LEABHARLANN CHOLÁISTE NA TRÍONÓIDE, BAILE ÁTHA CLIATH | TRINITY COLLEGE LIBRARY DUBLIN
Ollscoil Átha Cliath | The University of Dublin

Terms and Conditions of Use of Digitised Theses from Trinity College Library Dublin

Copyright statement

All material supplied by Trinity College Library is protected by copyright (under the Copyright and Related Rights Act, 2000 as amended) and other relevant Intellectual Property Rights. By accessing and using a Digitised Thesis from Trinity College Library you acknowledge that all Intellectual Property Rights in any Works supplied are the sole and exclusive property of the copyright and/or other IPR holder. Specific copyright holders may not be explicitly identified. Use of materials from other sources within a thesis should not be construed as a claim over them.

A non-exclusive, non-transferable licence is hereby granted to those using or reproducing, in whole or in part, the material for valid purposes, providing the copyright owners are acknowledged using the normal conventions. Where specific permission to use material is required, this is identified and such permission must be sought from the copyright holder or agency cited.

Liability statement

By using a Digitised Thesis, I accept that Trinity College Dublin bears no legal responsibility for the accuracy, legality or comprehensiveness of materials contained within the thesis, and that Trinity College Dublin accepts no liability for indirect, consequential, or incidental, damages or losses arising from use of the thesis for whatever reason. Information located in a thesis may be subject to specific use constraints, details of which may not be explicitly described. It is the responsibility of potential and actual users to be aware of such constraints and to abide by them. By making use of material from a digitised thesis, you accept these copyright and disclaimer provisions. Where it is brought to the attention of Trinity College Library that there may be a breach of copyright or other restraint, it is the policy to withdraw or take down access to a thesis while the issue is being resolved.

Access Agreement

By using a Digitised Thesis from Trinity College Library you are bound by the following Terms & Conditions. Please read them carefully.

I have read and I understand the following statement: All material supplied via a Digitised Thesis from Trinity College Library is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of a thesis is not permitted, except that material may be duplicated by you for your research use or for educational purposes in electronic or print form providing the copyright owners are acknowledged using the normal conventions. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

INFLUENCE OF CATCHMENT CHARACTERISTICS ON THE RELATIONSHIP BETWEEN LAND USE AND LAKE WATER QUALITY IN COUNTY CLARE

Volume I of II

By

Alice Wemaëre
BSc. (ENSCL, France), MSc. (ENSCL, France), MSc. (University of Dublin)

Thesis submitted in fulfilment for the degree of Doctor in Philosophy to Trinity College, University of Dublin

2005

Declaration

I hereby declare that this thesis is my own work, except where otherwise stated, and that it has not been previously submitted to this or any other university. I also give my permission to the library to lend or copy this thesis on request.

Alice Wemaëre

Summary

This research aims to identify the impacts of varying land use and physical environments on lake water quality based on an extensive study of sixty-nine catchments in County Clare, Ireland, combined with a more detailed study of a single catchment.

Between March 2000 and October 2001, a comprehensive monitoring of sixty-nine lakes was carried out in County Clare. Data on catchment characteristics (topography, slope, soil characteristics, hydrology, forestry, agricultural land use and human activities) were compiled and spatially analysed using a Geographic Information System (GIS). Two main types of landscape were identified among the catchments. Calcareous catchments, with permeable carboniferous limestone bedrock, were associated with lower elevation and well/moderately-drained soils, such as brown earths, rendzinas and grey-brown podzolics, while acidic catchments had impermeable shale bedrock and poorly drained soils, such as peats and gleys. Calcareous catchments usually had greater drainage areas and were associated with lakes of greater surface areas, volumes and shorelines than acidic catchments. Land use distribution among the catchments reflected the influence of the physical environment, with greater coverage of pasture and broadleaf forests observed in calcareous catchments, while peatlands and coniferous forests were associated with acidic catchments. Each catchment type was associated with a specific range of water chemistry. Higher alkalinity, pH and conductivity were observed among carboniferous limestone catchments. Lakes in calcareous catchments had lower mean colour levels and total dissolved organic carbon (TDOC) concentrations than acidic catchments. Compared with softer lakes, hard-water lakes were usually associated with higher mean concentrations of nitrate (NO_3-N) and higher ratios of mean total nitrogen (TN) to total phosphorus (TP) and mean NO_3-N to TN concentrations, while lower means of TN, TP and chlorophyll-*a* concentrations were observed among acidic lakes. The relationship between mean TP and chlorophyll-*a* concentrations was influenced by the lake colour, with a significant positive correlation ($r_p=0.80$, $p<0.01$, $n=11$) for calcareous lakes, while no significant correlations were found for high-colour lakes (> 50 PtCo) or acidic catchments. A key distinction between acidic and calcareous catchments was that the ratios of mean TP to chlorophyll-*a* and mean TP to maximum chlorophyll-*a* concentrations were significantly greater among calcareous lakes likely to be impacted by groundwater.

No significant difference was observed between annual area-weighted TP loading rates estimated for calcareous and acidic catchments. However, loading rates were significantly greater for the non-peaty catchments. Multiple regression models were derived for all catchments monitored seasonally in 2000-01 (n=30) and by grouping them based on their predominant bedrock (calcareous/acidic), soil drainage (well/moderately/poorly drained) and soil type (peaty/non-peaty) characteristics. For all six models, the predominant factors influencing annual average TP loading rates were the catchment slope (positive coefficient), soil P levels (positive coefficient) and desorption index (negative coefficient). The accuracy of the models was good ($R^2 \geq 0.67$, df=28) and increased when differentiating catchments based on their bedrock and soil characteristics. A map of potential risk of P loadings to surface waters was produced for the whole county based on the linear regression model, using GIS.

Intensive monitoring of stream, lake and soil was carried out in the Lickeen catchment in 2002-03 and provided a detailed study of nutrient loading within the catchment. Located in the northwest of County Clare, Lough Lickeen is a small and shallow lake, with a small lowland catchment, lying on shale bedrock and covered by peat and gley soils. Lough Lickeen is used as the main water supply for the northwest of the county and water abstraction was found to impact on the lake hydrological regime, especially during the summer. Lough Lickeen showed a moderate buffering capacity against acidification. A lowering of pH in run-off waters may result from increasing use of the catchment for conifer plantations.

The modelling approach applied in the Lickeen catchment combined statistical and spatial analyses in a stepwise process in order to improve both accuracy at the sub-catchment and entire catchment-scale. It suggested that soil characteristics and catchment topography were important factors in controlling P losses from soils to surface waters among the sub-catchments. A first step was to derive a linear equation based on the monitoring 2002-03 and sub-catchment characteristics. The linear model ($r_p=0.78$, $p\leq0.01$, $n=31$) predicted that annual average TP loading rates decreased with increasing elevation, mineral soils, high soil P desorption index, while they increased with % mixed grasslands. A second step was to derive specific export coefficients for each land use class in the sub-catchments ($r_p=0.47$, $p\leq0.05$, $n=30$). This approach was further improved by examining the impacts of sub-catchment characteristics, such as soil characteristics, elevation and slope ($r_p=0.75$, $p\leq0.01$, $n=30$). The distance-decay concept (riparian zone) was introduced but did not improve the accuracy of the predictions ($r_p=0.74$, $p\leq0.01$, $n=30$); however, this approach may benefit from further development. The best prediction of annual average TP loading rates for the sub-catchments and the entire catchment of Lough Lickeen ($r_p=0.75$, $p\leq0.01$, $n=30$) was based on mean elevation (negative coefficient), soil P desorption (negative coefficient) and exports from land uses. The model gave relatively good estimates ($r_p=0.79$, $p\leq0.01$, $n=9$) when applied to nine other acidic catchments in County Clare.

The extensive study of lakes in County Clare combined with the catchment-based analysis of the Lickeen catchment improved understanding of the relationship between pressures from catchment activities and impacts on water quality, important for the implementation of the Water Framework Directive (2000/60/EEC) in Ireland.

Acknowledgements

I thank my supervisor, Dr Kenneth Irvine, for his guidance, encouragement and his understanding throughout an eventful research programme.

This research was funded by Clare County Council and Entreprise Ireland. I would like to thank Mary Burke and Claire Cremin, as well as Clare County Council GIS services for all their help and support throughout the project.

Thanks to Jim Penny and Michael Burke (EPA) for their help with the monitoring in Lough Lickeen and Michael McCartaigh (EPA) for providing hydrological data on Lough Lickeen.

Thanks to all those that contributed in the collation of data on County Clare: Clare County Council, The Heritage Council, the Central Statistics Office, Met Eireann, Coillte, National Forestry Services, the Department of Agriculture and Food, the Geological Survey of Ireland and Paul Mills (Compass Informatics).

A special thanks to all of those that took part in the project (sorry if I forgot somebody!):
Thanks to Elvira, Ruth, Val, Graham, Anton, Dave, Liam, Andrew, Mieke and Conor for all their help during the sampling,
Thanks to Gary, Mark, Eddy and Dr Norman Allott and Dr Louise Scally for their help in the laboratory,
Thanks to Ian, Gary and Steve for their help with statistics,
A special thanks to Dave for all his help during the sampling, soil analyses and farm surveys.

Thanks to the Department of Geography for letting me use their GIS facilities, Dr K. Rybzuck and especially Tale for all their help with GIS
Thanks to all in the Centre for the Environment and Zoology Department.

I thank Liam and Steve for their patience and support.

Finally, a special thanks to Cormac, Charlotte and Luc, for putting up with an absent or absent-minded mother, who refused to share chocolate muffins, Milkybars and Seven-Up with them.

TABLE OF CONTENTS

VOLUME 1

VOLUME 2

Appendices

List of Abbreviations:

Alk.:	Alkalinity
$CaCO_3$:	Calcium carbonate
Chla:	chlorophyll-*a*
Co.:	County
Cond.:	Conductivity
CSO:	Central statistics office
DED:	District electoral division
DEM:	Digital elevation model
df:	Degrees of freedom
DO_2:	Dissolved oxygen
est.:	estimated
FIPS:	Forestry information parcel system
FR:	Flushing rate
GIS:	Geographic information system
GSI:	Geological survey of Ireland
HFM:	High frequency monitoring
HPG:	High productivity grassland
LFM:	Low frequency monitoring
LPG:	Low productivity grassland
LPIS:	Land parcel information systems
LRA:	Localised risk area
max:	maximum
MFM:	Medium frequency monitoring
MG:	Mixed grassland
min:	minimum
N:	Nitrogen
NFS:	National forestry services
NH_4-N:	Ammonium-nitrogen
NO_3-N:	Nitrate-nitrogen
obs.:	observed
OM:	Organic matter
OSI:	Ordnance survey of Ireland
P:	Phosphorus
PET:	Potential evapotranspiration
r:	Spearman's Rank correlation coefficient
R^2_{NS}:	Nash-Sutcliffe coefficient
resp.:	respectively
r_p:	Pearson's Product-Moment correlation coefficient
RT:	Retention time
SiO_4-Si:	Silicate-silicon
SRP:	Soluble reactive phosphorus
T:	Temperature
TDOC:	Total dissolved organic carbon
TDP:	Total dissolved phosphorus
TN:	Total nitrogen
TP:	Total phosphorus
TTS:	Three-tier sampling
Turb.:	Turbidity
95% CI:	95% confidence interval

List of Figures

VOLUME 1:

VOLUME 2:

List of Tables

VOLUME 1:

VOLUME 2:

CHAPTER 1: GENERAL INTRODUCTION

The abundant supply of fresh water constitutes an important resource for Ireland, in terms of economy and amenity. Tourism, in particular, relies on an image of Ireland as an unspoilt and natural location, offering some of the best angling conditions in Europe. With an estimated 6000 lakes with surface areas greater than one hectare (EPA, 2004), Ireland has one of the largest number of lakes in Europe, with the vast majority of them located in the midland, western and northwestern parts of the country.

I-1 Trends in lake water quality

Over the past 25 years, increasing concentrations of nutrients, especially phosphorus, have been recorded in rivers and streams entering lakes in Ireland (EPA, 2004; Lucey *et al*, 1999). In Ireland, long-term (since 1971) and recent (since 1994) national trends in water ecological quality show a distinct trend of continually increasing slight and moderate pollution and a recent reversal of the trend of decreasing serious pollution, which had been gradually reducing over the last 15 years (Lucey *et al*, 1999). The upward trend in the extent of slight and moderate pollution is attributed mainly to eutrophication by organic and artificial fertilisers and to a lesser extent by point source discharges. Based on national lake survey data collected in 1998-2000 (EPA, 2004), the status of lakes, in terms of water quality, is better than that observed for rivers and groundwater. 85% of the lakes surveyed showed satisfactory conditions, but eutrophication was still reported in many of the larger lakes. Eutrophication or nutrient enrichment is the principal threat to the water quality of Irish lakes. The role of nutrients in the eutrophication process of surface waters has been a matter of concern for many years. Considerable attention has been focused on the sources of nitrogen and phosphorus, because algal growths in lakes have usually been attributed to excessive inputs of one or both of these nutrients (Clesceri *et al*, 1986; Heathwaite *et al*, 1996; Lucey *et al*, 1999).

Acidification of surface freshwaters, especially lakes, has been widely reported in Europe over the last 30 years and is mainly attributed to the deposition of atmospheric pollutants (compounds of nitrogen and sulphur). While acidification of surface waters is not a widespread threat to water quality in Ireland, increased concentrations of acidic substances were recorded in the run-off waters from acid-sensitive catchments comprising coniferous plantations (Bowman, 1986, 1991; Kelly-Quinn *et al*, 1997). In Ireland, surface water acidification is usually associated with slowly weathering bedrock formations (shales, granite, gneiss and sandstones) and has an adverse impact on the water biology, which, in extreme cases, leads to elimination of fish stocks.

I-2 Eutrophication process

Eutrophication results in excessive open water production of planktonic forms of algae and Cyanobacteria, and in shallower areas, rooted plants and often of macrophytes and algae on and near shorelines adjacent to enriched inputs (Figure 1.1).

Figure 1.1: Algal mats observed in Lough Inchiquin (Co. Clare) in July 2000.

In freshwater, phosphate concentrations and to a lesser extent nitrogen compounds are of prime importance as it is the supply of these nutrients which regulates algal, Cyanobacterial and other aquatic plant growth. In extreme conditions, such as hypertrophic lakes, plant growth can be limited by other factors such as poor light penetration, silica exhaustion and trace element availability (Cole, 1975; Wetzel & Lickens, 1991; Flanagan, 1992; Lucey *et al*, 1999).

Nutrient-induced production of aquatic plants in freshwater has several detrimental consequences, such as algal mats, decaying algal clumps, odours and discolouration of the water. Dead macrophytes and phytoplankton settling to the bottom of lakes stimulate microbial breakdown processes that require oxygen, eventually leading to oxygen depletion. This can result, in extreme situations, in the death of desirable fish species (Lucey *et al*, 1999; Cole, 1975). Eutrophication interferes with the species composition and abundance of the lake fauna and flora and also has adverse impacts on lake use, such as water abstraction, salmon and trout fisheries and recreational and aesthetic uses, requiring high standard of water quality.

I-3 Phosphorus in lakes

Phosphorus (P) plays a major role in biological metabolism, as it is an important component of nucleotides. Nucleotides, themselves, form the essential polymers of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). Transfer of phosphates, particularly from adenosine diphosphate (ADP) and adenosine triphosphate (ATP), is also essential in energy transduction and metabolism. In comparison with other macronutrients required by biota, phosphorus is of low abundance and commonly the first element to limit biological production (Cole, 1975; Wetzel & Lickens, 1991).

Phosphorus in freshwater exists in either a particulate phase or a dissolved phase. Particulate matter includes living and dead plankton, precipitates of phosphorus, phosphorus adsorbed to particulates, and amorphous phosphorus. The dissolved phase includes inorganic phosphorus (usually in the soluble orthophosphate form), organic phosphorus excreted by organisms and macromolecular colloidal phosphorus. Orthophosphate (PO_4^{3-}) is the only bio-available form of soluble inorganic phosphorus. Phosphate is extremely reactive and interacts with many cations, such as iron and calcium, to form relatively insoluble compounds. Availability of phosphate can also be reduced by adsorption to inorganic colloids and particulate compounds, such as clays, carbonates and hydroxides. A large proportion of phosphorus in freshwaters is bound in organic phosphates and cellular constituents of both living and dead organisms, and into organic colloids (Lucey *et al*, 1999; Cole, 1975; Wetzel & Lickens, 1991; Daly, 2000).

Lake and reservoir sediments serve as phosphorus sinks; phosphorus-containing particles settle to the substrate and are rapidly covered by sediment. Continuous accumulation of sediment will leave some phosphorus too deep within the substrate to be reintroduced to the water column, permanently removing some phosphorus from bio-circulation (Cole, 1975; Daly, 2000). A portion of the phosphorus in the substrate may be reintroduced to the water column. Phosphorus stored in the uppermost layers of the bottom sediments of lakes and reservoirs is subject to bioturbation by benthic invertebrates and chemical transformations by water chemistry changes. The reducing conditions of hypolimnion often experienced during the summer months may stimulate the release of phosphorus from the benthos. Recycling of phosphorus often stimulates blooms of phytoplankton. Because of this phenomenon, a reduction in phosphorus loading may not be effective in reducing algal blooms for a number of years (Lucey *et al*, 1999; Cole, 1975; Wetzel & Lickens, 1991; Daly, 2000).

I-4 Legislation relating to water quality

The degree of enrichment of lakes is usually assessed by measurements of three key parameters: directly by determination of total phosphorus concentrations or indirectly by measuring chlorophyll-*a* concentrations or water transparency (Secchi disc). Based on the annual mean values of these parameters, a classification scheme for lakes into trophic status was described by the OECD (1982). As lake sampling in Ireland is usually infrequent and limited to the summer and autumnal period, a modified version of the OECD (1982) scheme (Lucey *et al*, 1999), based on maximum chlorophyll-*a* concentrations, was incorporated in the Local Government Regulations (DELG, 1998), which address the problem of water eutrophication, with an emphasis on phosphorus levels. The Phosphorus Regulations (DELG, 1998) require that water quality be maintained or improved by reference to the baseline trophic status assigned by the Environmental Protection Agency (EPA) in the 1995-97 review period or at the first occasion thereafter. Water quality targets set in the Regulations must be met by 2007 at the latest for waters surveyed in 1995-97 by the EPA and within a maximum of ten years for waters surveyed first after 1997. Local authorities were required to submit an Implementation Report to the EPA by the 31st of July 2002.

The EU Nitrate Directive (91/492/EEC) requires specific measures to protect surface waters and groundwater from nitrate contamination arising from agricultural activities. National regulations are due to be drafted in 2004 to apply this Directive. However, in most Irish rivers and lakes, it appears more important to control phosphorus than nitrogen in order to reduce the eutrophication of surface waters (EPA, 2004).

As part of a substantial restructuring of EU water policy and legislation, a Directive establishing a new framework for Community action in the field of water policy (2000/60/EC) came into force on the 22nd of December 2000. The Water Framework Directive (2000/60/EC) rationalises and updates existing water legislations and provides for water management on the basis of River Basin Districts (RBD).

The primary environmental quality objective in the Water Framework Directive is to achieve good surface, estuarine and groundwater quality and achieve compliance with any standards and objectives relating to Protected Areas. The status of a surface water body will be determined by both its ecological quality and chemical condition. Ecological status is an expression of the quality of the structure and function of an aquatic ecosystem. Ecological status is classified as high, good, moderate or poor, and encompasses biological, hydromorphological, chemical and physico-chemical elements in this classification. The classification of good ecological status for surface waters refers to unimpacted or slightly impacted waters where species composition and abundance are not different or slightly different from pristine conditions. Chemical status is related to the concentration of pollutants in that water body, relative to quality limit values and quality objectives established in the Phosphorus Regulations (DELG, 1998). The Water Framework Directive requires that ecological quality of lakes be set against baseline standards of "undisturbed conditions". For each surface water body type, type-specific hydromorphological and physico-chemical conditions should be established representing the values for that surface water body at high ecological status (or maximum ecological potential for heavily modified or artificial water bodies).

The Water Framework Directive requires consideration of lakes in terms of catchment usage, to estimate and identify potential pressures on the ecological quality of the water bodies, such as significant point and diffuse source pollution from urban, industrial, agricultural and other installations and activities; significant anthropogenic impacts on the status of surface waters; land use patterns and main urban, industrial and agricultural areas and where relevant, fisheries and forestry. Article 5 of the Water Framework Directive refers to the "characteristics of the river basin district, review of the environmental impact of human activity and economic analysis of water use" (CEC, 2000).

