_sulfates	9.21E-01	4.04E-01
Waldren Ale_TN	9.88E-01	9.92E-01
Waldren Ale_TP	**4.86E-01**	**4.38E-06**
Waldren Ale_TP	**4.80E-01**	**3.67E-06**
Waldren Ale_turb	**4.67E-01**	**2.65E-06**
Waldren Bla_alka	**7.31E-01**	**1.28E-02**
Waldren Bla_Ca	**7.09E-01**	**7.60E-03**
Waldren Bla_chloride	8.77E-01	2.54E-01
Waldren Bla_chloro	8.80E-01	2.71E-01
Waldren Bla_colour	**7.91E-01**	**4.83E-02**
Waldren Bla_DO	8.84E-01	2.90E-01
Waldren Bla_K	**7.64E-01**	**2.75E-02**
Waldren Bla_Mg	8.58E-01	1.82E-01
Waldren Bla_Na	9.54E-01	7.73E-01
Waldren Bla_nitrates	**6.54E-01**	**1.93E-03**
Waldren Bla_pH	9.38E-01	6.39E-01
Waldren Bla_silic	8.98E-01	3.62E-01
Waldren Bla_SRP	9.19E-01	4.99E-01
Waldren Bla_sulfates	8.75E-01	2.49E-01
Waldren Bla_TN	9.14E-01	4.63E-01
Waldren Bla_TP...142	9.42E-01	6.72E-01
Waldren Bla_TP...156	8.66E-01	2.12E-01
Waldren Bla_turb	8.13E-01	7.73E-02
Waldren Cara_alka	8.56E-01	1.09E-01
Waldren Cara_Ca	9.48E-01	7.13E-01
Waldren Cara_chloride	9.29E-01	5.11E-01
Waldren Cara_chloro	**7.55E-01**	**9.25E-03**
Waldren Cara_colour	9.56E-01	7.82E-01
Waldren Cara_DO	8.99E-01	2.83E-01
Waldren Cara_K	8.51E-01	1.25E-01
Waldren Cara_Mg	9.64E-01	8.54E-01
Waldren Cara_Na	8.94E-01	2.98E-01
Waldren Cara_nitrates	9.61E-01	8.23E-01
Waldren Cara_pH	8.98E-01	2.78E-01
Waldren Cara_silic	8.43E-01	8.09E-02
Waldren Cara_SRP	**7.98E-01**	**2.70E-02**
Waldren Cara_sulfates	8.78E-01	1.79E-01
Waldren Cara_TN	9.23E-01	4.58E-01
Waldren Cara_TP...143	8.97E-01	2.69E-01
Waldren Cara_TP...157	**4.18E-01**	**1.05E-06**
Waldren Cara_turb	9.74E-01	9.30E-01
Waldren Cool_alka	8.76E-01	1.41E-01
Waldren Cool_Ca	9.23E-01	4.58E-01
Waldren Cool_chloride	9.10E-01	3.18E-01