In December 2003, the Directive was transposed into national law: European Communities (Water Policy) Regulations, 2003 (SI No. 722) (DELG, 2003), providing for:

- the protection of the status of all waters and the achievement of at least "good" status by December 2015,
- the establishment of RBDs, as the administrative areas for implementation of the Directive,
- the coordination of actions by all relevant public authorities for water quality management in an RBD,
- the characterisation and establishment of environmental objectives of each RBD and
- the development and adoption of a river basin management plan in each RBD.

The regulations (DELG, 2003) assign responsibilities to the EPA, local authorities and other public authorities for implementation of the Water Framework Directive (2000/60/EC).

I-5 Nutrient export modelling

Several studies have shown that catchment geology, land uses (agriculture, crops, livestock), and human activity impact on N and P loadings into surface waters, often resulting in the degradation of the ecological quality of the lakes (Johnes, 1996; Johnes and Heathwaite, 1997; Allott *et al*, 1998). According to Heathwaite and Johnes (1996) increased P loading is most strongly correlated with an increase in human population density within catchments and in particular to point-source discharge of P-rich effluent to lake water. However, modelling studies and field based manipulation experiments have also demonstrated clearly the importance of non-point source P loading in lakes from their catchments as a key factor in trends of increasing P concentration, particularly in intensive agricultural regions of Europe (Heathwaite *et al*, 1996).

There is a need to evaluate possible control strategies for water pollution at a realistic scale for catchments (Johnes, 1996). To address the need for such information, considerable effort has been made to develop models and decision support tools which can simulate the effects of non-point source pollution problems within catchments and to evaluate the effectiveness of changes in management practices (Daly *et al*, 2000). However, the use of many of these tools has been limited because of the time, expertise and cost in acquiring suitable data for the models and interpreting model results (Engel *et al*, 1993). An alternative approach to the long-term and continuous measurements of hydrology and nutrient transport is to estimate nutrient transfer through a more generalised knowledge of a suite of factors including catchment geology, soil, topography and land-uses.

I-6 Research objectives

The research contained in this thesis aims to establish a protocol for monitoring lake ecological quality through risk assessment based on catchment characteristics (physical, hydrological, land uses and human activities), as required by the Water Framework Directive (2000/60/EC).

The main objectives of the research are to:

- Identify the different catchment types based on catchment physical, hydrological and land uses characteristics among the catchments monitored in County Clare in 2000-01,
- Assess the impact of variations in land use types on water quality (in particularly phosphorus) among catchments with similar physical features located in a restricted geographical region,

- Identify empirical relationships between catchment characteristics and in-lake nutrient status, which would prove to be an effective way of predicting phosphorus loading to lakes and reduce further requirements for data collection,
- Investigate the performance of existing nutrient export models,
- Validate the assumption that catchment activities impact on nutrient loadings to the lake,
- Illustrate the use of GIS as a tool for modelling and catchment management by modelling the spatial distribution of areas representing the greatest potential pressure to lake water quality.

I-7 Research methodology

A comprehensive sampling programme of sixty-nine lakes in County Clare was carried out over a two year-period, applying a three tier-sampling frequency. The high number of lakes monitored allowed the coverage of the water quality of about 20% of the lakes of the County, including all the major lakes in Clare in terms of size, amenity and water supply. It also developed a comprehensive database on water chemistry for the county, and assessed the impact of variations in land use types on water quality among catchments located in a fairly restricted geographical region with common physical features. In order to identify the main catchment types among the study lakes and assess the impacts of pressures from catchment activities on the lake water quality, data on physical characteristics (topography, soils, geology), hydrological factors and land use (agricultural, livestock and human activities) were compiled and analysed spatially by using Geographic Information System (GIS).

Nutrient export modelling was applied to a subset of catchments in order to assess the nutrient exports from the catchment based on their physical and anthropogenic characteristics. Different models, especially the ones described by Johnes (1996), based on catchment physical characteristics and land use types and by Jordan *et al* (2000), based on the CORINE land cover types, were applied and validated by comparison with the observed data in the field, allowing the assessment of the validity and limitations of the models. If common export coefficients could be applied across a range of catchments to estimate in-lake concentrations of phosphorus with a high reliability, the need for widespread sampling and chemical analyses in lake monitoring programme would be considerably reduced. Nevertheless, it is worth noting that although this process has been effectively applied within catchments, the extrapolation of P loads in other catchments is more controversial (Johnes *et al*, 1996).

Over the third year (2002-03), Lough Lickeen catchment was monitored intensively (streams, lakes and soil) applying the concept of nutrient exports to smaller sub-catchments. The lake was monitored over the period 2000-2001 and found to be eutrophic, based on the modified OECD (1982) scheme (Lucey *et al*, 1999). This small-scale study aimed to identify and assess pressures in terms of nutrient loadings to surface water within a catchment, as required by the Water Framework Directive (CEC, 2000). Dividing the catchment into sub-catchments established relationships between land use (agriculture, forestry and human population) and nutrient loadings within risk areas, taking into account diffuse and point source losses of nutrients.

I-8 Thesis outline

The collation and processing of catchment descriptive variables and the identification of the main catchment types among the studied catchments in County Clare are described in Chapter 2. Chapter 3 deals with the water quality status of the lakes monitored in 2000-01, as well as relationships between water chemistry and physical and hydrological catchment variables. Chapter 4 describes the modelling approach carried out to predict total phosphorus loadings into surface waters, while in Chapter 5, the general assumption that catchment activities impact on water quality is validated by closely studying one catchment, Lough Lickeen. Chapter 6 comprises an overall summary of the methodology and findings, and provides an overall conclusion to the thesis.

CHAPTER 2: CATCHMENT CHARACTERISTICS

II-1 Introduction

A comprehensive monitoring of sixty-nine lakes in County Clare (Ireland) was carried out over a two year-period (2000-01). The high number of lakes monitored allowed the assessment of the water quality of about 20% of the lakes of the county (Kennelly, 1997), including all the major lakes in Clare in terms of size, amenity and water supply. It also provided a comprehensive database on water chemistry for the county and allowed the assessment of different land uses on water quality among catchments located in a fairly restricted geographical region, County Clare, covering an area of 3448 km^2.

Catchment may be defined as the area including a river or lake and its associated drainage basin (Gower, 1980; Wetzel, 2001). Catchment characteristics describe the physical variables (topography, bedrock geology, soil types), hydrological variables (climate, bathymetry, stream network), and land uses (agricultural, forestry, human activities).

Much of what happens in a lake basin depends on the nature and use of the catchments (Johnes *et al*, 1998). The hydrological, chemical and biological characteristics of a water body reflect the climate, geology and vegetation cover of its drainage area (Wetzel, 2001). Several studies have shown that catchment geology, land uses (agriculture, crops, livestock), and human activity impact on the nitrogen (N) and phosphorus (P) loading into surface waters, often resulting in degradation of ecological quality of lakes (Jordan *et al*, 2000; Johnes *et al*, 1996; Johnes and Heathwaite, 1997; Allott *et al*, 1998).

In order to assess the impacts of pressures from catchment activities on the lake water quality, data on physical characteristics (topography, soils, geology), hydrological factors and land uses (agricultural, livestock and human activities) were compiled and analysed spatially by using Geographic Information System (G.I.S.). This assists the spatial modelling of potential pressure to impact lake ecological quality (Eirum, 1998; Goodchild, 1993; Fedra, 1993; Engel *et al*, 1993; Pullar, 2000; Behrendt *et al*, 1996).

This chapter describes the physical and hydrological variables and land uses of the catchments monitored in 2000-2001 in County Clare. It also describes the collation of the different catchment variables and interrelationships between catchment descriptive variables. The chapter aims to identify the different catchment types among the monitored lakes, based on their descriptive variables. Relationships with lake physico-chemical variables will be assessed in Chapter 3. Datasets compiled in this chapter were used in the more detailed study carried out in Lough requirements of the Phosphorus Regulations (DELG, 1998), Clare County Council required some lakes to be included in the study, especially lakes found previously to have impaired water quality, but this did not compromise the overall selection of coverage.

As some catchments constituted sub-catchments of others (Table 2.1), each variable had to be processed on three different layers of catchment boundaries.

Table 2.1: List and location of the catchments included in the research. Lake main catchment systems are also provided and lake location are expressed as Irish national grid reference (Irish NGR) and latitude and longitude.

ID	Name	Main Catchment	Latitude-North	Longitude-West	Irish NGR
1	**Achryane**	Achryane	52°43’38’’	09°12’28"	R184647
2	**Acrow**	Acrow	52°45’48’’	09°11’44’’	R193687
3	**Aillbrak**	Aillbrak	52°53’25’’	09°20’52’’	R093830
4	**Atedaun**	Ballyteige	52°56’34’’	09°02’45’’	R297885
5	**Ballyallia**	Ballyallia	52°52’30’’	08°58’39’’	R342809
6	**Ballybeg**	Ballybeg	52°48’43’’	08°59’32’’	R331739
7	**Ballycar**	Ballycar	52°46’08’’	08°52’06’’	R414690
8	**Ballycullinan**	Ballycullinan	52°55’19’’	09°03’05’’	R293862
9	**Ballydoolavan**	Ballydoolavan	52°42’49’’	09°14’03’’	R166632
10	**Ballyeighter**	Ballyteige	52°57’53’’	08°59’02’’	R339909
11	**Ballyleann**	Ballyleann	52°40’54’’	09°06’33’’	R250595
12	**Ballyteige**	Ballyteige	52°56’46’’	08°58’12’’	R348888
13	**Black** *Kilk*	Black *Kilk*	52°43’01’’	09°36’53’’	Q909641
14	**Black** *Dro*	Black *Dro*	52°55’19’’	08°57’38’’	R354861
15	**Bridget**	Castle	52°51’59’’	08°39’18’’	R559797
16	**Bunny**	Bunny	53°01’03’’	08°55’53’’	R375967
17	**Burke**	Drumcullaun	52°50’41’’	09°08’08’’	R235777
18	**Castle**	Castle	52°46’11’’	08°45’42’’	R486690
19	**Caum**	Drumcullaun	52°52’25’’	09°12’54’’	R182810
20	**Clonlea**	Castle	52°56’55’’	08°43’42’’	R509735
21	**Cloonmackan**	Drumcullaun	52°56’55’’	09°11’57’’	R194893
22	**Cloonsnaghta**	Gortglass	52°40’49’’	09°09’39’’	R215594
23	**Cullaun**	Ballyteige	52°57’43’’	09°01’05’’	R316906
24	**Cullaunyheeda**	Cullaunyheeda	52°49’14’’	08°47’43’’	R464747
25	**Curtins**	Drumcullaun	52°52’39’’	09°11’07’’	R202814
26	**Doolough**	Doolough	52°47’34’’	09°18’17’’	R120721
27	**Doon**	Castle	52°48’42’’	08°40’30’’	R545736
28	**Dromoland**	Dromoland	52°47’05’’	08°54’31’’	R387708
29	**Dromore**	Black *Dro*	52°55’12’’	08°58’21’’	R346859
30	**Drumcullaun**	Drumcullaun	52°53’11’’	09°12’18’’	R189824
31	**Druminure**	Druminure	52°54’11’’	09°10’00’’	R215842
32	**Eanagh**	Eanagh	52°43’15’’	09°05’58’’	R260824
33	**Effernan**	Effernan	52°38’52’’	09°08’59’’	R222558
34	**Farrihy**	Black	52°43’12’’	09°36’05’’	Q918644
35	**Finn**	Finn	52°46’30’’	08°45’05’’	R493696
36	**Garvillaun**	Drumcullaun	52°53’30’’	09°07’03’’	R248829
37	**Gash**	Gash	52°45’28’’	08°54’02’’	R392678
38	**George**	Ballyteige	52°58’10’’	08°58’41’’	R343914

Table 2.1 (continued)

ID	Name	Main Catchment	Latitude-North	Longitude-West	Irish NGR
39	**Girroga**	Girroga	52°51’51’’	08°58’22’’	R345797
40	**Goller**	Goller	53°00’31’’	09°18’03’’	R127961
41	**Gortaganniv**	Gortaganniv	52°49’44’’	09°06’41’’	R251759
42	**Gorteen**	Gorteen	52°42’21’’	08°45’22’’	R489619
43	**Gortglass**	Gortglass	52°40’30’’	09°08’56’’	R223588
44	**Graney**	Graney	52°59’06’’	08°39’46’’	R555929
45	**Inchichronan**	Inchichronan	52°54’55’’	08°54’20’’	R391853
46	**Inchiquin**	Ballyteige	52°57’11’’	09°05’21’’	R268897
47	**Keagh**	Keagh	52°52’24’’	09°20’07’’	R101811
48	**Kilgory**	Castle	52°51’13’’	08°40’59’’	R540783
49	**Killone**	Ballybeg	52°48’10’’	09°00’14’’	R323729
50	**Knockalough**	Knockalough	52°42’50’’	09°16’32’’	R138633
51	**Knockerra**	Knockerra	52°39’35’’	09°23’22’’	R060574
52	**Lickeen**	Lickeen	52°57’49’’	09°13’41’’	R175910
53	**Lisnahan**	Lisnahan	52°41’43’’	09°37’38’’	Q900617
54	**Luirk**	Luirk	53°07’01’’	09°04’26’’	M281079
55	**Luogh**	Luogh	52°59’09’’	09°23’54’’	R061937
56	**Moanmore**	Moanmore	52°41’29’’	09°30’37’’	Q979611
57	**Mooghna**	Mooghna	52°54’06’’	09°16’58’’	R137842
58	**More**	More	52°43’38’’	09°17’54’’	R123648
59	**Morgans**	Drumcullaun	52°53’50’’	09°06’26’’	R255835
60	**Muckanagh**	Ballyteige	52°58’56’’	08°56’12’’	R371928
61	**Muckinish**	Muckinish	53°07’29’’	09°05’21’’	M271088
62	**Namina**	Namina	52°47’02’’	09°13’12’’	R177710
63	**O'Briens** *Big Lough*	O'Briens *Big Lough*	52°53’21’’	08°52’47’’	R408824
64	**O'Grady**	O'Grady	52°54’10’’	08°34’31’’	R613837
65	**Rask**	Rask	53°07’05’’	09°08’07’’	M240081
66	**Rosconnell**	Drumcullaun	52°51’33’’	09°09’19’’	R222793
67	**Rosroe**	Rosroe	52°46’25’’	08°49’26’’	R444695
68	**Rushaun**	Drumcullaun	52°51’28’’	09°06’33’’	R253791
69	**Tullabrack**	Tullabrack	52°40’47’’	09°27’08’’	R018597

When available, photographs of the lakes included in the study are presented in Appendix 1 (Plates 1 to 63) and in the associated CD-Rom (Appendix 1/Plates).

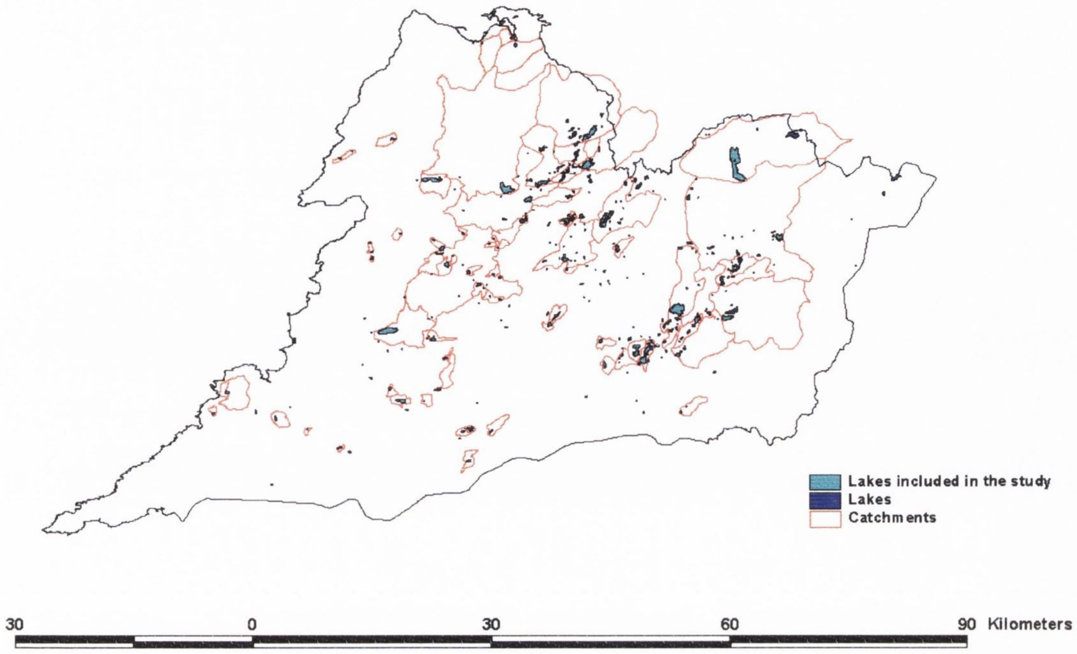

Figure 2.2: Location of the catchments included in the study, showing the geographical distribution of the studied lakes and their catchment boundaries. See Figure 2.5 for high resolution.

II-3 Geographic Information System

G.I.S. is based on the concept of layered analysis of mapped data. By superimposing layers, such as geology, soils and land cover, the key relationships between the different data sets can be analysed to identify the dominant landscape patterns. G.I.S. technology was used for the preparation and the analysis of the different datasets. The work was carried out using *Arc/Info* and *ArcView GIS 3.2* software systems from ESRI Inc, and *MapInfo Professional 4.5*.

The different types of data used were spatial data (geographic data that stores the geometric location of particular features, along with attribute information describing what these features represent), image data (including satellite images, air photographs and other remotely or scanned data), tabular data (any data set) and Info table (text files with fields separated by tabs or commas). The different digital data were obtained under several formats:

- ArcView compatible coverage (.shp, .shx and .dbf files),
- Arc/Info .e00 interchange files that were converted onto a coverage by using *ArcView Import Utility*,
- AutoCAD drawing files (.dwg, .dxf) that were imported into ArcView by loading the CAD Reader Extension and converted into a coverage by using the *Arc/Info DXFARC Utility*,

- MapInfo table files (.tab, .dat) that were exported into MapInfo Interchange files (.mif, .mid) and then converted onto an ArcView compatible format (.shp, .dbf, .shx) by using the *Mif to Shape ArcView Utility*,
- Image and Raster files (.tif) that were converted onto a .bmp format files, registered with *Arc/Info Register command* (converting the image coordinates to real-world coordinates) and then corrected onto an image file geo-referenced for ArcView.

The data were then processed into *ArcView* compatible formats in order to carry out a G.I.S. overlay of multiple map layers. The spatial nature of the datasets held by the G.I.S. allowed spatial and geographical patterns of each dataset to be analysed. Principal procedures performed in the G.I.S. included preparation of catchment and sub-catchment boundaries, area weighting of polygon zonal data, overlay of multiple map layers, conversion of point datasets to zonal patterns using spatial interpolation techniques and spatial aggregation of datasets. Details on catchment features were obtained by using the *Intersection command of the ArcView Geo-processing Wizard* and *Spatial Analyst Extension*. Data that were not available in digital format were added to a map by joining datasets tables with the attributes tables of existing coverages presenting a field in common. Raster grid modelling was carried out with the *Spatial Analyst* extension module of *ArcView* (Heywood *et al*, *1998*; Eirum, 1998; ESRI, 1997; Ormsby and Alvi, 1999).

II-4 Collation of catchment descriptive variables

II-4.1 Physical characteristics

Topography and slope

Hill slopes and floodplains have an influence on the catchment exports of nutrients and other material to lakes. High altitudes are often associated with high precipitation and low temperature (Black, 1996; Goodale *et al*, 1998). Catchments with steep slope tend to have fast runoff, which may increase erosion of soil particulates (Strahler, 1964). Steep slopes tend to be associated with thin stony soils, which are well drained with low organic matter, carbon and nitrogen (Young, 1972). Digital raster data on a MapInfo format were obtained from Clare County Council G.I.S. services based on the Pilot Study on Landscape Characterisation in County Clare carried out by the Heritage Council (2000). Using the *Spatial Analyst* extension of the *Arcview* software, slope and hillshade analyses were carried out.

Catchment boundaries

Catchment boundaries of the Clare lakes were determined based on the topography from the OSI maps 1:50,000 (sheets 51, 52, 57, 58, 63 & 64) and then digitised by using a digitising table and *Arc/Info* software. Using the *Hydromodelling* extension from the *ArcView* software, the boundaries were subsequently refined. Catchment areas, defined as the area within topographic divides including the lake, were estimated by using G.I.S. Drainage areas were calculated as catchment area minus lake area.