Waldren Cool_chloro	8.80E-01	1.57E-01
Waldren Cool_colour	9.56E-01	7.70E-01
Waldren Cool_DO	8.63E-01	1.03E-01
Waldren Cool_K	9.14E-01	3.82E-01
Waldren Cool_Mg	8.38E-01	7.13E-02
Waldren Cool_Na	9.39E-01	6.00E-01
Waldren Cool_nitrat	9.69E-01	8.90E-01
Waldren Cool_silic	9.15E-01	3.52E-01
Waldren Cool_SRP	**0.72636979**	**0.00288101**
Waldren Cool_sulfates	**0.65896909**	**4.70E-04**
Waldren Cool_TN	0.91142108	0.32594785
Waldren Cool_TP	8.85E-01	1.78E-01
Waldren Cool_TP	9.11E-01	3.26E-01
Waldren Cool_turb	**6.41E-01**	**2.87E-04**
Waldren Coy_alka	9.61E-01	8.17E-01
Waldren Coy_Ca	8.88E-01	2.63E-01
Waldren Coy_chloride	9.20E-01	4.30E-01
Waldren Coy_chloro	8.58E-01	1.14E-01
Waldren Coy_colour	8.68E-01	1.77E-01
Waldren Coy_DO	9.11E-01	3.60E-01
Waldren Coy_K	9.05E-01	3.61E-01
Waldren Coy_Mg	9.29E-01	5.43E-01
Waldren Coy_Na	8.31E-01	8.10E-02
Waldren Coy_nitrates	8.54E-01	1.04E-01
Waldren Coy_pH	**8.12E-01**	**3.89E-02**
Waldren Coy_silic	9.30E-01	5.15E-01
Waldren Coy_SRP	9.44E-01	6.54E-01
Waldren Coy_sulfates	**7.90E-01**	**2.25E-02**
Waldren Coy_TN	8.94E-01	2.53E-01
Waldren Coy_TP	8.86E-01	2.15E-01
Waldren Coy_TP	9.17E-01	4.06E-01
Waldren Coy_turb	8.38E-01	7.17E-02
Waldren Gea_alka	**7.99E-01**	**2.01E-02**
Waldren Gea_Ca	9.38E-01	5.87E-01
Waldren Gea_chloride	**7.40E-01**	**4.10E-03**
Waldren Gea_chloro	9.43E-01	6.17E-01
Waldren Gea_colour	9.24E-01	4.66E-01
Waldren Gea_DO	**8.26E-01**	**4.07E-02**
Waldren Gea_K	8.34E-01	6.51E-02
Waldren Gea_Mg	8.79E-01	1.84E-01
Waldren Gea_Na	9.57E-01	7.78E-01
Waldren Gea_nitrates	8.75E-01	1.40E-01
Waldren Gea_pH	9.67E-01	8.71E-01
Waldren Gea_silic	9.73E-01	9.18E-01
Waldren Gea_SRP	**6.17E-01**	**1.53E-04**
Waldren Gea_sulfates	**7.13E-01**	**2.02E-03**
Waldren Gea_TN	9.42E-01	6.07E-01
Waldren Gea_TP	8.44E-01	6.48E-02
Waldren Gea_TP	**3.90E-01**	**3.22E-07**
Waldren Gea_turb	**7.12E-01**	**1.95E-03**
Waldren Ske_alka	9.78E-01	9.49E-01
Waldren Ske_Ca	8.96E-01	3.48E-01

Waldren Ske_chloride	8.25E-01	7.10E-02
Waldren Ske_chloro	9.05E-01	3.62E-01
Waldren Ske_colour	7.60E-01	2.51E-02
Waldren Ske_DO	**7.71E-01**	**2.11E-02**
Waldren Ske_K	9.26E-01	5.52E-01
Waldren Ske_Mg	8.91E-01	3.21E-01
Waldren Ske_Na	8.90E-01	3.20E-01
Waldren Ske_nitrates	**8.08E-01**	**4.96E-02**
Waldren Ske_pH	8.77E-01	2.15E-01
Waldren Ske_silic	**7.22E-01**	**6.36E-03**
Waldren Ske_SRP	8.06E-01	4.65E-02
Waldren Ske_sulfates	9.48E-01	7.08E-01
Waldren Ske_TN	**8.03E-01**	**4.36E-02**
Waldren Ske_TP...147	**5.23E-01**	**3.24E-05**
Waldren Ske_TP...161	**5.57E-01**	**8.28E-05**
Waldren Ske_turb	9.25E-01	5.10E-01

Table F.6*. T-tests comparing the water data surveyed in 2018 (once off) with the monthly water data from 2018-2019 to test whether a sample taken near the highest flooding level is representative of the turlough water chemistry. In bold, parameters showing significant differences (α =0.05).*