The western limestone lowlands of Ireland are an example of karst area where surface water and groundwater are closely interlinked. The existence of an efficient subterranean karst drainage network together with a surface drainage pattern often leads to complex interactions between the two hydrological systems (Coxon and Drew, 1999). This is the case with the River Fergus catchment. The upper reaches of the Fergus River (upstream of Lough Inchiquin) drain both the shale lands to the south of Kilfenora and also, underground, a considerable part of the Burren to the north and northwest of the river (Drew, 1988; Deakin, 2000; Kilroy, 2001; Drew and Daly, 1993). Topographic boundaries for the lakes located in the west of the carboniferous limestone bedrock may, therefore, not concur with groundwater boundaries. The potential influence of the groundwater on the lake water quality is assessed in Chapter 3. Digital coverage of underlying aquifers was provided by Clare County Council G.I.S. services (Heritage Council, 2000). Catchments potentially influenced by groundwater interactions are illustrated by Figure 2.3, showing the distribution of underlying karstified bedrock aquifers in Clare; and Figure 2.4, emphasising the Fergus catchment.

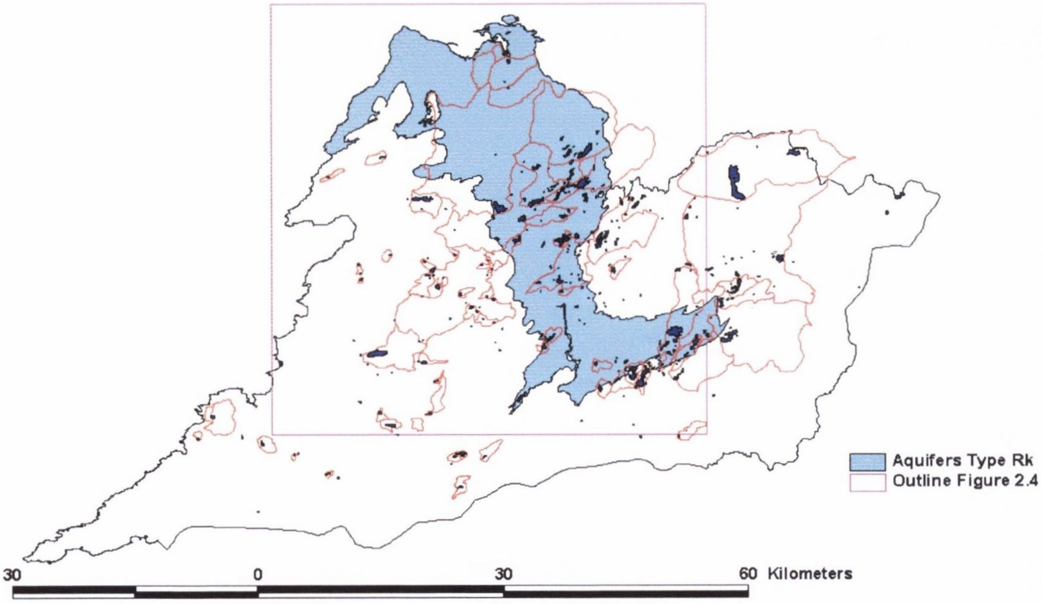

Figure 2.3: Location of karstified bedrock aquifers (Rk) in County Clare. Topographic catchment boundaries of the lakes included in this study and outline of Figure 2.4 are also shown.

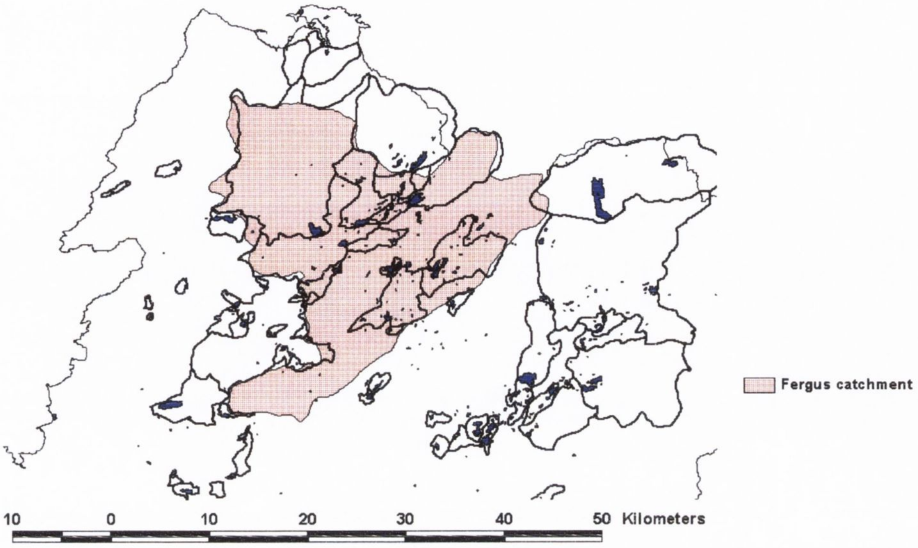

Figure 2.4: Location of the Fergus catchment (Kilroy, 2001)

Bedrock geology

Bedrock types and underlying aquifers determine the influence of groundwater on lake chemistry, nature of the lake sediments and influence of the bedrock on the lake physico-chemistry (buffering capacity, risk of acidification, bedrock permeability). Digital coverage of the bedrock geology in County Clare was obtained from the Geological Survey of Ireland (G.S.I.) in an AutoCAD format. Simplified coverages of the bedrock geology and aquifer mapping were obtained from Clare County Council G.I.S. services, based on Heritage Council (2000). Bedrock geology types found in County Clare were grouped into eight categories (Table 2.2).

Soil types

Variations in nutrient export are linked with soil type and structure. Data on soil type distribution and vulnerability were obtained from the National Soil Survey of Ireland (Finch *et al*, 1971). Digital data on soil distribution and vulnerability were obtained from Clare County Council G.I.S. services (Heritage Council, 2000). In order to assess the influence of the nature of the soil on nutrient loadings into the lake, soil P indices (based on soil P status), as described in Daly (2000), were used. Digital data on Soil Morgan P levels were obtained from Teagasc on a 10 by 10-km grid (Daly *et al*, 2000).

Table 2.2: Bedrock type association (GSI, 1999; Drew and Daly, 1993; Sleeman and Pracht, 1999) relevant to catchments of Co. Clare. Bedrock type and associated unit name are provided. Related bedrock composition groups are also listed.

Bedrock type	Unit name	Bedrock composition
BUaw	Aillwee Member	Carboniferous Limestones
SLay	Aylecotty Member	Carboniferous Limestones
BUbd	Ballard Member	Carboniferous Limestones
BC	Ballycar Formation	Carboniferous Limestones
BA	Ballysteen Formation	Carboniferous Limestones
BU	Burren Formation	Carboniferous Limestones
TUcm	Cregmahon Member	Carboniferous Limestones
BUfn	Fanore Member	Carboniferous Limestones
FL	Finlough Formation	Carboniferous Limestones
LR	Lough Gur Formation	Carboniferous Limestones
BUmc	Maumcaha Member	Carboniferous Limestones
oo	Oolitic limestone	Carboniferous Limestones
SL	Slievenaglasha Formation	Carboniferous Limestones
TU	Tubber Formation	Carboniferous Limestones
VIS	Visean Limestones (undifferentiated)	Carboniferous Limestones
WA	Waulsortian Limestones	Carboniferous Limestones
ch	Chert	Chert
SLtu	Turret Volcanic Member	Igneous Rocks
V	Volcaniclastic Rocks	Igneous Rocks
ORS	Old Red Sandstone (undifferentiated)	Old Red Sandstones
BO	Ballymalone Formation	Ordovician
CCG	Central Clare Group	Shales & Similar rock types
CS	Clare Shale Formation	Shales & Similar rock types
GI	Gull Island Formation	Shales & Similar rock types
RS	Ross Sandstone Formation	Shales & Similar rock types
TS	Tullig Sandstone	Shales & Similar rock types
BT	Ballymartin Formation	Shales/Limestones
LLS	Lower Limestone Shale	Shales/Limestones
mk	Mudbank limestone	Shales/Limestones
BF	Broadford Formation	Silurian Quartzite
CR	Cratloes Formation	Silurian Quartzite
pg	Purple grit	Silurian Quartzite
SB	Slieve Bernagh Formation	Silurian Quartzite
SIL	Silurian Quartzite	Silurian Quartzite

Soil type data were grouped into three groups based on their drainage capacity, as shown in Table 2.3. The soil category "complexes" is associated with variable soil types, referring to transition area between two determined soil groups (Finch *et al*, 1971).

Based on laboratory analyses of eleven major types of grassland soils, Daly (2000) identified four groups of soil with different P desorption classes. Brown earths, podzolics and grey podzolics were associated with high desorption rates (S1), gleys with moderate to high desorption rates (S2), peaty gleys and peaty podzols with low to moderate desorption rates (S3) and finally peats with low desorption rates (S4). Daly (2000) then assigned to each soil P desorption class a weighting factor relative to the lowest soil P desorption values of S4 soils (peats), based on soil P desorption results using the iron-oxide paper strip test.

As described in Daly *et al* (2000), soil P desorption classes (S1 to S4) were attributed to the different soil groups found in Co. Clare and area weighted average soil P desorption (soil P desorption index) was then calculated for each catchment by giving the index value "1.0" to S4-soils, "1.4" to S3-soils and "1.9" to S1 and S2-soils (Daly, 2000; Daly *et al*, 2000). An average value of "1.4" was attributed to the soil category "complexes", as it describes a transitional area between two soil groups.

Table 2.3: Soil type association (Finch *et al*, 1971; Daly, 2000) presenting soil series and associated great soil groups found in Co. Clare. Related P desorption class and drainage capacity are also provided.

Soil Groups	**Soil Series**	**P Desorption Class**	**Drainage**
Brown Earths	Baggotstown	S1	Well/Moderate
Brown Earths	Ballincurra	S1	Well/Moderate
Brown Earths	Ballylanders	S1	Well/Moderate
Brown Earths	Ballynalacken	S1	Well/Moderate
Brown Earths	Derk	S1	Well/Moderate
Brown Earths	Kilfergus	S1	Well/Moderate
Brown Earths	Kinvarra	S1	Well/Moderate
Brown Earths	Kinvarra bouldery phase	S1	Well/Moderate
Brown Earths	Knocknaskeha	S1	Well/Moderate
Brown Earths	Tullig	S1	Well/Moderate
Brown Earths	Waterpark	S1	Well/Moderate
Brown Podzolics	Cooga	S1	Well/Moderate
Brown Podzolics	Doonglara	S1	Well/Moderate
Brown Podzolics	Mountcollins	S1	Well/Moderate
Complexes	Attyquin-Howardstown	n/a	Variable
Complexes	Burren-Ballinacurra	n/a	Variable
Complexes	Mountcollins-Kilrush	n/a	Variable
Complexes	Puckane-Slieveragh	n/a	Variable
Gleys	Abbeyfeale non peaty phase	S2	Imperfect/Poor
Gleys	Abbeyfeale sandy phase	S2	Imperfect/Poor
Gleys	Camoge	S2	Imperfect/Poor
Gleys	Drombanny	S2	Imperfect/Poor
Gleys	Feale	S2	Imperfect/Poor
Gleys	Glenomra	S2	Imperfect/Poor
Gleys	Gortaclareen	S2	Imperfect/Poor
Gleys	Howardstown	S2	Imperfect/Poor
Gleys	Kilrush	S2	Imperfect/Poor
Gleys	Puckane	S2	Imperfect/Poor
Gleys	Puckane alkaline p.m. phase	S2	Imperfect/Poor
Gleys	Puckane peaty phase	S2	Imperfect/Poor
Gleys	Sellernaun	S2	Imperfect/Poor
Gleys	Shannon	S2	Imperfect/Poor

Table 2.3 (continued)

Soil Groups	Soil Series	P Desorption Class	Drainage
Grey Brown Podzolics	Elton	S1	Well/Moderate
Grey Brown Podzolics	Kilfenora	S1	Well/Moderate
Grey Brown Podzolics	Patrickswell	S1	Well/Moderate
Grey Brown Podzolics	Patrickswell bouldery phase	S1	Well/Moderate
Grey Brown Podzolics	Patrickswell lithic phase	S1	Well/Moderate
Lithosols	Slievereagh	S3	Imperfect/Poor
Peats	Allen	S4	Imperfect/Poor
Peats	Allen cutover	S4	Imperfect/Poor
Peats	Aughty	S4	Imperfect/Poor
Peats	Aughty cutover	S4	Imperfect/Poor
Peats	Banagher	S4	Imperfect/Poor
Podzols	Knockaceol	S1	Well/Moderate
Podzols	Knockaceol bouldery phase	S1	Well/Moderate
Podzols	Knockanattin	S1	Well/Moderate
Podzols	Knockanimpaha	S1	Well/Moderate
Podzols	Knockastanna	S1	Well/Moderate
Podzols	Knockastanna peaty phase	S1	Well/Moderate
Podzols	Seefin	S1	Well/Moderate
Regosols	Kilgory	S3	Imperfect/Poor
Regosols	Rathborney	S3	Imperfect/Poor
Regosols	Seafield	S3	Imperfect/Poor
Rendzinas	Burren	S1	Well/Moderate
Rendzinas	Burren deeper phase	S1	Well/Moderate
Rendzinas	Burren extremely rocky phase	S1	Well/Moderate
Rendzinas	Burren rocky phase	S1	Well/Moderate
Rendzinas	Burren very rocky phase	S1	Well/Moderate
Rendzinas	Kilcolgan	S1	Well/Moderate
Rendzinas	Kilcolgan bouldery phase	S1	Well/Moderate

II-4.2 Hydrological variables

The geomorphology of a lake controls the nature of its drainage, the inputs of nutrients to the lake and the volume of influx in relation to flushing-renewal time. These factors affect the distribution of dissolved gases, nutrients and organisms in the lake (Wetzel, 2001; Cole, 1975).

Climate

Temperature, rainfall and wind influence the rate of nutrient loadings to a lake. They also affect the lake mixing regime, temperature and oxygen distribution and stratification (Lickens and Wetzel, 1991; Cole, 1975; Wetzel, 2001).

Net annual rainfall data were calculated based on the contemporary rainfall data (2000 and 2001) recorded throughout County Clare (Met Eireann, 2000 and 2001) minus the evapotranspiration, which is a measure of the total water loss from a basin by transpiration and evaporation (Fetter, 2001). Evapotranspiration was estimated using data from Shannon airport weather station (Met Eireann, 2000 and 2001). Annual past average rainfall data (1961-1990) were also collated from Met Eireann. Met Eireann data were provided as measurements at specific locations in County Clare.

Further processing of such point-based meteorological data was required to derive area-based run-off patterns. This was realised by using a multi-stage process in G.I.S. employing spatial interpolation functions based on a TIN (Triangular Irregular Network) vector data model (Fetter, 2001; Goodale *et al*, 1998; Daly *et al*, 2000). Monthly and annual rainfall data were then estimated for each catchment based on the grid coverage of surface rainfall produced by spatial interpolation using the *Spatial Analyst* extension of *ArcView* software.

Morphometric parameters

Partial digital coverage of the water features (lake and river outlines) was obtained from Clare County Council G.I.S. services (Mary Burke (Clare County Council), Personal communication) and was completed by manual digitising based on the OSI maps (1:50,000). Lake area (A) and shoreline (L) were then estimated for each lake. Shoreline development (D_L), which reflects the potential for greater development of littoral communities in proportion to the volume of the lake (Wetzel, 2001), was calculated from:

$$\mathbf{D_L = L / [2 (\pi A)^{0.5}]} \qquad \textbf{Equation 2.1}$$

Lake to catchment area ratios (expressed as % main lake), indicating the size of a lake relative to its catchment, were calculated. A high value indicates that a lake constitutes a significant part of the catchment. Such lakes are likely to have long residence times and nutrient chemistry influenced by internal processes. The response of in-lake nutrient concentrations to localised point-source pollution or important rainfall events is likely to be balanced by dilution effects (Fetter, 2001; Wetzel, 2001; Schindler, 1971). Upstream lakes can also influence the chemistry of downstream lakes. This can occur by upstream nutrient loss to lake sediments or increase in particulate fractions of some elements (Zhou *et al*, 2000).

Bathymetric parameters

Depth and lake volumes data were collated from previous studies for ten of the lakes included in this study. Bathymetric maps were produced for Loughs Ballycullinan, Black, Cullaun, Dromore and Inchiquin, as part of a survey carried out in 1983 (Allott, 1990). Bathymetric data for Lough Clonlea were extracted from a report issued by Clare County Council (Clare County Council, 1990). Maps for Doolough and Lough Lickeen were available from a study carried out in 1996/97 (Irvine *et al*, 1998) and data for Lough Bunny from a study carried out in 1993 (Ragneborn-Tough, 1993). Data for Lough Graney were collated from a survey carried out in 1996/97 (Irvine *et al*, 2001).

Field bathymetric surveys were carried out on fifteen lakes in October 2001, mainly including lakes that were the most frequently monitored during the study. Lake depth was recorded from an inflatable boat using a portable depth sounder. The position of each sampling site was recorded using a portable GPS providing a positional accuracy of 5-10 m. One depth measurement was taken per lake hectare. Lake area was determined initially using G.I.S. All bathymetric data provided a point coverage of depth measurements.

To facilitate the calculation of lake volume, mathematical interpolation techniques, using raster-modelling with the *Spatial Analyst* extension of *ArcView* provided a continuous estimate of the depth across the lake and subsequently estimates of the lake volume, mean and maximum depth. The continuous surface of depth was reclassified by grouping the grid cells into new classes of depth intervals, resulting in a graduated classification of the depth surface. An estimated depth value was then attributed to each class by rounding the depth values to the nearest number or half number. A statistical analysis of the new surface provided the number of cells and the total lake area for each new class. Volumes related to each class were obtained by multiplying the corresponding estimated depth value by the total class area. Total lake volumes were subsequently obtained by summing all the class volumes. This process could be described as dividing the lake into several columns having all the same base-area of 5 by 5 m ($25m^2$) and having for height the estimated depth attributed in the reclassification process.

Based on the estimates of lake volumes and net annual rainfall across each catchment, lake flushing rate (per year) and retention time (in days) were calculated by:

Flushing Rate = Net Annual Rainfall * Catchment Area / Lake Volume **Equation 2.2**

Lake Retention Time = 365 / Flushing rate **Equation 2.3**

When the lake is used for water supply, abstraction can result in large fluctuations of water depth, which affect natural hydrometrics. This will render less accurate calculations of water retention time of the lake that are based wholly on catchment and rainfall data (Cole, 1975; Irvine *et al*, 1998). Data on water abstraction in County Clare were therefore collated from Clare County Council Environmental Services (Mary Burke (Clare County Council), Personal communication).

II-4.3 Land cover variables

CORINE Land covers

The CORINE land cover database, derived from 1:100,000 scale satellite imagery data, recorded by the Landsat Thematic Mapper Satellite, acquired in 1989 and 1990 (O'Sullivan, 1992; Cruickshank and Tomlinson, 1996), was used to characterise the different catchment land cover types. The CORINE project separated the satellite images into forty-four hierarchical categories by computer-assisted photo-interpretation. Two of the standard categories were sub-divided for Ireland – pasture areas and peat bogs (O'Sullivan, 1992). As the data were more than ten years old, the main changes were expected to be in the forest blocks. For this reason, the CORINE land cover was revised using data from the National Forest Services (FIPS, 1998). The merged coverage between FIPS data and CORINE land cover was obtained from Clare County Council G.I.S. services, based on Heritage Council (2000).

CSO farmland usages

Information on farmland usages was obtained from the Agricultural Census of County Clare (CSO, 2000), on a District Electoral Division (DED) basis. Cattle and sheep densities were also estimated based on cattle and sheep numbers provided on a DED basis by the Agricultural Census (CSO, 2000). The data were imported onto an *ArcView* compatible format by joining the census datasets to the table of attributes of the DED boundaries coverage obtained from the Heritage Council (2000). Overlaying and intersecting the coverages of DEDs and catchment boundaries, data for each catchment were extrapolated by assuming the proportional distribution and density among DEDs.

Other agricultural land use datasets collated

The Land Parcel Information System (LPIS, 2000) of the Department of Agriculture, Food and Rural Development described the present-day limits of fields and categorised their main usage. The LPIS is restricted to farmers claiming area aid and/or participating in the Rural Environment Protection Scheme (REPS) and has been developed in *Microstation*. It provides a comprehensive analysis of field boundary patterns. The LPIS digital data (2000) were obtained from Clare County Council G.I.S. services (Heritage Council, 2000) and by the Department of Agriculture.