parameter	t_test_statistic	t_test_parameter	pvalue	Conf_int_low	Conf_int_high	stderr
Ale_pH	-1.95E+00	1.00E+01	8.00E-02	7.58E+00	8.36E+00	1.74E-01
Cara_pH	**-3.00E+00**	**1.10E+01**	**1.21E-02**	**7.51E+00**	**8.10E+00**	**1.34E-01**
Cool_pH	**-6.89E+00**	**1.10E+01**	**2.63E-05**	**7.24E+00**	**7.79E+00**	**1.24E-01**
Gea_pH	**-6.10E+00**	**1.10E+01**	**7.76E-05**	**7.62E+00**	**8.12E+00**	**1.13E-01**
Bla_colour	2.36E+00	7.00E+00	5.04E-02	7.29E+01	1.34E+02	1.30E+01
Cool_colour	9.50E-01	1.10E+01	3.62E-01	9.44E+00	3.96E+01	6.84E+00
Coy_colour	**4.93E+00**	**1.10E+01**	**4.50E-04**	**5.05E+01**	**8.67E+01**	**8.23E+00**
Ske_colour	**3.18E+00**	**9.00E+00**	**1.12E-02**	**2.06E+01**	**4.36E+01**	**5.07E+00**
Bla_turb	**-3.37E+00**	**8.00E+00**	**9.75E-03**	**3.23E+00**	**7.59E+00**	**9.45E-01**
Cara_turb	1.35E+00	1.10E+01	2.04E-01	4.78E+00	1.73E+01	2.84E+00
Ale_EC	1.58E+00	9.00E+00	1.49E-01	2.09E+02	3.12E+02	2.28E+01
Bla_EC	**3.35E+00**	**7.00E+00**	**1.22E-02**	**2.53E+02**	**3.26E+02**	**1.54E+01**
Cara_EC	-1.75E+00	1.10E+01	1.08E-01	2.68E+02	3.47E+02	1.80E+01
Coy_EC	9.24E-01	1.10E+01	3.75E-01	2.51E+02	3.17E+02	1.52E+01
Gea_EC	**3.56E+00**	**1.10E+01**	**4.46E-03**	**2.37E+02**	**2.68E+02**	**6.97E+00**
Ske_EC	9.62E-02	8.00E+00	9.26E-01	2.10E+02	3.70E+02	3.47E+01
Bla_alka	1.09E+00	7.00E+00	3.12E-01	1.19E+02	1.91E+02	1.53E+01
Cara_alka	**-5.13E+00**	**1.10E+01**	**3.27E-04**	**1.65E+02**	**2.24E+02**	**1.33E+01**
Cool_alka	-1.54E-02	1.00E+01	9.88E-01	2.06E+02	2.43E+02	8.25E+00
Ske_alka	-1.42E+00	8.00E+00	1.93E-01	1.60E+02	2.16E+02	1.20E+01
Bla_TOC	**5.58E+00**	**7.00E+00**	**8.34E-04**	**2.06E+01**	**3.70E+01**	**3.47E+00**
Coy_TOC	**3.86E+00**	**1.10E+01**	**2.66E-03**	**1.35E+01**	**3.25E+01**	**4.33E+00**
Ske_TOC	**3.01E+00**	**8.00E+00**	**1.67E-02**	**8.96E+00**	**3.73E+01**	**6.15E+00**

Cara_TN	6.46E-01	8.00E+00	5.36E-01	8.28E-01	3.17E+00	5.07E-01
Cool_TN	2.15E+00	8.00E+00	6.34E-02	2.99E-01	1.24E+00	2.03E-01
Coy_TN	**4.02E+00**	**8.00E+00**	**3.86E-03**	**7.29E-01**	**1.70E+00**	**2.10E-01**
Gea_TN	**2.37E+00**	**8.00E+00**	**4.51E-02**	**3.95E-01**	**7.60E-01**	**7.92E-02**
Ale_SRP	**2.89E+00**	**1.10E+01**	**1.46E-02**	**8.81E-03**	**2.04E-02**	**2.62E-03**
Bla_SRP	1.51E+00	7.00E+00	1.74E-01	6.20E-03	2.73E-02	4.46E-03
Ske_SRP	**2.40E+00**	**8.00E+00**	**4.33E-02**	**3.30E-03**	**1.83E-02**	**3.24E-03**
Ale_TP	**2.55E+00**	**1.00E+01**	**2.87E-02**	**1.59E-03**	**2.33E-02**	**4.88E-03**
Bla_TP	8.48E-01	7.00E+00	4.25E-01	-1.14E-02	2.42E-02	7.52E-03
Coy_TP	**3.20E+00**	**1.10E+01**	**8.44E-03**	**1.21E-02**	**6.55E-02**	**1.21E-02**

***Table F.7**. Wilcoxon test (two-sided) comparing the non-normally-distributed groups between 2018 data and the monthly data. In bold, significant differences (α =0.05).*

para_turl	t_test_statistic	t_test_parameter	t_test_pvalue	t_test_confidence_interval_lower	t_test_conf. _inter._upper	t_test_stderr
Bla_pH	**-5.59E+00**	**8.00E+00**	**5.18E-04**	**7.76E+00**	**8.11E+00**	**7.44E-02**
Coy_pH	**-2.23E+00**	**1.10E+01**	**4.75E-02**	**7.82E+00**	**8.41E+00**	**1.34E-01**
Ske_pH	**-3.79E+00**	**8.00E+00**	**5.32E-03**	**7.19E+00**	**8.18E+00**	**2.15E-01**
Ale_colour	**2.34E+00**	**1.00E+01**	**4.15E-02**	**1.06E+01**	**3.59E+01**	**5.68E+00**
Cara_colour	**2.88E+00**	**1.10E+01**	**1.49E-02**	**1.55E+01**	**5.10E+01**	**8.07E+00**
Cool_colour	9.50E-01	1.10E+01	3.62E-01	9.44E+00	3.96E+01	6.84E+00
Gea_colour	1.09E+00	1.10E+01	3.00E-01	6.47E+00	2.44E+01	4.06E+00
Ale_turb	**3.01E+00**	**1.00E+01**	**1.32E-02**	**1.84E+00**	**1.01E+01**	**1.86E+00**
Cara_turb	1.35E+00	1.10E+01	2.04E-01	4.78E+00	1.73E+01	2.84E+00
Cool_turb	1.78E+00	1.10E+01	1.03E-01	1.57E+00	9.20E+00	1.73E+00
Coy_turb	1.12E+00	1.10E+01	2.87E-01	2.03E+00	7.62E+00	1.27E+00
Gea_turb	**2.94E+00**	**1.10E+01**	**1.34E-02**	**9.78E-01**	**6.19E+00**	**1.18E+00**
Ske_turb	**3.08E+00**	**9.00E+00**	**1.31E-02**	**9.55E-01**	**2.91E+00**	**4.32E-01**
Ale_alka	1.75E+00	1.00E+01	1.11E-01	1.56E+02	2.03E+02	1.07E+01
Coy_alka	**2.56E+00**	**1.10E+01**	**2.66E-02**	**1.42E+02**	**1.95E+02**	**1.20E+01**
Gea_alka	**4.95E+00**	**1.10E+01**	**4.35E-04**	**1.36E+02**	**1.50E+02**	**3.20E+00**
Ale_TOC	2.07E+00	1.10E+01	6.31E-02	5.61E+00	2.55E+01	4.51E+00
Cool_TOC	**3.13E+00**	**1.10E+01**	**9.52E-03**	**1.05E+01**	**3.91E+01**	**6.49E+00**
Gea_TOC	**3.13E+00**	**1.10E+01**	**9.66E-03**	**5.96E+00**	**2.34E+01**	**3.96E+00**
Ale_TN	1.10E+00	8.00E+00	3.02E-01	1.53E-01	2.21E+00	4.46E-01
Cara_TN	6.46E-01	8.00E+00	5.36E-01	8.28E-01	3.17E+00	5.07E-01
Ske_TN	1.94E+00	5.00E+00	1.10E-01	1.92E-01	1.07E+00	1.71E-01
Cara_SRP	1.88E+00	1.10E+01	8.71E-02	7.20E-03	1.81E-02	2.48E-03

Cool_SRP	**2.92E+00**	**1.10E+01**	**1.40E-02**	**3.47E-03**	**1.25E-02**	**2.06E-03**
Coy_SRP	**2.58E+00**	**1.10E+01**	**2.57E-02**	**8.21E-03**	**4.58E-02**	**8.54E-03**
Gea_SRP	**4.21E+00**	**1.10E+01**	**1.47E-03**	**3.06E-03**	**9.77E-03**	**1.52E-03**
Cara_TP	**-3.25E+00**	**1.10E+01**	**7.79E-03**	**-4.06E-02**	**-7.78E-03**	**7.44E-03**
Cool_TP	**-2.32E+00**	**1.10E+01**	**4.06E-02**	**-2.55E-02**	**-6.67E-04**	**5.64E-03**
Gea_TP	**2.33E+00**	**1.10E+01**	**3.96E-02**	**1.94E-04**	**6.64E-03**	**1.46E-03**
Ske_TP	2.01E+00	8.00E+00	7.89E-02	-3.10E-03	4.58E-02	1.06E-02