Forestry

Forests can have a beneficial effect on surface waters such as reducing temperature fluctuations in streams during summer but may also impact negatively by increasing the acid status of streams in poorly buffered catchments. Forest operations at both establishment and felling phase may give rise to erosion, nutrient pulses and high silt loads to streams (Lucey *et al*, 1999; MCO'Sullivan, 2001).
Digital vector data on forestry cover, type and management practices were obtained from Coillte Teoranta (1999) and the National Forest Services (FIPS, 1998).

II-4.4 Human variables

Factors such as human population density, use of septic tanks, degree of sewage treatment and use of P stripping, can result in point source pollution to lakes (Lucey *et al*, 1999). The distribution of human population in County Clare was obtained from the Human Population Census (CSO, 2002). The data were provided on a DED basis and imported onto an *ArcView* compatible format.

The proliferation of septic tanks in the county was so widespread (Mary Burke (Clare County Council), Personal communication), that most rural housings were associated with the use of a septic tank. For the urban areas, Clare County Council provided a list of the wastewater treatment plants in 1999 and details of their treatment process. The list of industries in County Clare was also obtained from the Shannon Directories (1999). Waste water treatment plant and industry data were mapped by manually digitising their location and joining the associated datasets to the table of attributes of the new themes.

II-4.5 Statistical analyses

In order to identify relationships between the different catchment descriptive variables, Spearman's Rank correlation tables were calculated in *DataDesk 6.0*. Cluster and principal component analyses based on the catchment bedrock geology and soil characteristics were carried out with *Primer 5* software. These were also used to highlight more significant relationships between catchment land uses and ecological variables at a latter stage (Chapter 4).

II-5 Results

II-5.1 Physical catchment variables

All data presented in this section are also provided in the associated CD-Rom (Appendix 1/Summary catchment descriptive variables and Appendix 1/Outline catchment boundaries).

Catchment and drainage areas

Catchment boundaries were derived based on the topography. The catchments included in the research (Table 2.4, Figure 2.5) cover about 53% of the county area. They included eleven catchments with an area less than 100 ha, thirty-one with an area between 100 and 500 ha, eight between 500 and 1,000 ha, thirteen between 1,000 and 10,000 ha and six with an area greater than 10,000 ha.

Table 2.4: Total catchment and drainage areas (km^2) (including upstream catchments) of the lakes included in the study, estimated by G.I.S.

ID	Catchment	Catchment Area (km²)	Drainage Area (km²)
1	Achryane	4.50	4.43
2	Acrow	0.57	0.51
3	Aillbrak	0.75	0.71

Table 2.4 (continued)

ID	Catchment	Catchment Area (km²)	Drainage Area (km²)
4	Atedaun	282.50	282.12
5	Ballyallia	24.73	24.40
6	Ballybeg	4.14	3.94
7	Ballycar	3.67	3.64
8	Ballycullinan	5.80	5.51
9	Ballydoolavan	1.71	1.71
10	Ballyeighter	8.69	8.42
11	Ballyleann	2.97	2.91
12	Ballyteige	290.42	290.28
13	Black *Kilk*	12.39	12.39
14	Black *Dro*	2.13	2.05
15	Bridget	7.03	6.49
16	Bunny	77.50	76.47
17	Burke	2.30	2.19
18	Castle	132.35	132.12
19	Caum	5.19	5.12
20	Clonlea	5.52	5.12
21	Cloonmackan	2.84	2.61
22	Cloonsnaghta	1.23	1.15
23	Cullaun	81.32	80.83
24	Cullaunyheeda	29.43	27.91
25	Curtins	0.63	0.62
26	Doolough	22.75	21.44
27	Doon	99.71	99.12
28	Dromoland	2.39	2.27
29	Dromore	1.67	1.17
30	Drumcullaun	92.14	91.92
31	Druminure	0.68	0.65
32	Eanagh	1.08	1.07
33	Effernan	2.76	2.65
34	Farrihy	10.80	10.67
35	Finn	4.09	3.35
36	Garvillaun	0.70	0.67
37	Gash	2.89	2.70
38	George	5.26	5.25
39	Girroga	1.09	1.05
40	Goller	2.66	2.57
41	Gortaganniv	2.03	2.00
42	Gorteen	3.87	3.84
43	Gortglass	2.10	1.81
44	Graney	111.62	107.93
45	Inchichronan	33.34	32.17
46	Inchiquin	147.14	146.07
47	Keagh	0.32	0.25
48	Kilgory	18.18	17.82
49	Killone	1.28	1.09
50	Knockalough	2.57	2.23
51	Knockerra	0.46	0.39
52	Lickeen	8.67	7.82
53	Lisnahan	0.77	0.71
54	Luirk	15.64	15.53
55	Luogh	1.41	1.36

Table 2.4 (continued)

ID	Catchment	Catchment Area (km²)	Drainage Area (km²)
56	Moanmore	3.35	3.22
57	Mooghna	1.27	1.23
58	More	1.21	1.11
59	Morgans	0.30	0.28
60	Muckanagh	39.35	38.39
61	Muckinish	2.21	2.18
62	Naminna	2.07	1.87
63	O'Briens *Big Lough*	2.80	2.61
64	O'Grady	160.79	160.34
65	Rask	8.40	8.39
66	Rosconnell	1.29	1.20
67	Rosroe	3.89	2.81
68	Rushaun	1.23	1.19
69	Tullabrack	0.44	0.42

Catchments with more than 60% of their area covered by underlying karstified bedrock aquifers and/or included in the Fergus catchment are shown in Table 2.5.

Table 2.5: Catchments likely to be influenced by groundwater, also showing the coverage by underlying karstified aquifers (expressed as % of total catchment area). Catchments that are not part of the Fergus catchment are underlined.

ID	Name	Karstified bedrock aquifers (%)
4	Atedaun	70
5	Ballyallia	80
6	Ballybeg	82
8	Ballycullinan	40
10	Ballyeighter	100
12	Ballyteige	71
14	Black Dro	100
16	Bunny	86
20	Clonlea	73
23	Cullaun	66
28	Dromoland	100
29	Dromore	100
32	Eanagh	
38	George	100
39	Girroga	100
45	Inchichronan	
46	Inchiquin	78
54	Luirk	100
59	Morgans	
60	Muckanagh	90
61	Muckinish	100
65	Rask	100

Topography and slope

Catchments included in this study had a large range of elevation and slope (Table 2.6, Figures 2.6 and 2.7), with the highest altitude of 521 m recorded within Lough Doon catchment. Mean catchment elevation ranged from 13 m for Lough Girroga to 203 m for Lough Acrow. Catchment mean slope ranged from 0 degree-slope for Lough Tullabrack to 7.9 degree-slope for Lough Muckinish, with the maximum slope value of 26.9 degree-slope recorded within Lough Bunny catchment.

Table 2.6: Catchment elevation and slope, expressed as minimum (min), maximum (max) and mean value. Datasets only available for the Clare part of the catchments are underlined.

ID	Name	Elevation	(m)		Slope	(degree)	
		Min	Max	Mean	Min	Max	Mean
1	Achryane	80	207	119	0.0	5.1	1.6
2	Acrow	190	226	203	0.0	4.5	1.1
3	Aillbrak	144	190	170	0.2	5.7	2.6
4	Atedaun	20	310	94	0.0	19.5	2.3
5	Ballyallia	10	84	19	0.0	10.9	1.0
6	Ballybeg	10	63	21	0.0	6.4	1.9
7	Ballycar	30	50	34	0.0	3.5	0.8
8	Ballycullinan	21	179	73	0.0	11.4	2.8
9	Ballydoolavan	60	90	78	0.0	3.9	1.3
10	Ballyeighter	20	148	25	0.0	16.9	1.0
11	Ballyleann	40	90	55	0.0	6.0	1.8
12	Ballyteige	20	310	92	0.0	19.5	2.2
13	Black *Kilk*	10	50	21	0.0	4.9	1.1
14	Black *Dro*	20	35	21	0	2	0
15	Bridget	31	64	43	0.0	4.7	1.0
16	Bunny	10	310	63	0.0	26.9	2.9
17	Burke	60	96	72	0.1	6.9	2.3
18	Castle	20	522	119	0.0	25.9	4.4
19	Caum	50	133	83	0.0	6.3	2.4
20	Clonlea	30	57	35	0.0	4.3	0.8
21	Cloonmackan	51	140	80	0.0	6.4	2.4
22	Cloonsnaghta	70	117	86	0.0	7.5	2.5
23	Cullaun	20	229	41	0.0	16.9	1.5
24	Cullaunyheeda	30	81	44	0.0	10.0	0.9
25	Curtins	52	70	62	0.0	2.5	1.0
26	Doolough	90	238	140	0.0	7.8	2.7
27	Doon	20	522	133	0.0	25.9	4.8
28	Dromoland	10	57	23	0.0	5.4	2.1
29	Dromore	20	35	21	0	2	0
30	Drumcullaun	50	375	101	0.0	16.8	2.4
31	Druminure	99	139	110	0.0	6.3	2.4
32	Eanagh	125	179	145	0.4	6.0	3.1
33	Effernan	56	103	76	0.0	5.0	1.8
34	Farrihy	10	50	21	0.0	3.6	1.0
35	Finn	30	59	34	0.0	4.4	0.9
36	Garvillaun	94	129	107	0.2	4.3	1.8
37	Gash	20	48	27	0.0	3.3	1.2

Table 2.6 (continued)

ID	**Name**	**Elevation**	**(m)**		**Slope**	**(degree)**	
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
38	George	20	39	22	0.0	3.2	0.5
39	Girroga	10	22	13	0.0	3.5	1.1
40	Goller	82	150	101	0.0	6.9	1.7
41	Gortaganniv	70	107	81	0.1	5.3	1.7
42	Gorteen	82	296	169	0.3	10.6	4.3
43	Gortglass	69	117	80	0.0	7.5	1.9
44	Graney	50	388	140	0.0	19.4	3.5
45	Inchichronan	23	240	72	0.0	8.4	1.8
46	Inchiquin	30	310	124	0.0	19.5	2.6
47	Keagh	189	190	190	0.0	1.4	0.3
48	Kilgory	30	149	52	0.0	7.4	1.5
49	Killone	11	63	28	0.2	6.0	2.8
50	Knockalough	61	108	77	0.0	6.3	1.9
51	Knockerra	58	88	66	0.0	4.5	1.8
52	Lickeen	70	156	98	0.0	5.9	2.4
53	Lisnahan	49	90	71	0.1	4.6	2.3
54	Luirk	10	300	97	0.0	23.1	7.0
55	Luogh	157	196	172	0.1	6.2	1.9
56	Moanmore	10	29	14	0.0	2.4	0.4
57	Mooghna	90	135	107	0.1	6.8	3.0
58	More	80	108	89	0.1	4.1	1.8
59	Morgans	100	113	103	0.0	3.9	1.5
60	Muckanagh	20	40	23	0.0	3.4	0.4
61	Muckinish	10	250	77	0.0	20.7	7.9
62	Naminna	170	256	188	0.0	6.6	1.7
63	O'Briens *Big Lough*	50	78	58	0.0	4.5	1.0
64	O'Grady	40	389	128	0.0	16.1	3.5
65	Rask	10	299	109	0.0	19.5	6.8
66	Rosconnell	50	98	68	0.0	4.5	1.9
67	Rosroe	30	51	32	0.0	5.2	0.7
68	Rushaun	70	118	90	0.2	5.1	2.6
69	Tullabrack	40	40	40	0.0	0.0	0.0

Significant positive correlations ($n=69$, $p<0.01$), were found between Log(Catchment Area) and Log(Drainage Area), and Log(Maximum catchment elevation) (respectively, $r=0.37$ and $r=0.38$); and with Log(Maximum catchment slope) (respectively, $r=0.57$ and $r=0.58$).

Negative significant correlations were found between minimum catchment elevation ($n=69$, $p<0.01$) and Log(Catchment Area) ($r=-0.50$) and Log(Drainage Area) ($r=-0.49$).

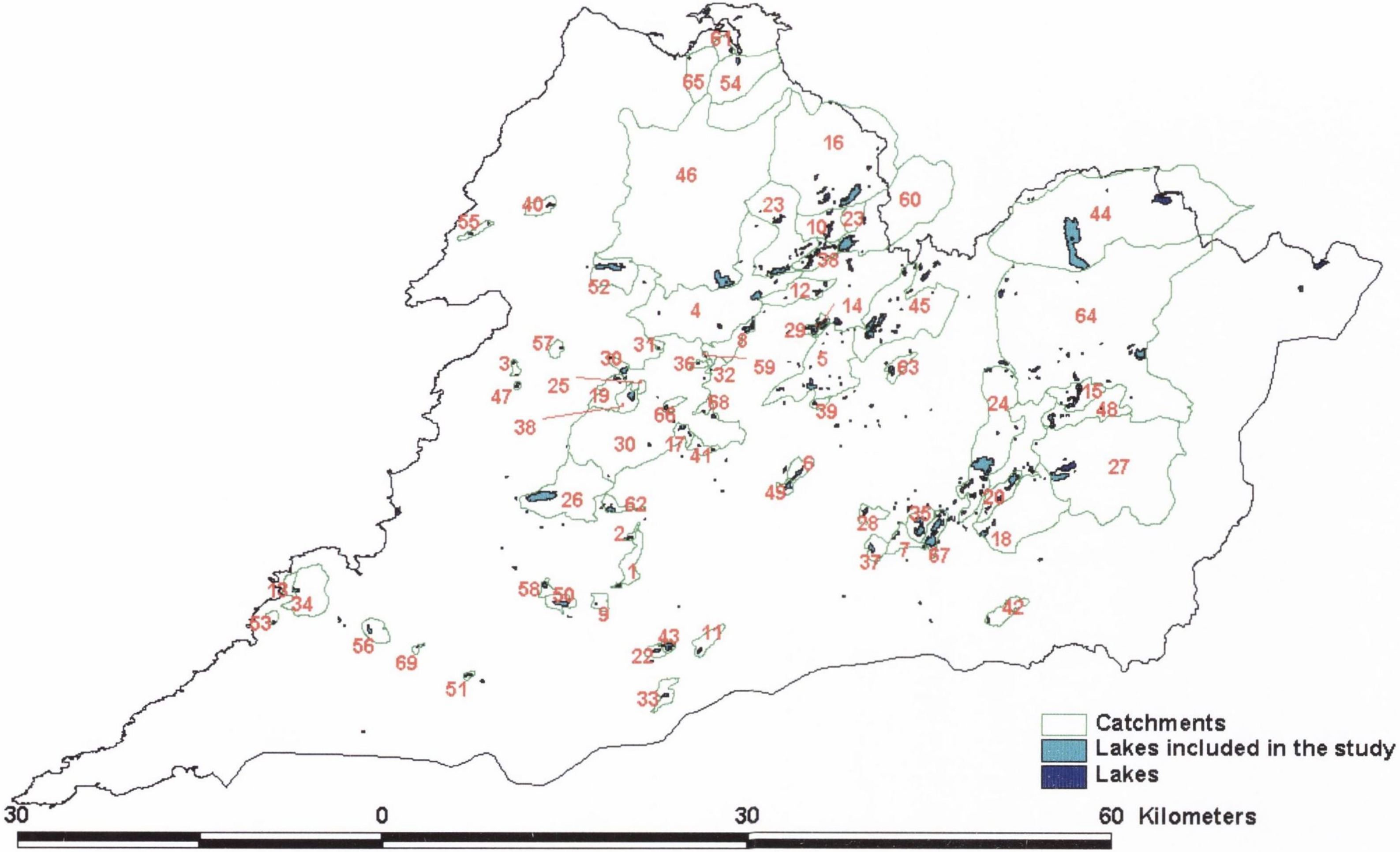

Figure 2.5: Location of the catchments included in the study. ID numbers refers to Table 2.4

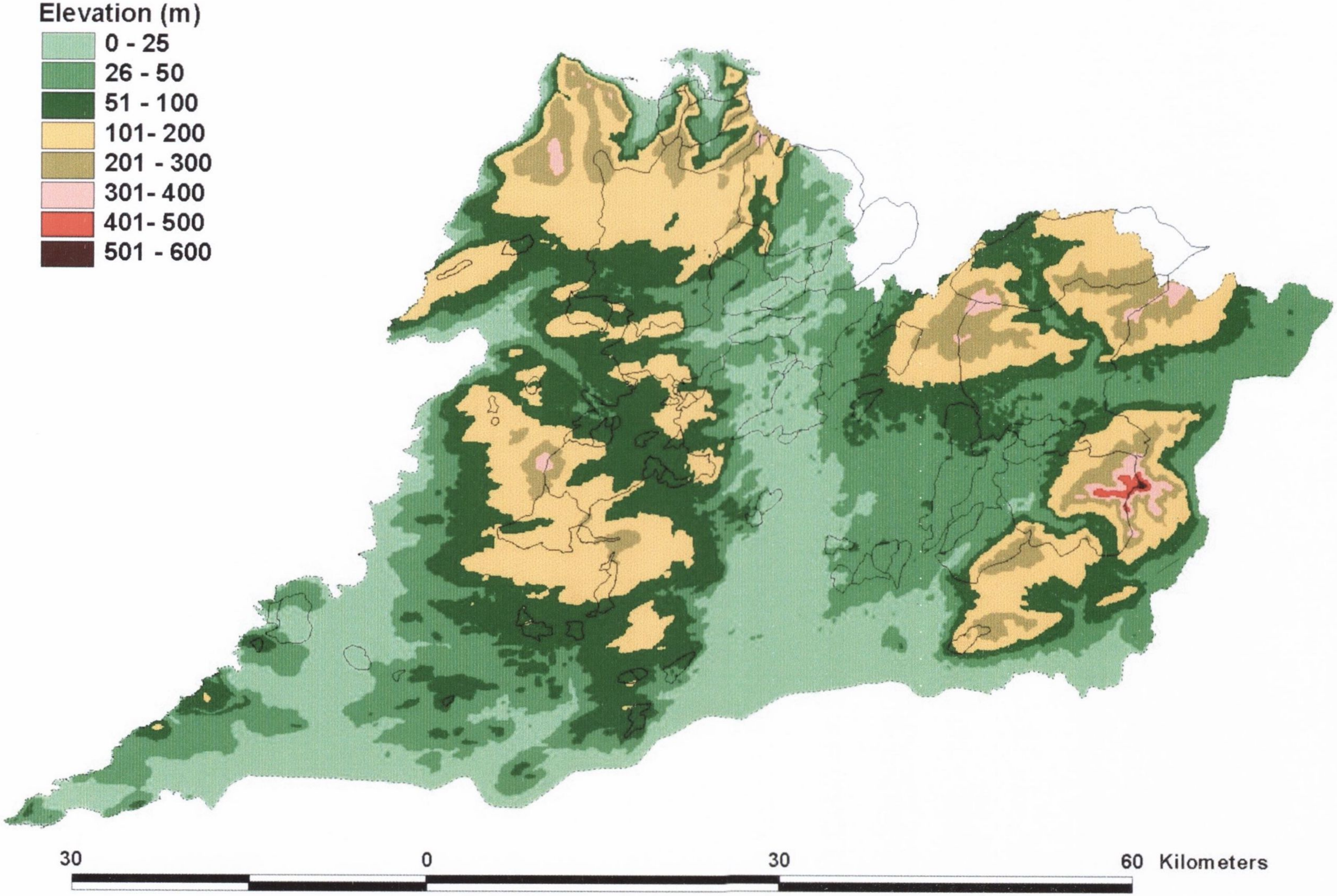

Figure 2.6: Elevation grid coverage in m for County Clare, also showing the boundaries of the catchments included in the study. Data were not available for the Galway parts of the eastern catchments.