Table F.8. *Two-sided t-tests comparing water quality parameters from this thesis and from Waldren et al. (2015). In bold, significant differences (α =0.05).*

para_turl	t_test_statistic	t_test_parameter	t_test_pvalue	Conf_int_low	Conf_int_high	stderr
Ale_pH	-6.84E-01	1.15E+01	5.07E-01	-5.19E-01	2.72E-01	1.80E-01
Cara_pH	-2.41E+00	**1.48E+01**	**2.97E-02**	**-6.64E-01**	**-3.97E-02**	**1.46E-01**
Cool_pH	-4.78E+00	**1.52E+01**	**2.35E-04**	**-9.45E-01**	**-3.63E-01**	**1.37E-01**
Gea_pH	-2.64E+00	**1.19E+01**	**2.19E-02**	**-5.54E-01**	**-5.22E-02**	**1.15E-01**
Bla_colour	1.71E+00	1.16E+01	1.14E-01	-8.80E+00	7.17E+01	1.84E+01
Coy_colour	1.72E-02	9.57E+00	9.87E-01	-3.85E+01	3.91E+01	1.73E+01
Ske_colour	9.33E-01	1.39E+01	3.67E-01	-7.93E+00	2.01E+01	6.54E+00
Bla_turb	2.52E+00	**1.17E+01**	**2.72E-02**	**3.62E-01**	**5.05E+00**	**1.07E+00**
Bla_DO	7.18E+00	**5.00E+00**	**8.18E-04**	**9.44E+00**	**1.19E+01**	**4.72E-01**
Cara_DO	4.19E+00	**7.00E+00**	**4.10E-03**	**9.33E+00**	**1.28E+01**	**7.24E-01**
Cool_DO	1.29E+01	**8.00E+00**	**1.26E-06**	**1.08E+01**	**1.20E+01**	**2.61E-01**
Coy_DO	4.54E+00	**7.00E+00**	**2.67E-03**	**9.27E+00**	**1.35E+01**	**8.84E-01**
Gea_DO	1.22E+01	**8.00E+00**	**1.92E-06**	**1.04E+01**	**1.19E+01**	**3.19E-01**
Ske_DO	1.98E+00	6.00E+00	9.56E-02	7.70E+00	1.19E+01	8.57E-01
Bla_alka	-4.24E-01	8.90E+00	6.81E-01	-7.62E+01	5.22E+01	2.83E+01
Cara_alka	-1.33E+00	1.80E+01	2.01E-01	-5.83E+01	1.32E+01	1.70E+01
Ske_alka	-6.27E-01	1.40E+01	5.41E-01	-4.34E+01	2.38E+01	1.57E+01
Bla_TN	-2.05E+00	6.79E+00	8.04E-02	-9.98E-01	7.34E-02	2.25E-01
Cool_TN	-1.67E+00	1.58E+01	1.15E-01	-1.15E+00	1.38E-01	3.03E-01
Coy_TN	-9.84E-01	1.48E+01	3.41E-01	-8.49E-01	3.13E-01	2.72E-01
Gea_TN	-2.28E-01	1.52E+01	8.23E-01	-2.38E-01	1.92E-01	1.01E-01
Bla_chlor.	-4.37E+00	**6.91E+00**	**3.39E-03**	**-1.23E+01**	**-3.63E+00**	**1.82E+00**
Cara_chlor.	5.32E-01	5.75E+00	6.15E-01	-8.08E+00	1.25E+01	4.16E+00
Cool_chlor.	-1.25E+00	6.06E+00	2.59E-01	-2.47E+00	8.02E-01	6.70E-01