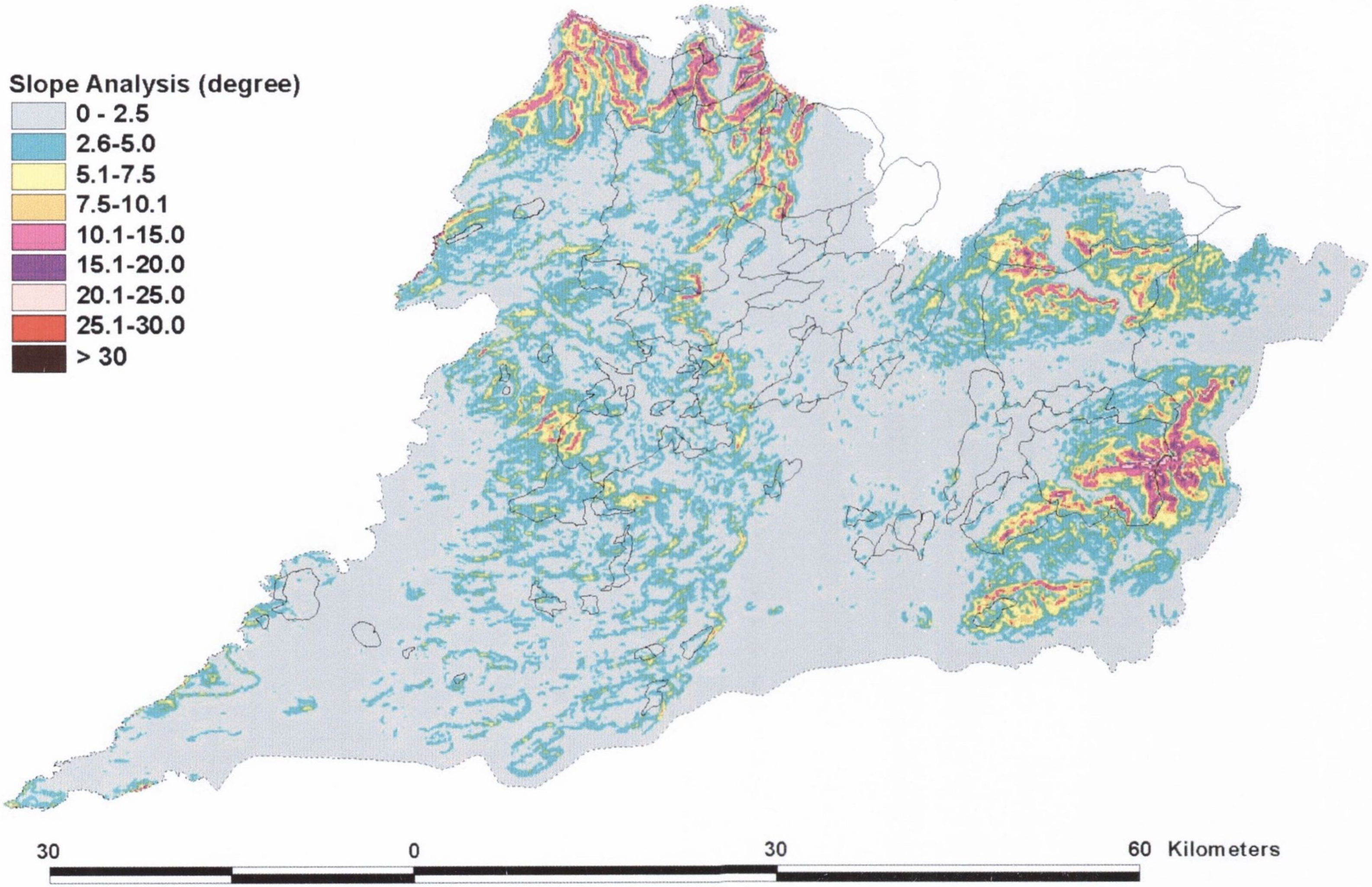

Figure 2.7: Slope analysis in degree of slope for County Clare derived from the elevation grid, also showing the boundaries of the catchments included in the study. Data were not available for the Galway parts of the eastern catchments.

Bedrock geology

Overall, two main types of bedrock were present (Table 2.7). Shales and similar rock types accounted for the entire catchment area of thirty-five catchments, while in twenty-six catchments, over 70% of the catchment area was underlain by carboniferous limestone. Old red sandstones were present in seven catchments, while eight catchments contained some Silurian quartzite (Figure 2.8).

A cluster analysis (similarity matrix done by using Euclidean distance and standardisation of the results) and principal components analysis highlighted the presence of two main groups of catchments based on bedrock composition (Table 2.7). Group A included catchments with bedrock composed mainly of shales and similar rock types, with no occurrence of old red sandstones. It was then subdivided into A_1: catchments with 100% coverage of shales and similar rock types, and A_2: catchments located at the boundary shales/carboniferous limestones, with roughly equal distribution of the two main types. Group B included catchments with low or no coverage of shales and similar rock types. It was further divided into B_1, catchments with over 70% of carboniferous limestones and B_2, catchments with old red sandstones and Silurian quartzite (Figure 2.9).

Owing to the natural variability of bedrock geology among catchments, distributions of the bedrock types were skewed. Nevertheless, when carrying out Spearman's Rank correlations between bedrock composition and other catchment physical and hydrological variables (as described later), statistically significant relationships ($p<0.01$) were found. The skewness of the relationships needs, however, to be taken into consideration, when interpreting relationship between such geological distributions and other catchment characteristics.

Occurrence of shales and similar rock types was significantly negatively correlated ($n=69$, $p<0.01$) with Log(Catchment area) ($r=-0.60$, Figure 2.10), while carboniferous limestone was negatively correlated ($n=69$, $p<0.01$) with mean catchment elevation ($r=-0.52$, Figure 2.11). Two-sample t-tests ($\alpha=0.05$, $p\leq0.0001$) carried out with *DataDesk 6.0* showed that Log(Catchment area) values recorded for the catchments with 0% shales and similar rock types were significantly different from those recorded for the catchments with 100% shales and similar rock types. In addition, catchment mean elevation values were found to be significantly different between catchments presenting 0% carboniferous limestones and 100% carboniferous limestones.

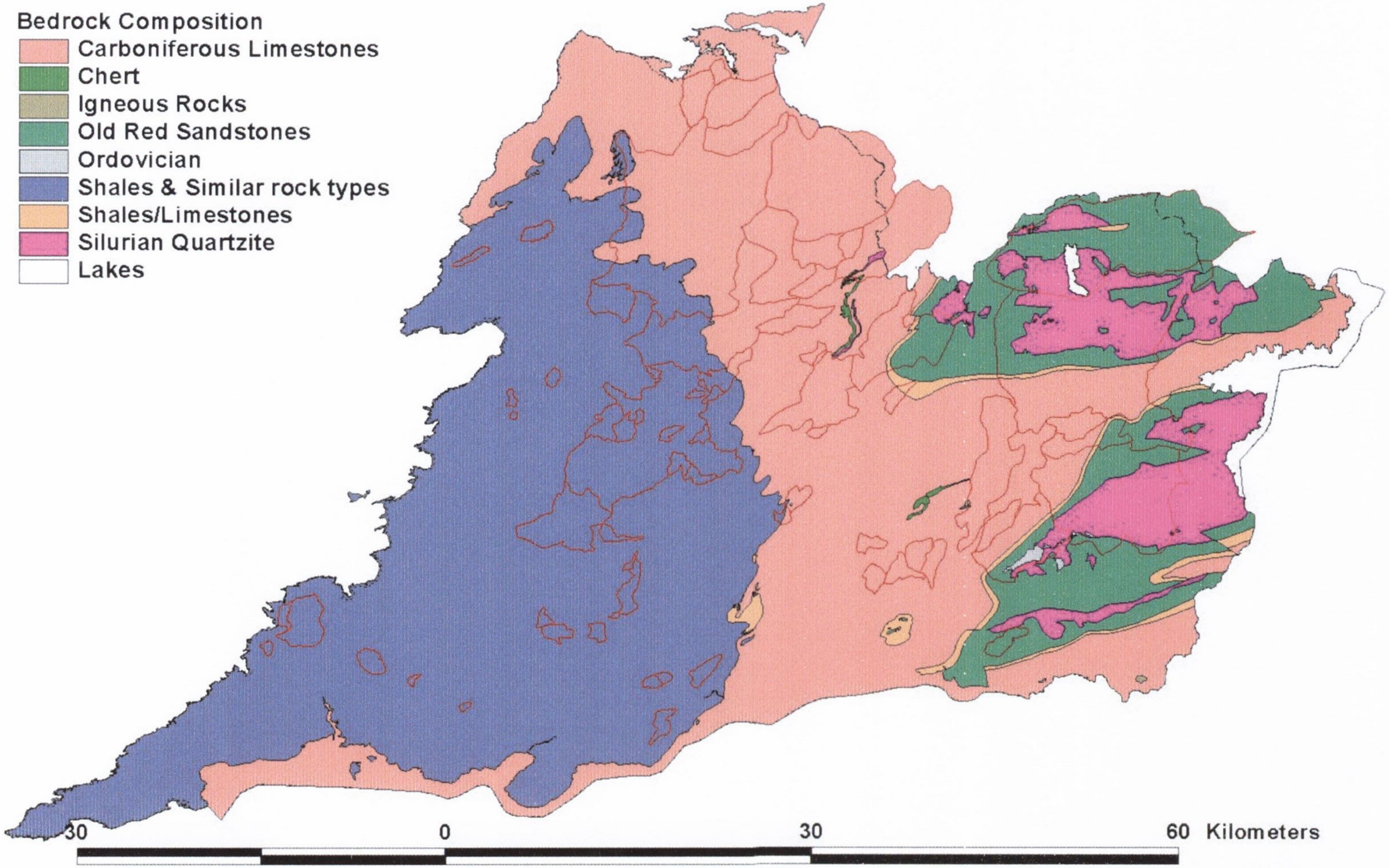

Figure 2.8: Bedrock composition of the catchments included in the study. Catchment boundaries are also outlined.

Table 2.7: Bedrock composition of the catchments included in the study, expressed as proportion of the total catchment area (%). Results of the cluster analysis area also shown as Bedrock Group.

Name	Bedrock Group	Carboniferous Limestones	Chert	Igneous Rocks	Old Red Sandstones	Ordovician	Shales & Similar rock types	Shales/Limestones	Silurian Quartzite
Achryane	A_1	0	0	0	0	0	100	0	0
Acrow	A_1	0	0	0	0	0	100	0	0
Aillbrak	A_1	0	0	0	0	0	100	0	0
Atedaun	B_1	79	0	0	0	0	20	0	0
Ballyallia	B_1	100	0	0	0	0	0	0	0
Ballybeg	B_1	82	0	0	0	0	18	1	0
Ballycar	B_1	100	0	0	0	0	0	0	0
Ballycullinan	A_2	40	0	0	0	0	60	0	0
Ballydoolavan	A_1	0	0	0	0	0	100	0	0
Ballyeighter	B_1	100	0	0	0	0	0	0	0
Ballyleann	A_1	0	0	0	0	0	100	0	0
Ballyteige	B_1	80	0	0	0	0	20	0	0
Black *Kilk*	B_1	0	0	0	0	0	100	0	0
Black *Dro*	A_1	100	0	0	0	0	0	0	0
Bridget	A_1	100	0	0	0	0	0	0	0
Bunny	B_1	100	0	0	0	0	0	0	0
Burke	A_1	0	0	0	0	0	100	0	0
Castle	B_2	32	0	0	25	2	0	4	37
Caum	A_1	0	0	0	0	0	100	0	0
Clonlea	B_1	100	0	0	0	0	0	0	0
Cloonmackan	A_1	0	0	0	0	0	100	0	0
Cloonsnaghta	A_1	0	0	0	0	0	100	0	0
Cullaun	B_1	98	0	0	0	0	0	0	1
Cullaunyheeda	B_1	100	0	0	0	0	0	0	0
Curtins	A_1	0	0	0	0	0	100	0	0
Doolough	A_1	0	0	0	0	0	100	0	0
Doon	B_2	26	0	0	26	0	0	3	44

Table 2.7 (continued)

Name	Bedrock Group	Carboniferous Limestones	Chert	Igneous Rocks	Old Red Sandstones	Ordovician	Shales & Similar rock types	Shales/Limestones	Silurian Quartzite
Dromoland	B_1	100	0	0	0	0	0	0	0
Dromore	B_1	100	0	0	0	0	0	0	0
Drumcullaun	A_1	0	0	0	0	0	100	0	0
Druminure	A_1	0	0	0	0	0	100	0	0
Eanagh	A_1	0	0	0	0	0	100	0	0
Effernan	A_1	0	0	0	0	0	100	0	0
Farrihy	A_1	0	0	0	0	0	100	0	0
Finn	B_1	100	0	0	0	0	0	0	0
Garvillaun	A_1	0	0	0	0	0	100	0	0
Gash	B_1	100	0	0	0	0	0	0	0
George	B_1	100	0	0	0	0	0	0	0
Girroga	B_1	100	0	0	0	0	0	0	0
Goller	A_1	0	0	0	0	0	100	0	0
Gortaganniv	A_1	0	0	0	0	0	100	0	0
Gorteen	B_2	0	0	0	98	0	0	0	2
Gortglass	A_1	0	0	0	0	0	100	0	0
Graney	B_2	0	0	0	70	0	0	1	26
Inchichronan	B_2	53	0	0	38	0	0	5	3
Inchiquin	B_1	78	0	0	0	0	22	0	0
Keagh	A_1	0	0	0	0	0	100	0	0
Kilgory	B_1	74	0	0	20	0	0	6	0
Killone	A_2	51	0	0	0	0	49	0	0
Knockalough	A_1	0	0	0	0	0	100	0	0
Knockerra	A_1	0	0	0	0	0	100	0	0
Lickeen	A_1	0	0	0	0	0	100	0	0
Lisnahan	A_1	0	0	0	0	0	100	0	0
Luirk	B_1	100	0	0	0	0	0	0	0
Luogh	A_1	0	0	0	0	0	100	0	0
Moanmore	A_1	0	0	0	0	0	100	0	0
Mooghna	A_1	0	0	0	0	0	100	0	0

Table 2.7 (continued)

Name	Bedrock Group	Carboniferous Limestones	Chert	Igneous Rocks	Old Red Sandstones	Ordovician	Shales & Similar rock types	Shales/Limestones	Silurian Quartzite
More	A_1	0	0	0	0	0	100	0	0
Morgans	A_1	0	0	0	0	0	100	0	0
Muckanagh	B_1	97	1	0	0	0	0	0	2
Muckinish	B_1	100	0	0	0	0	0	0	0
Naminna	A_1	0	0	0	0	0	100	0	0
O'Briens *Big Lough*	B_1	76	0	0	0	0	0	24	0
O'Grady	B_2	27	0	0	29	0	0	2	41
Rask	B_1	100	0	0	0	0	0	0	0
Rosconnell	A_1	0	0	0	0	0	100	0	0
Rosroe	B_1	100	0	0	0	0	0	0	0
Rushaun	A_1	0	0	0	0	0	100	0	0
Tullabrack	A_1	0	0	0	0	0	100	0	0

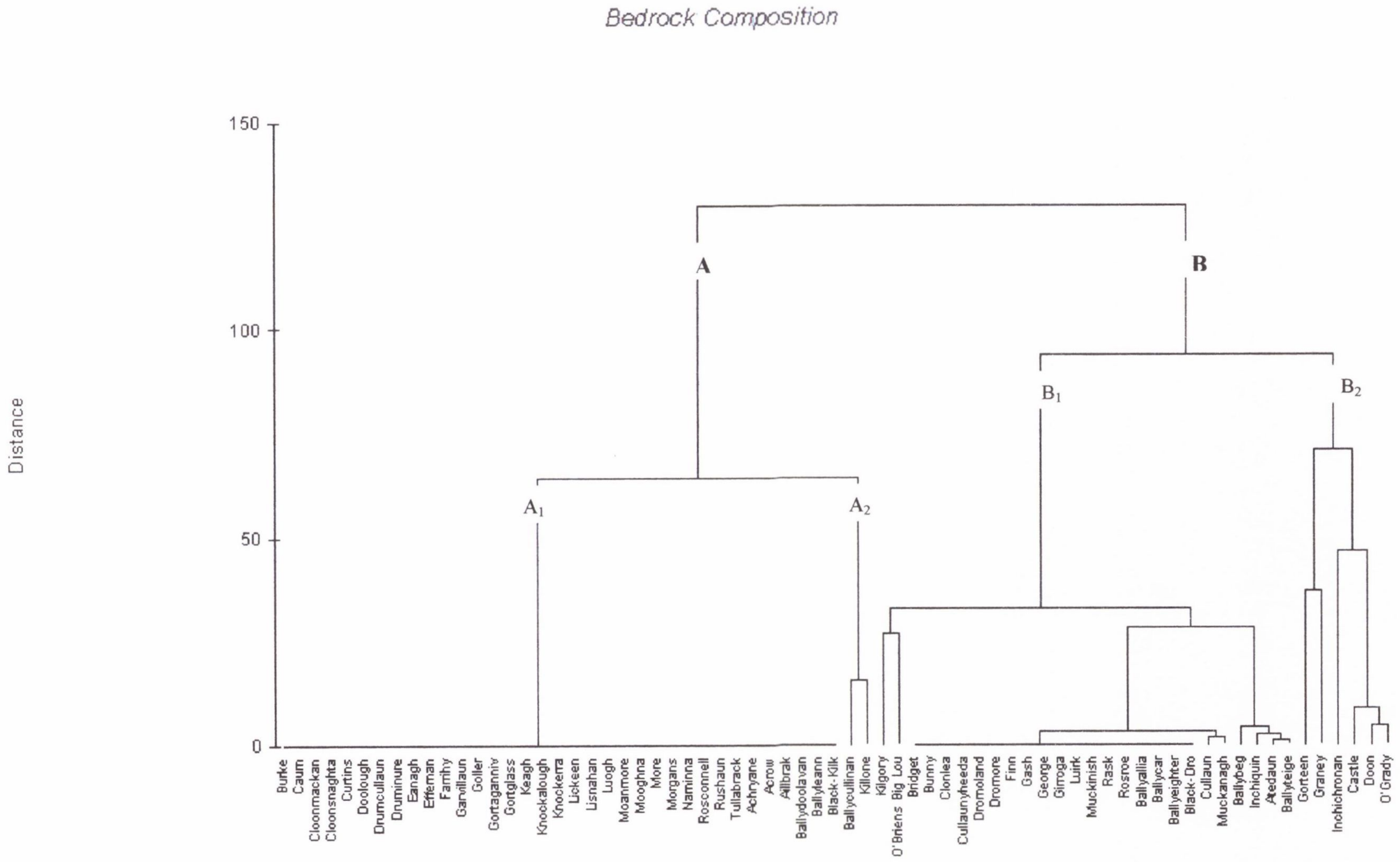

Figure 2.9: Cluster Analysis based on the bedrock composition of the 69 catchments included in the study

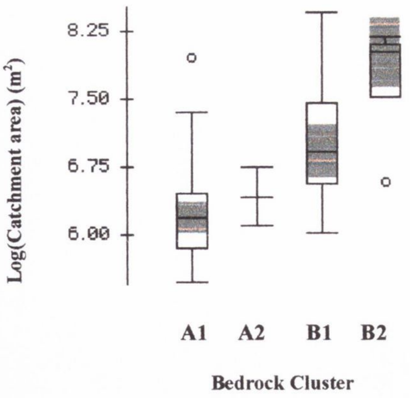

Figure 2.10: Distribution of Log(Catchment Area) (m^2) among the different bedrock cluster types, as described in Table 2.7.

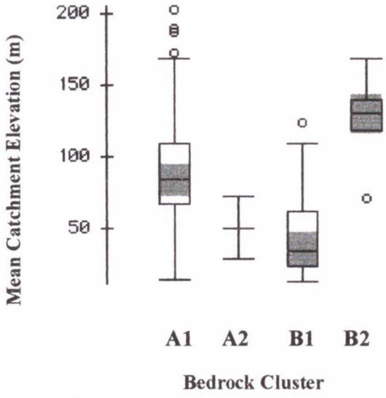

Figure 2.11: Distribution of Mean catchment elevation (m) among the different bedrock cluster types, as described in Table 2.7.

Soil types

The main soil types present in the catchments are peats, gleys and rendzinas (Table 2.8; Figure 2.12). Eight catchments had over 60% peats, while seventeen over 60% gleys. Sixteen catchments had over 60% of soils with well/moderate drainage capacity, while thirty-three were covered by over 60% of soils with poor/imperfect drainage. The average soil Morgan P levels recorded over the catchments was 6.7 mg l^{-1}, with a minimum of 4 and maximum of 9 mg l^{-1}. Soil test P level estimates for each catchment were based on the current map available from Teagasc, which displayed an average soil P level per 10*10 km^2 cell based on the National grid. Within each cell, soil Morgan P averages were based on variable number of soil P tests. Soil characteristics, drainage capacity, soil P desorption indices and soil Morgan P levels for the catchments included in the study are shown in Table 2.9.

A cluster analysis (similarity matrix done by using Euclidean distance and standardisation of the results) and principal components analysis based on the different soil variables differentiated three main groups of catchments (Figure 2.13). Group A included two catchments covered by more than 60% of the soil category “complexes”. Group B included catchments with less than 60% of the soil category “complexes”. B was then subdivided into B_1 and B_2 based on the soil drainage capacity characteristics with, respectively, B_1 including catchments covered by less than 66% of poorly drained soils and B_2 including catchments covered by more than 66% of poorly drained soils (Table 2.8).

Carboniferous limestones were positively correlated ($n=69$, $p<0.01$) with the occurrence of brown earths ($r=0.34$), rendzinas ($r=0.64$), grey brown podzolics ($r= 0.74$) and mean soil Morgan P ($r=0.53$), while negatively correlated with peats ($r=-0.50$) and gleys ($r=-0.55$). Shales and similar rock types were positively correlated ($n=69$, $p<0.01$) with peats ($r=0.36$) and gleys ($r=0.56$), while negatively correlated with brown earths ($r=-0.40$), rendzinas ($r=-0.52$), grey brown podzolics ($r=-0.74$) and mean soil Morgan P ($r=-0.55$).

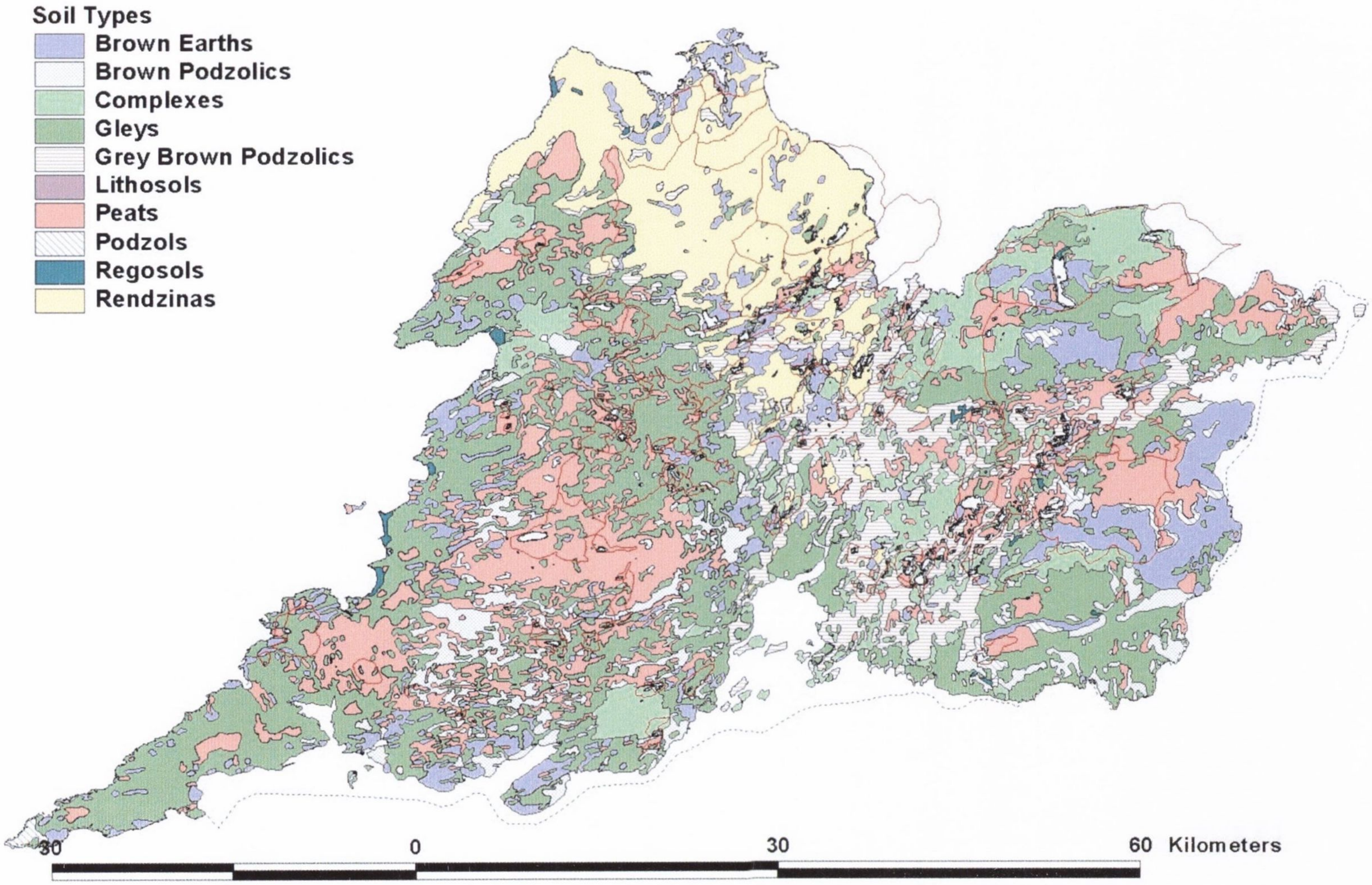

Figure 2.12: Soil type distribution among the catchments included in the study, also outlining the catchment boundaries.

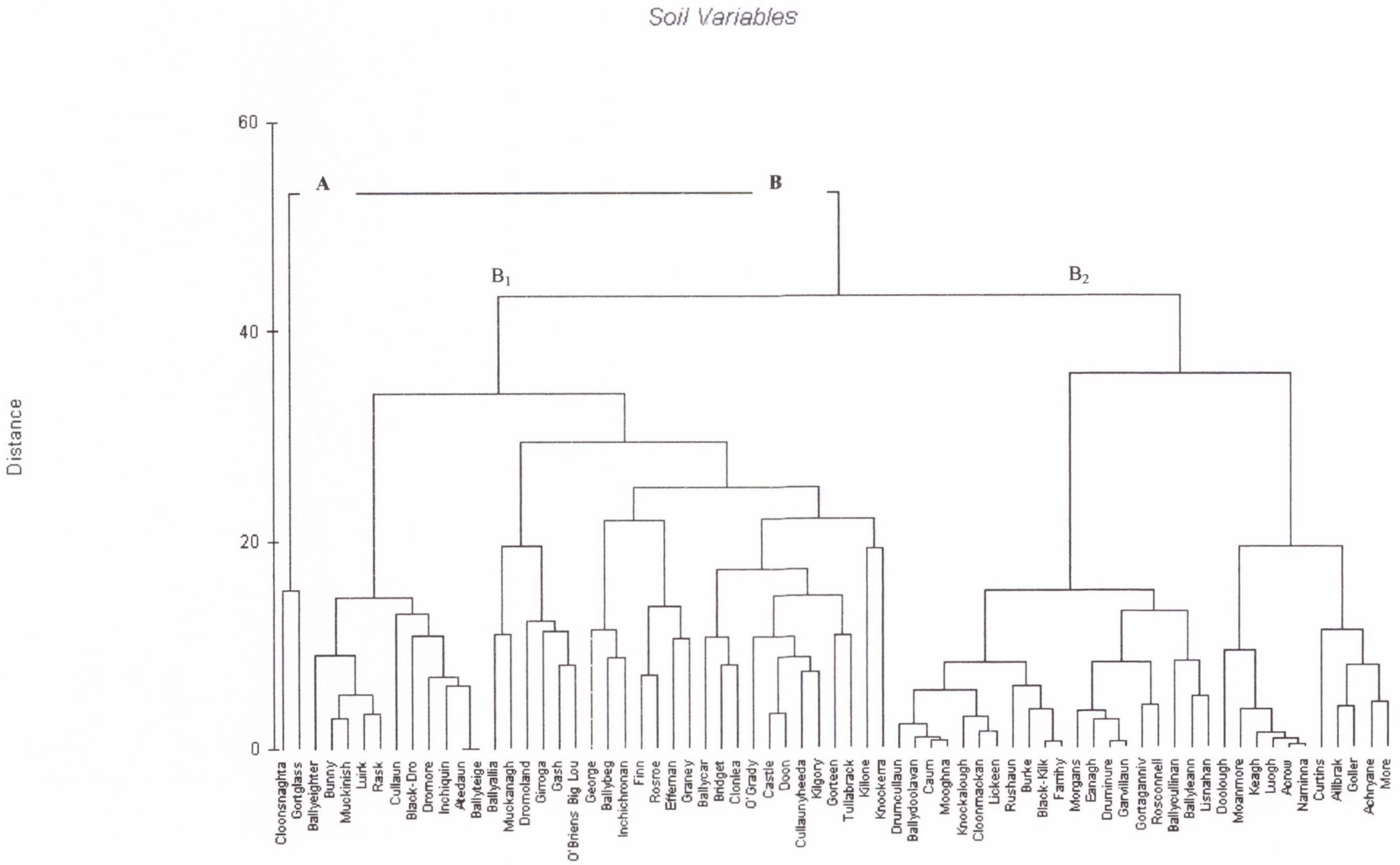

Figure 2.13: Cluster Analysis based on Catchment Soil Characteristics

Table 2.8: Soil group distribution of the catchments included in the study, expressed as proportion of the total catchment area (%). Results of the cluster analysis are also shown as Soil Groups

ID	Name	Soil Groups	Brown Earths	Rendzinas	Grey Brown Podzolics	Regosols	Peats	Gleys	Complexes	Brown Podzolics	Podzols
1	Achryane	B_2	0	0	0	0	68	19	11	0	0
2	Acrow	B_2	0	0	0	0	100	0	0	0	0
3	Aillbrak	B_2	0	0	0	0	61	29	4	0	0
4	Atedaun	B_1	15	52	7	0	6	16	1	0	1
5	Ballyallia	B_1	32	15	34	0	1	9	0	0	8
6	Ballybeg	B_1	17	23	8	0	0	10	0	0	29
7	Ballycar	B_1	0	0	50	0	14	14	0	0	21
8	Ballycullinan	B_2	6	16	4	0	0	68	0	0	0
9	Ballydoolavan	B_2	0	0	0	0	28	72	0	0	0
10	Ballyeighter	B_1	2	74	0	0	9	2	0	0	6
11	Ballyleann	B_2	12	0	0	0	0	79	5	0	0
12	Ballyteige	B_1	15	52	7	0	6	16	1	0	1
13	Black *Kilk*	B_1	14	32	0	0	0	6	0	0	0
14	Black *Dro*	B_2	10	0	0	0	28	60	0	0	0
15	Bridget	B_1	18	0	32	0	27	1	0	0	11
16	Bunny	B_1	8	87	0	0	0	4	0	0	0
17	Burke	B_2	13	0	0	0	21	61	0	0	0
18	Castle	B_1	24	0	12	0	28	19	2	5	7
19	Caum	B_2	1	0	0	0	28	69	0	0	0
20	Clonlea	B_1	0	0	47	0	25	7	0	0	5
21	Cloonmackan	B_2	0	0	0	0	34	58	0	0	0
22	Cloonsnaghta	A	0	0	0	0	2	0	3	0	87
23	Cullaun	B_1	31	42	9	0	9	1	0	0	3
24	Cullaunyheeda	B_1	3	0	31	0	33	15	1	0	9
25	Curtins	B_2	0	0	0	0	51	49	0	0	0
26	Doolough	B_2	1	0	0	0	77	15	1	0	0
27	Doon	B_1	26	0	8	0	34	16	3	6	4

Table 2.8 (continued)

ID	Name	Soil Groups	Brown Earths	Rendzinas	Grey Brown Podzolics	Regosols	Peats	Gleys	Complexes	Brown Podzolics	Podzols
28	Dromoland	B_1	4	6	85	0	0	0	0	0	0
29	Dromore	B_1	23	39	0	0	0	3	0	0	0
30	Drumcullaun	B_2	3	0	0	0	28	67	1	0	0
31	Druminure	B_2	0	0	0	0	4	96	0	0	0
32	Eanagh	B_2	0	0	0	0	9	91	0	0	0
33	Effernan	B_1	0	0	0	0	31	2	10	0	52
34	Farrihy	B_2	11	0	0	0	28	60	0	0	0
35	Finn	B_1	0	0	17	0	29	0	0	0	31
36	Garvillaun	B_2	0	0	0	0	5	95	0	0	0
37	Gash	B_1	0	0	74	0	9	0	0	0	9
38	George	B_1	14	14	6	0	6	0	0	0	37
39	Girroga	B_1	0	0	75	0	1	19	0	0	0
40	Goller	B_2	0	0	0	0	59	36	0	0	0
41	Gortaganniv	B_2	4	0	0	0	12	83	1	0	0
42	Gorteen	B_1	2	0	0	0	58	5	20	15	0
43	Gortglass	A	0	0	0	0	1	10	9	0	61
44	Graney	B_1	11	0	0	0	30	15	0	1	41
45	Inchichronan	B_1	0	20	20	0	11	7	3	6	29
46	Inchiquin	B_1	7	67	5	0	4	16	1	0	0
47	Keagh	B_2	0	0	0	0	82	0	0	0	0
48	Kilgory	B_1	10	0	27	0	25	27	0	0	4
49	Killone	B_1	44	1	6	0	0	31	0	0	0
50	Knockalough	B_2	0	0	0	0	31	53	4	0	0
51	Knockerra	B_1	0	0	0	0	8	25	46	0	0
52	Lickeen	B_2	0	0	0	0	35	54	0	0	0
53	Lisnahan	B_2	24	0	0	0	0	76	0	0	0
54	Luirk	B_1	15	75	9	0	0	0	0	0	0
55	Luogh	B_2	0	0	0	0	96	0	0	0	0
56	Moanmore	B_2	0	0	0	0	92	5	0	0	0

Table 2.8 (continued)

ID	Name	Soil Groups	Brown Earths	Rendzinas	Grey Brown Podzolics	Regosols	Peats	Gleys	Complexes	Brown Podzolics	Podzols
57	Mooghna	B_2	0	0	0	0	27	66	1	0	0
58	More	B_2	0	0	0	0	57	23	13	0	0
59	Morgans	B_2	0	0	0	0	0	100	0	0	0
60	Muckanagh	B_1	60	11	17	0	9	0	0	0	0
61	Muckinish	B_1	12	88	0	0	0	0	0	0	0
62	Naminna	B_2	0	0	0	0	90	0	0	0	0
63	O'Briens *Big Lough*	B_1	0	0	66	0	21	0	0	4	1
64	O'Grady	B_1	18	0	10	0	21	36	0	3	11
65	Rask	B_1	19	81	0	0	0	0	0	0	0
66	Rosconnell	B_2	8	0	0	0	13	68	0	0	0
67	Rosroe	B_1	0	0	20	0	18	0	0	0	23
68	Rushaun	B_2	17	0	0	0	15	64	0	0	0
69	Tullabrack	B_1	7	0	0	0	42	23	27	0	0

Table 2.9: Catchment soil characteristics, expressed as % of total catchment area, showing soil drainage capacity with well/moderate drainage (Well/Mod), poor/imperfect drainage (Poor/Imp) and variable, soil P desorption classes and overall average desorption index (Soil P Des. Index). Soil Morgan P levels in mg l^{-1}, expressed as minimum (Min P), maximum (Max P) and mean (Mean P) are also shown.

Name	Well/Mod.	Poor/Imp.	Variable	S1	S2	S3	S4	Soil P Des. Index	Min P	Max P	Mean P
Achryane	11	87	0	11	19	0	68	1.27	6	6	6
Acrow	0	100	0	0	0	0	100	1.00	6	6	6
Aillbrak	4	90	0	4	29	0	61	1.32	6	7	6
Atedaun	75	22	1	75	16	0	6	1.57	5	9	7
Ballyallia	80	9	8	80	9	0	1	1.77	8	9	9
Ballybeg	49	10	29	49	10	0	0	1.60	8	8	8
Ballycar	50	28	21	50	14	0	14	1.67	7	7	7
Ballycullinan	26	68	0	26	68	0	0	1.82	7	7	7

Table 2.9 (continued)

Name	Well/Mod.	Poor/Imp.	Variable	S1	S2	S3	S4	Soil P Des. Index	Min P	Max P	Mean P
Ballydoolavan	0	100	0	0	72	0	28	1.65	6	6	6
Ballyeighter	76	11	6	76	2	0	9	1.38	5	5	5
Ballyleann	18	79	0	18	79	0	0	1.90	6	6	6
Ballyteige	75	22	1	75	16	0	6	1.57	5	9	7
Black-Dro	46	6	0	46	6	0	0	1.89	9	9	9
Black-Kilk	10	88	0	10	60	0	28	1.65	8	8	8
Bridget	50	28	11	50	1	0	27	1.57	6	7	7
Bunny	95	4	0	95	4	0	0	1.46	5	11	7
Burke	13	82	0	13	61	0	21	1.70	5	5	5
Castle	43	47	7	43	19	0	28	1.58	6	6	6
Caum	1	97	0	1	69	0	28	1.64	5	6	5
Clonlea	47	33	5	47	7	0	25	1.60	7	8	8
Cloonmackan	0	92	0	0	58	0	34	1.57	5	6	5
Cloonsnaghta	3	2	87	3	0	0	2	1.41	6	6	6
Cullaun	82	10	3	82	1	0	9	1.57	5	9	7
Cullaunyheeda	34	49	9	34	15	0	33	1.53	6	8	8
Curtins	0	100	0	0	49	0	51	1.44	6	7	7
Doolough	2	92	0	2	15	0	77	1.17	5	6	5
Doon	43	50	4	43	16	0	34	1.53	6	7	6
Dromoland	95	0	0	95	0	0	0	1.87	7	8	8
Dromore	63	3	0	62	3	0	0	1.25	9	9	9
Drumcullaun	4	94	0	4	67	0	28	1.65	5	7	5
Druminure	0	100	0	0	96	0	4	1.86	7	7	7
Eanagh	0	100	0	0	91	0	9	1.82	7	7	7
Effernan	10	32	52	10	2	0	31	1.33	6	6	6
Farrihy	11	88	0	11	60	0	28	1.65	8	8	8
Finn	17	29	31	17	0	0	29	1.36	7	8	8
Garvillaun	0	100	0	0	95	0	5	1.86	7	7	7
Gash	74	9	9	74	0	0	9	1.76	7	7	7
George	34	6	37	34	0	0	6	1.49	5	5	5
Girroga	75	19	0	75	19	0	1	1.89	8	9	8
Goller	0	95	0	0	36	0	59	1.34	6	6	6

Table 2.9 (continued)

Name	Well/Mod.	Poor/Imp.	Variable	S1	S2	S3	S4	Soil P Des. Index	Min P	Max P	Mean P
Gortaganniv	5	95	0	5	83	0	12	1.79	5	5	5
Gorteen	37	63	0	37	5	0	58	1.30	7	7	7
Gortglass	9	11	61	9	10	0	1	1.51	6	6	6
Graney	12	45	41	12	15	0	30	1.41	5	9	7
Inchichronan	50	18	29	50	7	0	11	1.51	8	9	8
Inchiquin	79	20	0	79	16	0	4	1.53	5	10	7
Keagh	0	82	0	0	0	0	82	1.00	6	7	6
Kilgory	37	52	4	37	27	0	25	1.63	5	7	7
Killone	51	31	0	51	31	0	0	1.89	8	8	8
Knockalough	4	84	0	4	53	0	31	1.58	6	6	6
Knockerra	46	33	0	46	25	0	8	1.81	7	7	7
Lickeen	0	89	0	0	54	0	35	1.55	6	6	6
Lisnahan	24	76	0	24	76	0	0	1.90	8	8	8
Luirk	99	0	0	99	0	0	0	1.52	7	10	7
Luogh	0	96	0	0	0	0	96	1.00	4	4	4
Moanmore	0	97	0	0	5	0	92	1.05	8	8	8
Mooghna	1	93	0	1	66	0	27	1.64	6	6	6
More	13	80	0	13	23	0	57	1.35	6	6	6
Morgans	0	100	0	0	100	0	0	1.90	7	7	7
Muckanagh	88	9	0	88	0	0	9	1.76	5	9	8
Muckinish	100	0	0	100	0	0	0	1.46	7	7	7
Naminna	0	90	0	0	0	0	90	1.00	5	5	5
O'Briens	70	21	1	70	0	0	21	1.67	8	8	8
O'Grady	31	57	11	31	36	0	21	1.64	5	9	7
Rask	100	0	0	100	0	0	0	1.50	7	7	7
Rosconnell	8	81	0	8	68	0	13	1.77	5	7	5
Rosroe	20	18	23	20	0	0	18	1.45	7	8	8
Rushaun	17	78	0	17	64	0	15	1.76	5	7	5
Tullabrack	34	66	0	34	23	0	42	1.52	7	7	7

Figures 2.14 to 2.18 illustrate the distribution of rendzina, grey brown podzolic, peat and gley soils, as well as catchment mean soil Morgan P levels, among the different bedrock cluster types described in Table 2.7.

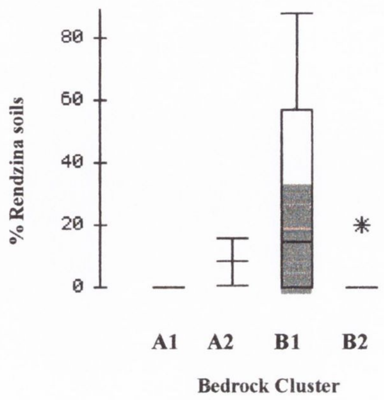

Figure 2.14: Distribution of % Rendzina soils among the different bedrock cluster types, as described in Table 2.7.