Coy_chlor.	-8.84E-01	7.53E+00	4.04E-01	-9.46E+00	4.26E+00	2.94E+00
Gea_chlor.	**-2.47E+00**	**1.27E+01**	**2.84E-02**	**-1.14E+01**	**-7.55E-01**	**2.47E+00**
Ske_chlor.	-2.49E+00	3.27E+00	8.15E-02	-1.11E+01	1.10E+00	2.00E+00
Ale_sulph.	1.36E+00	4.05E+00	2.45E-01	-2.02E+00	5.92E+00	1.44E+00
Bla_sulph.	**3.63E+00**	**4.28E+00**	**1.97E-02**	**6.64E-01**	**4.54E+00**	**7.17E-01**
Cara_sulph.	6.74E-01	6.50E+00	5.24E-01	-8.29E-01	1.48E+00	4.80E-01
Gea_sulph.	**3.42E+00**	**5.93E+00**	**1.43E-02**	**1.85E-01**	**1.12E+00**	**1.91E-01**
Ske_sulfates	1.17E+00	3.19E+00	3.22E-01	-1.37E+00	3.04E+00	7.16E-01
Ale_nitrates	8.48E-01	4.09E+00	4.43E-01	-2.21E+00	4.17E+00	1.16E+00
Bla_nitrates	1.69E+00	6.69E+00	1.38E-01	-1.64E-01	9.54E-01	2.34E-01
Cool_nitrates	6.16E-01	6.12E+00	5.60E-01	-1.12E+00	1.88E+00	6.18E-01
Coy_nitrates	3.09E-01	6.13E+00	7.67E-01	-1.03E+00	1.33E+00	4.85E-01
Gea_nitrates	9.87E-01	5.32E+00	3.66E-01	-3.93E-01	8.98E-01	2.56E-01
Ske_nitrates	-1.26E+00	6.04E+00	2.56E-01	-9.10E-01	2.92E-01	2.46E-01
Ale_chloro	-4.70E-01	8.65E+00	6.50E-01	-8.67E+01	5.70E+01	3.16E+01
Coy_chloro	1.98E+00	1.11E+01	7.33E-02	-7.75E+00	1.47E+02	3.52E+01
Ale_SRP	9.12E-01	1.77E+01	3.74E-01	-4.68E-03	1.18E-02	3.93E-03
Bla_SRP	-1.82E+00	1.20E+01	9.41E-02	-2.36E-02	2.14E-03	5.91E-03
Ske_SRP	1.24E+00	1.35E+01	2.36E-01	-3.62E-03	1.35E-02	3.97E-03
Ale_TP	-1.48E+00	1.82E+01	1.57E-01	-9.25E-02	1.61E-02	2.59E-02
Bla_TP	-1.97E+00	1.17E+01	7.33E-02	-3.61E-02	1.89E-03	8.70E-03
Coy_TP	-2.78E-01	2.00E+01	7.84E-01	-3.44E-02	2.63E-02	1.46E-02

Table F.9. *Wilcoxon tests comparing water quality parameters from this thesis and from Waldren et al. (2015) for non-normally-distributed groups In bold, significant differences (α =0.05).*parameter.

parameter	wilc_test_statistic	wilc_test_pvalue	parameter	wilc_test_statistic	wilc_test_pvalue
Bla_pH	2.15E+01	5.55E-01	Cool_TN	2.50E+01	1.90E-01
Coy_pH	5.70E+01	5.11E-01	Ske_TN	1.60E+01	5.34E-01
Ske_pH	2.80E+01	7.50E-01	Ale_chlorides	1.30E+01	2.40E-01
Ale_colour	5.90E+01	2.29E-01	Cool_sulfates	3.50E+01	3.88E-01
Cara_colour	4.70E+01	7.01E-01	**Coy_sulfates**	**4.20E+01**	**2.00E-02**
Cool_colour	3.60E+01	3.73E-01	Cara_nitrates	1.35E+01	1.96E-01
Gea_colour	6.05E+01	3.53E-01	Ale_chloro	6.60E+01	2.30E-01
Ale_turb	5.90E+01	5.03E-01	**Bla_chloro**	**4.40E+01**	**1.17E-02**
Cara_turb	**8.50E+01**	**4.85E-03**	**Cara_chloro**	**8.70E+01**	**5.29E-05**
Cool_turb	5.60E+01	9.17E-01	Cool_chloro	7.90E+01	8.15E-02
Coy_turb	5.40E+01	6.78E-01	**Coy_chloro**	**8.40E+01**	**4.10E-03**
Gea_turb	**9.40E+01**	**4.98E-03**	**Gea_chloro**	**1.03E+02**	**6.44E-04**
Ske_turb	3.35E+01	9.22E-01	Ske_chloro	3.70E+01	6.06E-01
Ale_DO	**4.20E+01**	**2.43E-02**	**Cara_SRP**	**9.35E+01**	**4.39E-04**
Ale_alka	6.80E+01	1.71E-01	Cool_SRP	7.80E+01	9.28E-02
Cool_alka	5.70E+01	6.03E-01	Coy_SRP	4.40E+01	7.87E-01
Coy_alka	7.00E+01	9.79E-02	**Cara_TP**	**1.75E+02**	**2.54E-04**
Gea_alka	8.20E+01	5.06E-02	**Cool_TP**	**5.40E+01**	**2.31E-02**
Ale_TN	2.00E+01	7.72E-02	**Gea_TP**	**1.89E+02**	**5.50E-04**
Cara_TN	2.90E+01	5.31E-01	Ske_TP	4.70E+01	3.27E-01
Cool_TN	2.50E+01	1.90E-01			