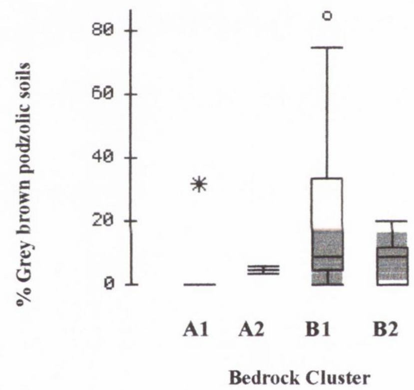

Figure 2.15: Distribution of % Grey brown podzolic soils among the different bedrock cluster types, as described in Table 2.7.

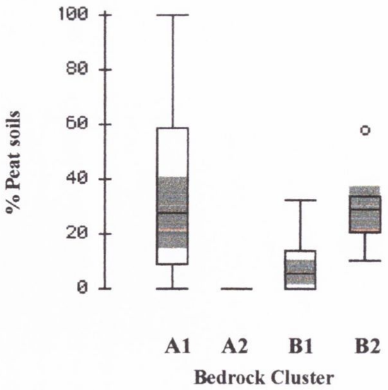

Figure 2.16: Distribution of % Peat soils among the different bedrock cluster types, as described in Table 2.7.

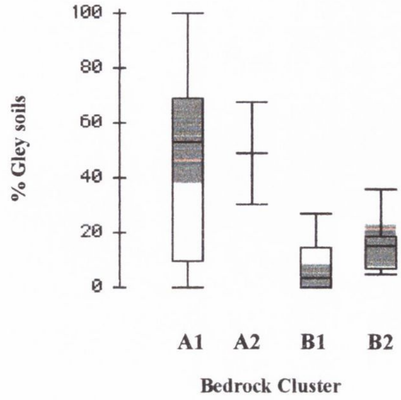

Figure 2.17: Distribution of % Gley soils among the different bedrock cluster types, as described in Table 2.7.

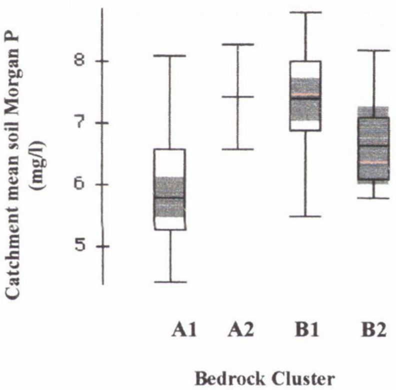

Figure 2.18: Distribution of catchment mean soil Morgan P levels (mg l^{-1}) among the different bedrock cluster types, as described in Table 2.7.

Maximum catchment elevation was positively correlated (n=69) with the occurrence of peats (r=0.51, p<0.01) and gleys (r=0.29, p<0.05), while negatively correlated (n=69, p<0.01) with the occurrence of brown earths (r=-0.55), rendzinas (r=-0.64) and grey brown podzolics (r=-0.51). Mean catchment elevation was positively correlated (n=69, p<0.01) with poor/imperfect soil drainage capacity (r=0.46), while negatively correlated with well/moderate soil drainage (r=-0.45) and mean soil Morgan P (r=-0.57). Mean soil Morgan P was positively correlated (n=69, p<0.01) with well/moderate soil drainage (r=0.49), while negatively correlated with poor/imperfect soil drainage (r=-0.41).

II-5.2 Limnological and meteorological variables

Limnological variables

Summary of the results of the bathymetric survey carried out on fifteen lakes in October 2001 are presented in Appendix 1 (Table 1). Bathymetric maps were produced for each lake surveyed (Figures 1 to 15 – Appendix 1). Results and maps from the bathymetric survey are also provided in the associated CD-Rom (Appendix 1/Bathymetric survey).

Areas of the lakes included in the study ranged from 0.001 km^2 estimated for Lough Black (near Kilkee) to 3.681 km^2 for Lough Graney (Table 2.10). Lough Acrow recorded the highest lake altitude with 200 m. Lough Black (near Kilkee) had an area covering less than 1% of its catchment area, while Lough Dromore covered 29.5 % of its catchment area. Upstream lakes were absent in twenty-five catchments, while covering more than 10% of the total catchment area for only two catchments with 20.3% of the catchment area for Lough Ballyallia and 60.3% for Lough Black (near Dromore) (Table 2.10).

Table 2.10: Lake characteristics estimated from GIS coverages. Main lake (%) and Upstream lakes (%) are expressed as % of the total catchment area.

Name	Altitude (m)	Area (km^2)	Shoreline (m)	Shoreline D_L	Main Lake (%)	Upstream Lakes (%)
Achryane	80	0.074	1229	1.3	1.6	0.4
Acrow	200	0.054	1131	1.4	9.5	2.2
Aillbrack	148	0.045	848	1.1	5.9	3.5
Atedaun	22	0.380	3155	1.4	0.1	1.5
Ballyallia	10	0.326	3361	1.7	1.3	20.3
Ballybeg	10	0.197	3446	2.2	4.8	4.6
Ballycar	30	0.030	771	1.3	0.8	1.9
Ballycullinan	24	0.286	4071	2.1	4.9	0.0
Ballydoolavan	80	0.005	281	1.1	0.3	0.0
Ballyeighter	17	0.276	4961	2.7	3.2	1.4
Ballyleann	46	0.053	1264	1.6	1.8	0.0
Ballyteige	20	0.142	2010	1.5	0.0	1.6
Black *Kilk*	11	0.001	113	1.1	0.0	4.1
Black *Dro*	20	0.075	1608	1.7	3.5	60.3
Bridget	40	0.537	9336	3.6	7.6	0.7
Bunny	20	1.026	8290	2.3	1.3	0.8

Table 2.10 (continued)

Name	Altitude (m)	Area (km^2)	Shoreline (m)	Shoreline D_L	Main Lake (%)	Upstream Lakes (%)
Burke	62	0.103	1825	1.6	4.5	0.8
Castle	20	0.231	2977	1.7	0.2	2.1
Caum	51	0.068	1277	1.4	1.3	0.5
Clonlea	30	0.401	3054	1.4	7.3	4.0
Cloonmackan	60	0.234	2118	1.2	8.3	0.0
Cloonsnaghta	72	0.086	1187	1.1	6.9	0.0
Cullaun	25	0.497	4597	1.8	0.6	3.0
Cullaunyheeda	30	1.528	7229	1.6	5.2	2.6
Curtins	58	0.012	413	1.0	2.0	0.0
Doolough	91	1.302	6386	1.6	5.7	0.0
Doon	22	0.591	4028	1.5	0.6	1.6
Dromoland	10	0.117	1853	1.5	4.9	0.0
Dromore	20	0.491	5666	2.3	29.5	1.3
Drumcullaun	50	0.220	1933	1.2	0.2	0.9
Druminure	100	0.028	661	1.1	4.2	0.0
Eanagh	131	0.010	411	1.2	0.9	0.0
Effernan	60	0.103	1984	1.7	3.7	0.0
Farrihy	10	0.127	1549	1.2	1.2	0.0
Finn	20	0.739	6262	2.1	18.1	0.0
Garvillaun	100	0.023	616	1.1	3.3	0.4
Gash	20	0.186	2218	1.4	6.5	0.0
George	20	0.013	446	1.1	0.2	9.7
Girroga	12	0.046	1004	1.3	4.2	0.0
Goller	91	0.089	1743	1.6	3.4	0.0
Gortaganniv	80	0.032	843	1.3	1.6	1.1
Gorteen	89	0.034	861	1.3	0.9	0.2
Gortglass	70	0.292	3310	1.7	13.9	4.1
Graney	53	3.681	13636	2.0	3.3	0.8
Inchichronan	30	1.167	11957	3.1	3.5	0.9
Inchiquin	35	1.069	6365	1.7	0.7	0.0
Keagh	190	0.069	1238	1.3	21.9	0.0
Kilgory	30	0.357	3847	1.8	2.0	3.5
Killone	15	0.191	1992	1.3	14.9	0.0
Knockalough	70	0.339	3199	1.5	13.2	0.0
Knockerra	61	0.073	1415	1.5	15.9	0.0
Lickeen	71	0.844	6287	1.9	9.7	0.3
Lisnahan	54	0.059	954	1.1	7.7	0.0
Luirk	10	0.112	1518	1.3	0.7	0.0
Luogh	159	0.049	1051	1.3	3.5	0.6
Moanmore	10	0.121	1624	1.3	3.6	0.0
Mooghna	91	0.033	802	1.2	2.6	0.0
More	80	0.093	1204	1.1	7.8	0.1
Morgans	100	0.012	439	1.1	4.0	0.0
Muckanagh	20	0.961	6277	1.8	2.4	0.2
Muckinish	29	0.026	985	1.7	1.2	0.2
Naminna	170	0.200	2016	1.3	9.7	0.3
O'Briens *Big Lough*	51	0.189	2322	1.5	6.8	0.5
O'Grady	40	0.455	4782	2.0	0.3	0.5
Rask	10	0.018	539	1.1	0.2	0.0
Rosconnell	50	0.090	1267	1.2	7.0	0.0
Rosroe	30	1.085	8644	2.3	27.9	2.4
Rushaun	71	0.034	756	1.2	2.8	0.1
Tullabrack	40	24598	701	1.3	5.6	1.1

Based on the bathymetric data collated from previous studies for ten of the studied lakes and the results of the survey carried out on fifteen lakes in October 2001, a positive significant correlation was found between Log_{10}(Lake area) and Log_{10}(Lake volume) (Pearson's Product-Moment correlation, $r_p=0.86$, $n=25$, $p<0.01$) (Figure 2.19). Estimates of the lake volume were then calculated for the lakes that were not surveyed (Table 2.11), based on the linear regression model ($R^2=0.74$, $p\leq0.0001$), by applying:

$$\textbf{Log}_{10}\textbf{(Lake Volume)} = 1.1891 * \textbf{Log}_{10}\textbf{(Lake Area)} - 6.4779 \qquad \textbf{Equation 2.4}$$

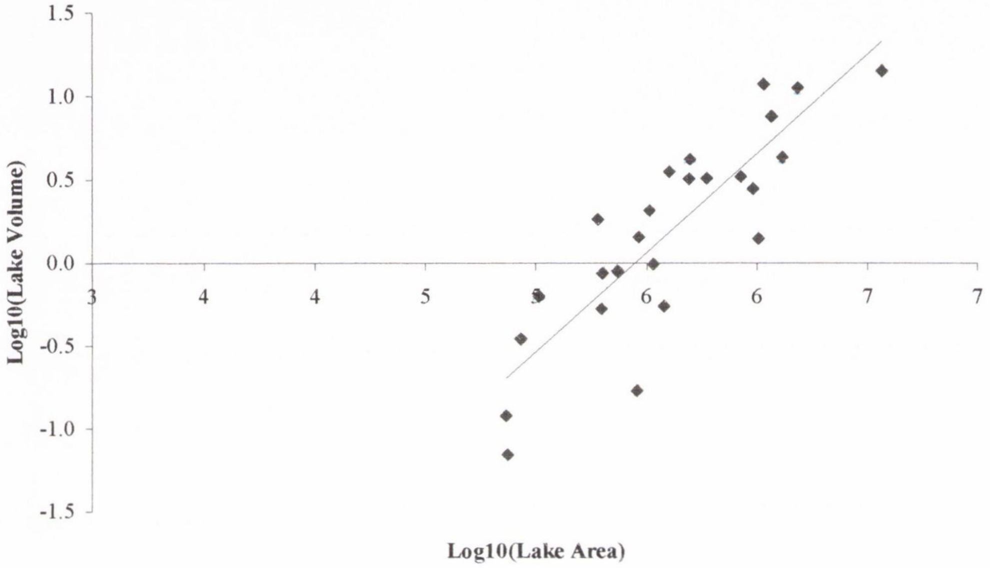

Figure 2.19: Linear Regression Log_{10}(Lake area) compared with Log_{10}(Lake volume) ($r_p=0.86$, $p<0.01$, $n=25$) based on the bathymetric data collated from previous studies for ten lakes and bathymetric survey carried out in October 2001 for fifteen lakes. Lake volume are expressed in 10^6 m^3 and lake area in m^2, with ♦: Log_{10}(Lake Volume) and —: Linear regression (Log_{10}(Lake volume)) ($y = 1.1891*x - 6.4779$; $R^2=0.74$, $p\leq0.0001$)

Table 2.11: Lake Bathymetry, presenting lake area and lake volume. Lake volume data have been collated either from previous studies; GPS survey in 2001 or estimated by applying the linear regression model (Equation 2.4). Mean depth, estimated based on the ratio lake volume/lake area is also shown

Name	Area (km^2)	Lake Vol. (10^6 m^3)	Mean Depth (m)	Source
Achryane	0.074	0.20	2.8	Linear regression
Acrow	0.054	0.14	2.6	Linear regression
Aillbrack	0.045	0.11	2.5	Linear regression
Atedaun	0.380	0.55	1.4	GPS Survey
Ballyallia	0.326	2.07	6.3	GPS Survey
Ballybeg	0.197	0.53	2.7	GPS Survey
Ballycar	0.030	0.07	2.3	Linear regression
Ballycullinan	0.286	0.17	0.6	Allott, 1990
Ballydoolavan	0.005	0.01	1.7	Linear regression
Ballyeighter	0.276	0.93	3.6	Linear regression
Ballyleann	0.053	0.14	2.6	Linear regression

Table 2.11 (continued)

Name	**Area** (km^2)	**Lake Vol.** **(10^6 m^3)**	**Mean Depth** **(m)**	**Source**
Ballyteige	0.142	0.45	3.1	Linear regression
Black *Kilk*	0.001	0.00	1.2	Linear regression
Black *Dro*	0.075	0.07	0.9	Allott, 1990
Bridget	0.537	2.17	4.0	Linear regression
Bunny	1.026	1.4	1.4	Ragneborn-Tough, 1993
Burke	0.103	0.63	6.1	Linear regression
Castle	0.231	0.79	3.4	Linear regression
Caum	0.068	0.18	2.7	Linear regression
Clonlea	0.401	3.52	8.8	Clare County Council, 1990
Cloonmackan	0.234	0.89	3.8	GPS Survey
Cloonsnaghta	0.086	0.35	4.1	GPS Survey
Cullaun	0.497	4.2	8.5	Allott, 1990
Cullaunyheeda	1.528	11.24	7.4	GPS Survey
Curtins	0.012	0.02	2.0	Linear regression
Doolough	1.302	4.3	3.3	Irvine *et al*, 1998
Doon	0.591	3.23	5.5	GPS Survey
Dromoland	0.117	0.35	3.0	Linear regression
Dromore	0.491	3.2	6.5	Allott, 1990
Drumcullaun	0.220	0.75	3.4	Linear regression
Druminure	0.028	0.07	2.3	Linear regression
Eanagh	0.010	0.02	1.9	Linear regression
Effernan	0.103	0.30	3.0	Linear regression
Farrihy	0.127	0.39	3.1	Linear regression
Finn	0.739	3.16	4.3	Linear regression
Garvillaun	0.023	0.05	2.2	Linear regression
Gash	0.186	0.62	3.3	Linear regression
George	0.013	0.02	2.0	Linear regression
Girroga	0.046	0.12	2.5	Linear regression
Goller	0.089	0.26	2.9	Linear regression
Gortaganniv	0.032	0.08	2.4	Linear regression
Gorteen	0.034	0.08	2.4	Linear regression
Gortglass	0.292	1.43	4.9	GPS Survey
Graney	3.681	14.2	3.9	Irvine *et al*, 2001
Inchichronan	1.167	7.55	6.5	GPS Survey
Inchiquin	1.069	11.8	11.0	Allott, 1990
Keagh	0.069	0.19	2.7	Linear regression
Kilgory	0.357	1.33	3.7	Linear regression
Killone	0.191	1.82	9.5	GPS Survey
Knockalough	0.339	0.98	2.9	GPS Survey
Knockerra	0.073	0.12	1.6	GPS Survey
Lickeen	0.844	3.3	3.9	Irvine *et al*, 1998
Lisnahan	0.059	0.16	2.7	Linear regression
Luirk	0.112	0.33	3.0	Linear regression
Luogh	0.049	0.13	2.6	Linear regression
Moanmore	0.121	0.37	3.0	Linear regression
Mooghna	0.033	0.08	2.4	Linear regression
More	0.093	0.27	2.9	Linear regression
Morgans	0.012	0.02	2.0	Linear regression
Muckanagh	0.961	2.79	2.9	GPS Survey
Muckinish	0.026	0.06	2.3	Linear regression
Naminna	0.200	0.87	4.4	GPS Survey
O'Briens *Big Lough*	0.189	0.63	3.3	Linear regression
O'Grady	0.455	1.78	3.9	Linear regression
Rask	0.018	0.04	2.1	Linear regression

Table 2.11 (continued)

Name	Area (km^2)	Lake Vol. (10^6 m^3)	Mean Depth (m)	Source
Rosconnell	0.090	0.26	2.9	Linear regression
Rosroe	1.085	5.00	4.6	Linear regression
Rushaun	0.034	0.08	2.4	Linear regression
Tullabrack	24598	0.06	2.3	Linear regression

Ten lakes had an estimated mean depth (based on the ratio Lake volume / Lake area) greater than 5.0 m, with a maximum value of 11.0 m estimated for Lough Inchiquin. The lowest mean depth (0.6m) was estimated for Lough Ballycullinan (Table 2.11). Three lakes had a volume greater than 10 10^6m^3, with a maximum of 14.2 10^6m^3 estimated for Lough Graney; while forty-nine lakes had a volume less than 10^6m^3, with a minimum value of 0.0010 10^6m^3 estimated for Lough Black (near Kilkee) (Table 2.11). Limnological variables were significantly correlated with catchment physical characteristics (Table 2.12).

Table 2.12: Spearman's Rank correlation coefficients between limnological variables and catchment physical characteristics ($n=69$, $p \leq 0.01$).

	% Carboniferous Limestones	% Shales & Similar rocks	Log(Catchment area)	Log (Maximum Catchment Slope)
Log(Lake Area)	0.33	-0.41	0.66	0.36
Log(Lake Volume)	0.31	-0.39	0.69	0.33
Log(Lake Shoreline)	0.37	-0.44	0.64	
% Upstream Lakes	0.38	-0.43		
Lake altitude	-0.74	0.66	-0.53	
% Main Lake			-0.42	-0.41

Climate data

Monthly rainfall data were estimated for each catchment for 2000 and 2001, as well as based on the past annual averages rainfall 1961-1990 (Tables 2 to 4 – Appendix 1). Maps of surface rainfall were also produced using G.I.S. and are presented in Appendix 1 (Figures 16 to 18). Tables and maps of rainfall are also provided in the associated CD-Rom (Appendix 1/Rainfall data).

Rainfall estimates were based on monthly rainfall data recorded in twenty-two stations in Clare, located at variable altitude (6 to 343 m) and in fourteen stations in 2001, with altitude ranging between 12 and 122 m. Summary rainfall data were calculated as annual rainfall averages for each catchment in 2000, 2001 and over the monitoring period 2000-01. Also, summary annual rainfall averages were estimated based on the past data 1961-90 (Table 2.13). Minimum annual rainfall was recorded for Lough Dromoland and maximum rainfall for Lough Caum (Table 2.13). The mean difference recorded between annual rainfall 2000 and 2001 was 418 mm with greater rainfall recorded in 2000. Annual rainfall averages 2000-01 were positively correlated (n=69, p<0.01) with mean catchment elevation (r=0.51) and mean catchment slope (r=0.33).

Table 2.13: Long-term and Contemporary Run-off data for the catchments included in the study, expressed as gross rainfall in mm for 1961-90, 2000, 2001 and over the monitoring period 2000-01. Evapotranspiration data (mm) recorded at Shannon Airport are also shown.

ID	Name	1961-90	2000	2001	2000-01
1	Achryane	1295	1542	1131	1337
2	Acrow	1303	1584	1160	1372
3	Aillbrak	1258	1592	1130	1361
4	Atedaun	1370	1559	1060	1309
5	Ballyallia	1147	1412	978	1195
6	Ballybeg	1121	1374	975	1174
7	Ballycar	1058	1234	893	1064
8	Ballycullinan	1243	1530	1081	1305
9	Ballydoolavan	1223	1498	1101	1300
10	Ballyeighter	1284	1508	994	1251
11	Ballyleann	1129	1403	1046	1225
12	Ballyteige	1366	1557	1058	1307
13	Black *Kilk*	1085	1387	1036	1212
14	Black *Dro*	1179	1414	967	1190
15	Bridget	1097	1289	900	1095
16	Bunny	1358	1548	1029	1289
17	Burke	1313	1641	1186	1414
18	Castle	1099	1301	908	1105
19	Caum	1501	1723	1278	1500
20	Clonlea	1080	1267	928	1097
21	Cloonmackan	1483	1705	1257	1481
22	Cloonsnaghta	1151	1444	1068	1256
23	Cullaun	1266	1487	993	1240
24	Cullaunyheeda	1085	1243	923	1083
25	Curtins	1413	1671	1215	1443
26	Doolough	1373	1608	1190	1399
27	Doon	1105	1310	902	1106
28	Dromoland	1037	1207	864	1036
29	Dromore	1185	1426	970	1198
30	Drumcullaun	1404	1665	1216	1440
31	Druminure	1334	1599	1143	1371
32	Eanagh	1254	1557	1109	1333
33	Effernan	1127	1415	1051	1233
34	Farrihy	1084	1386	1036	1211
35	Finn	1067	1248	907	1078
36	Garvillaun	1278	1581	1130	1355
37	Gash	1048	1221	881	1051
38	George	1241	1476	983	1229
39	Girroga	1121	1403	980	1192
40	Goller	1373	1541	1063	1302
41	Gortaganniv	1263	1613	1168	1390
42	Gorteen	1069	1276	936	1106
43	Gortglass	1149	1442	1067	1254

Table 2.13 (continued)

ID	Name	1961-90	2000	2001	2000-01
44	Graney	1124	1344	905	1125
45	Inchichronan	1131	1350	945	1148
46	Inchiquin	1461	1607	1093	1350
47	Keagh	1270	1606	1145	1375
48	Kilgory	1098	1293	896	1095
49	Killone	1124	1379	984	1182
50	Knockalough	1196	1484	1087	1285
51	Knockerra	1109	1373	1051	1212
52	Lickeen	1345	1532	1058	1295
53	Lisnahan	1093	1398	1041	1220
54	Luirk	1476	1597	1156	1376
55	Luogh	1285	1542	1069	1306
56	Moanmore	1081	1381	1035	1208
57	Mooghna	1297	1610	1134	1372
58	More	1200	1484	1083	1283
59	Morgans	1267	1564	1115	1339
60	Muckanagh	1218	1437	973	1205
61	Muckinish	1484	1593	1181	1387
62	Naminna	1339	1623	1196	1409
63	O'Briens *Big Lough*	1124	1335	945	1140
64	O'Grady	1108	1309	876	1092
65	Rask	1497	1596	1197	1397
66	Rosconnell	1351	1645	1188	1416
67	Rosroe	1070	1256	917	1087
68	Rushaun	1261	1608	1152	1380
69	Tullabrack	1092	1383	1040	1212
	Evapotranspiration	535	564	537	551

Water abstraction

Nine lakes included in the study are used as source of water supply by Clare County Council (Table 2.14). Lake flushing rates and retention time for these lakes (Table 2.14) could be influenced by the volume abstracted for water supply.

Table 2.14: List of lakes used as source of water supply, main towns and areas supplied and annual volumes abstracted.

Id	Lakes	Supply	DailyVolume abstracted (m^3 day^{-1})
7	Ballycar	Newmarket on Fergus	418
18	Castle		9091
26	Doolough	West Clare	15000
43	Gortglass	Kiladysert	1000
44	Graney	Flagmount	41
46	Inchiquin	Corrofin	454
47	Keagh	Miltown Mallbay	550
52	Lickeen	Ennistymon	4200
53	Lisnahan	Kilkee	365

Lake flushing rate and retention time

Lake flushing rates and retention times were estimated for each catchment in 2000, 2001 and over the monitoring period 2000-01 (Table 2.15). Over the monitoring period, annual average lake flushing rates ranged from 0.1 flushings/year for Lough Keagh, corresponding to a retention time of 4 years to 450.6 flushings/year for Lough Atedaun, corresponding to a retention time of less than a day.

The highest estimates of lake flushing rates found for Loughs Atedaun (450.6 flushings/year) and Ballyteige (258 flushings/year) are very high. Both lakes are receiving water from very large areas, draining both the Gort Lowlands and Fergus catchment. However, as they are located in karstic area, their hydrological regimes are highly influenced by underground groundwater connections (Coxon and Drew, 1999) (groundwater inputs from springs and outputs from swallow holes and sinks) and the catchment boundaries based on topographic divides may not represent accurately the lake drainage area.

Aquifers

Aquifer types in Clare were divided into three main categories. Area with locally important aquifers included sand/gravel locally important aquifers (Lg) and bedrock which is moderately productive only in local zones (Ll). Poor and unproductive aquifer areas included bedrock which is generally unproductive except for local zones (Pl) and bedrock which is generally unproductive (Pu). Finally, regionally important aquifers included karstified bedrock aquifers (Rk) (Deakin, 2000; Drew and Daly, 1993; GSI, 1999).

Forty-three catchments had more than 60% underlying locally important aquifers, while seventeen had more than 60% underlying karstified bedrock aquifers. Only two catchments (Loughs O'Grady and Graney) had more than 60% underlying poor and unproductive aquifers (Table 2.16; Figure 2.20).

Table 2.15: Estimates of annual average lake flushing rate (FR) and retention time (RT). Flushing rates are expressed per year and retention time in days for the years 2000, 2001 and over the monitoring period 2000-01. Estimates of annual past average flushing rates and retention time for the period 1961/90 are also shown. Flushing rates and retention time likely to be influenced by groundwater are underlined.

		1961-90		2000		2001		2000-01	
ID	Name	FR	RT	FR	RT	FR	RT	FR	RT
1	Achryane	4.8	0.2	6.2	0.2	5.0	0.2	5.6	0.2
2	Acrow	0.7	1.4	0.9	1.1	0.7	1.4	0.8	1.3
3	Aillbrak	0.9	1.1	1.3	0.8	1.0	1.1	1.2	0.9
4	Atedaun	429.0	0.0	511.3	0.0	389.8	0.0	450.6	0.0
5	Ballyallia	7.3	0.1	10.1	0.1	7.7	0.1	8.9	0.1
6	Ballybeg	4.6	0.2	6.3	0.2	4.9	0.2	5.6	0.2
7	Ballycar	3.3	0.3	4.3	0.2	3.2	0.3	3.8	0.3
8	Ballycullinan	24.2	0.0	32.9	0.0	25.7	0.0	29.3	0.0
9	Ballydoolavan	2.7	0.4	3.7	0.3	2.9	0.4	3.3	0.3
10	Ballyeighter	6.6	0.2	8.3	0.1	4.0	0.2	6.2	0.2
11	Ballyleann	2.8	0.4	4.0	0.3	3.2	0.3	3.6	0.3
12	Ballyteige	245.1	0.0	292.9	0.0	223.2	0.0	258.0	0.0
13	Black Kilk	3.3	0.3	0.6	1.7	2.2	0.5	1.4	1.1
14	Black Dro	0.7	1.4	5.6	0.2	3.0	1.1	4.3	0.7
15	Bridget	1.5	0.6	2.0	0.5	1.5	0.8	1.7	0.6
16	Bunny	45.6	0.0	54.5	0.0	40.9	0.0	47.7	0.0
17	Burke	2.8	0.4	3.9	0.3	3.1	0.3	3.5	0.3
18	Castle	53.3	0.0	70.4	0.0	52.3	0.0	61.4	0.0
19	Caum	7.3	0.1	8.8	0.1	7.2	0.1	8.0	0.1
20	Clonlea	0.9	1.2	1.1	0.9	0.9	1.3	1.0	1.1
21	Cloonmackan	3.0	0.3	3.6	0.3	3.0	0.4	3.3	0.3
22	Cloonsnaghta	2.2	0.5	3.1	0.3	2.5	0.4	2.8	0.4
23	Cullaun	14.2	0.1	17.9	0.1	13.3	0.1	15.6	0.1
24	Cullaunyheeda	1.4	0.7	1.8	0.6	1.4	0.8	1.6	0.7
25	Curtins	1.2	0.8	1.5	0.7	1.2	0.9	1.4	0.8

Table 2.15 (continued)

		1961-90		2000		2001		2000-01	
ID	**Name**	**FR**	**RT**	**FR**	**RT**	**FR**	**RT**	**FR**	**RT**
26	Doolough	3.2	0.3	4.3	0.2	3.2	0.3	3.7	0.3
27	Doon	17.6	0.1	23.0	0.0	17.1	0.1	20.1	0.1
28	Dromoland	1.4	0.7	1.7	0.6	1.3	0.9	1.5	0.7
29	Dromore	0.3	3.0	0.4	2.2	0.2	4.4	0.3	3.3
30	Drumcullaun	61.8	0.0	78.3	0.0	63.3	0.0	70.8	0.01
31	Druminure	1.0	1.0	1.3	0.8	1.0	1.0	1.2	0.9
32	Eanagh	1.7	0.6	2.4	0.4	1.9	0.6	2.1	0.5
33	Effernan	2.0	0.5	2.8	0.4	2.3	0.5	2.6	0.4
34	Farrihy	6.4	0.2	9.6	0.1	7.7	0.1	8.6	0.1
35	Finn	0.6	1.5	0.8	1.2	0.6	1.7	0.7	1.5
36	Garvillaun	1.0	1.0	1.4	0.7	1.1	1.0	1.2	0.8
37	Gash	1.3	0.8	1.6	0.6	1.2	0.9	1.4	0.8
38	George	8.0	0.1	10.3	0.1	7.7	0.1	9.0	0.1
39	Girroga	1.1	0.9	1.5	0.7	1.2	0.9	1.3	0.8
40	Goller	2.9	0.3	3.4	0.3	2.6	0.4	3.0	0.4
41	Gortaganniv	2.7	0.4	3.9	0.3	3.1	0.3	3.5	0.3
42	Gorteen	3.8	0.3	5.0	0.2	3.9	0.3	4.5	0.2
43	Gortglass	0.6	1.5	1.0	1.0	0.8	1.4	0.9	1.2
44	Graney	4.6	0.2	6.1	0.2	4.5	0.3	5.3	0.2
45	Inchichronan	2.6	0.4	3.5	0.3	2.6	0.4	3.1	0.4
46	Inchiquin	11.5	0.1	13.0	0.1	10.0	0.1	11.5	0.1
47	Keagh	0.0	21.9	0.2	5.4	0.1	2.7	0.1	4.0
48	Kilgory	5.6	0.2	7.2	0.1	5.4	0.2	6.3	0.2
49	Killone	0.4	2.4	0.6	1.7	0.4	2.5	0.5	2.1
50	Knockalough	1.7	0.6	2.4	0.4	1.9	0.6	2.2	0.5
51	Knockerra	2.2	0.5	3.1	0.3	2.5	0.4	2.8	0.4
52	Lickeen	1.7	0.6	2.1	0.5	1.5	0.8	1.8	0.6
53	Lisnahan	0.5	2.2	0.8	1.3	0.6	1.9	0.7	1.6
54	Luirk	17.1	0.1	18.7	0.1	15.0	0.1	16.9	0.1

Table 2.15 (continued)

		1961-90		2000		2001		2000-01	
ID	**Name**	**FR**	**RT**	**FR**	**RT**	**FR**	**RT**	**FR**	**RT**
55	Lough	1.7	0.6	2.3	0.4	1.7	0.6	2.0	0.5
56	Moanmore	2.0	0.5	3.0	0.3	2.4	0.4	2.7	0.4
57	Mooghna	1.8	0.6	2.4	0.4	1.9	0.6	2.2	0.5
58	More	1.0	1.0	1.4	0.7	1.1	1.0	1.3	0.8
59	Morgans	0.5	2.1	0.6	1.6	0.5	2.1	0.6	1.9
60	Muckanagh	9.6	0.1	12.3	0.1	9.2	0.1	10.8	0.1
61	Muckinish	4.0	0.2	4.4	0.2	3.6	0.3	4.0	0.3
62	Naminna	1.9	0.5	2.5	0.4	2.0	0.5	2.3	0.5
63	O'Briens Big Lough	1.4	0.7	1.8	0.5	1.4	0.8	1.6	0.7
64	O'Grady	41.2	0.0	53.6	0.0	39.0	0.0	46.3	0.0
65	Rask	16.6	0.1	17.8	0.1	14.6	0.1	16.2	0.1
66	Rosconnell	1.4	0.7	1.8	0.6	1.4	0.7	1.6	0.6
67	Rosroe	0.4	2.3	0.6	1.8	0.4	2.5	0.5	2.1
68	Rushaun	1.6	0.6	2.3	0.4	1.8	0.6	2.1	0.5
69	Tullabrack	0.5	2.1	0.7	1.4	0.6	1.9	0.6	1.6

Table 2.16: Catchment underlying aquifer coverage, expressed as % of total catchment area. Aquifer types are described as Locally important aquifers (L), sub-divided into Lg and Ll; poor and unproductive aquifers (P), sub-divided into Pl and Pu; and regionally important aquifers (R), with Rk. Datasets only available for the Clare part of the catchments are underlined.

		L		P		R
ID	**Name**	**Lg**	**Ll**	**Pl**	**Pu**	**Rk**
1	Achryane	0	100	0	0	0
2	Acrow	0	100	0	0	0
3	Aillbrak	0	100	0	0	0
4	Atedaun	0	15	0	6	70
5	Ballyallia	0	20	0	0	80
6	Ballybeg	0	11	0	8	82
7	Ballycar	0	80	0	0	20
8	Ballycullinan	0	55	0	4	40
9	Ballydoolavan	0	100	0	0	0
10	Ballyeighter	0	0	0	0	100
11	Ballyleann	0	100	0	0	0
12	Ballyteige	0	14	0	5	71
13	Black *Kilk*	0	100	0	0	0
14	Black *Dro*	0	0	0	0	100
15	Bridget	0	100	0	0	0
16	Bunny	0	0	0	0	86
17	Burke	0	100	0	0	0
18	Castle	5	50	36	2	7
19	Caum	0	100	0	0	0
20	Clonlea	0	27	0	0	73
21	Cloonmackan	0	100	0	0	0
22	Cloonsnaghta	0	100	0	0	0
23	Cullaun	0	0	0	0	66
24	Cullaunyheeda	0	47	0	0	53
25	Curtins	0	100	0	0	0
26	Doolough	0	100	0	0	0
27	Doon	7	48	41	0	3
28	Dromoland	0	0	0	0	100
29	Dromore	0	0	0	0	100
30	Drumcullaun	0	100	0	0	0
31	Druminure	0	100	0	0	0
32	Eanagh	0	100	0	0	0
33	Effernan	0	100	0	0	0
34	Farrihy	0	100	0	0	0
35	Finn	0	75	0	0	25
36	Garvillaun	0	100	0	0	0
37	Gash	0	70	0	0	30
38	George	0	0	0	0	100
39	Girroga	0	0	0	0	100
40	Goller	0	100	0	0	0
41	Gortaganniv	0	100	0	0	0
42	Gorteen	0	98	2	0	0
43	Gortglass	0	100	0	0	0
44	Graney	0	0	82	0	0

Table 2.16 (continued)

		L		P		R
ID	**Name**	**Lg**	**Ll**	**Pl**	**Pu**	**Rk**
45	Inchichronan	0	53	47	0	0
46	Inchiquin	0	13	0	10	78
47	Keagh	0	100	0	0	0
48	Kilgory	0	93	6	0	2
49	Killone	0	31	0	17	51
50	Knockalough	0	100	0	0	0
51	Knockerra	0	100	0	0	0
52	Lickeen	0	100	0	0	0
53	Lisnahan	0	100	0	0	0
54	Luirk	0	0	0	0	100
55	Luogh	0	100	0	0	0
56	Moanmore	0	100	0	0	0
57	Mooghna	0	100	0	0	0
58	More	0	100	0	0	0
59	Morgans	0	100	0	0	0
60	Muckanagh	0	0	0	0	30
61	Muckinish	0	0	0	0	100
62	Naminna	0	100	0	0	0
63	O'Briens *Big Lough*	0	76	24	0	0
64	O'Grady	0	33	67	0	0
65	Rask	0	0	0	0	100
66	Rosconnell	0	100	0	0	0
67	Rosroe	0	100	0	0	0
68	Rushaun	0	100	0	0	0
69	Tullabrack	0	100	0	0	0

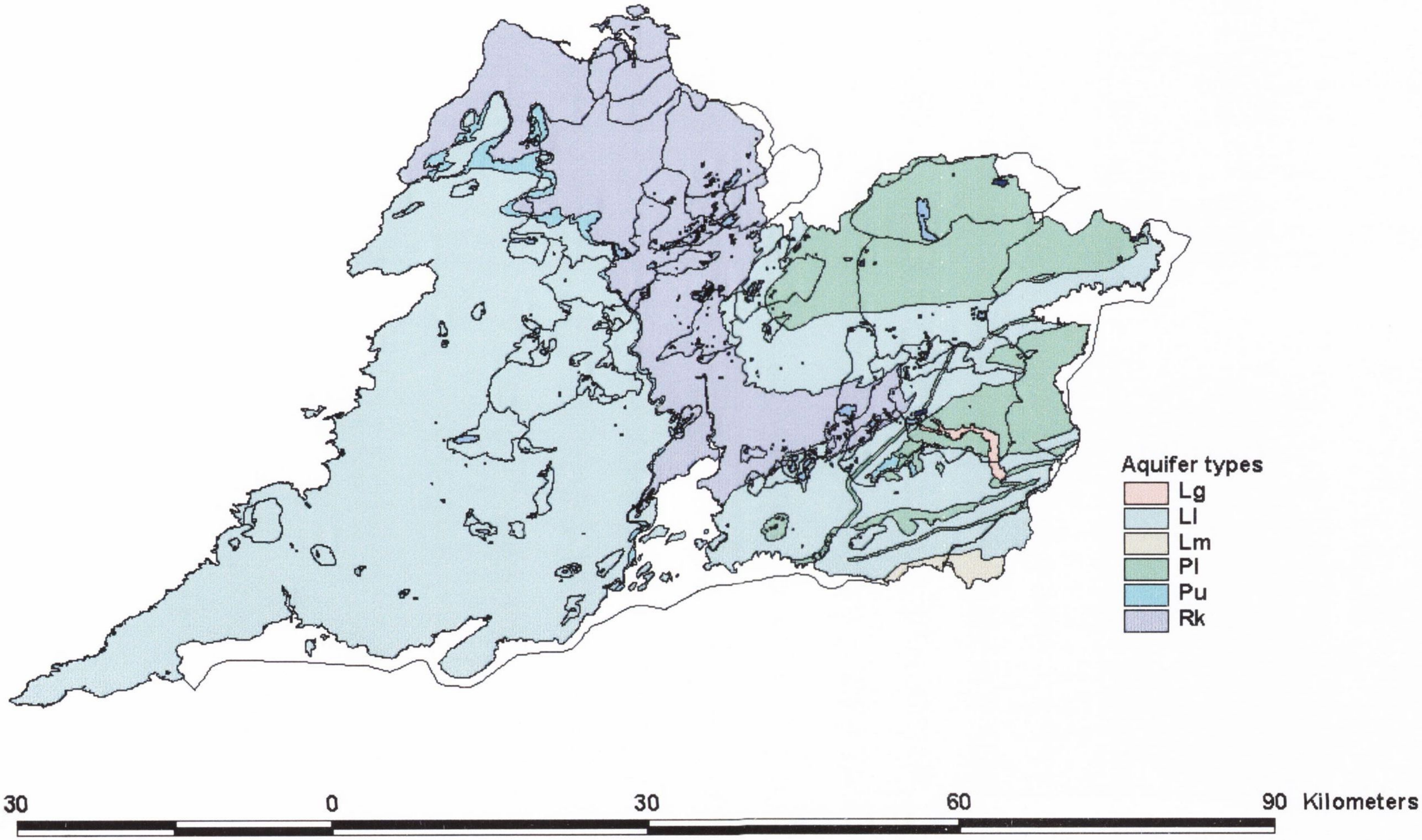

Figure 2.20: Underlying aquifer types, referring to Table 2.15; also showing the boundaries of the catchments included in the study. Data were not available for the Galway parts of the eastern catchments.

II-5.3 Land cover variables

CORINE land cover

Based on the CORINE datasets from 1989/90 updated by the forestry coverage from 1998 (FIPS, 1998), land cover coverages were estimated for each catchment included in the study (Figure 2.21). Land covers were summarised into:

- improved, unimproved and mixed grasslands; arable and mixed agriculture (including complex cultivation and principally agricultural land cover classes) (Table 2.17),
- total peatlands (including unexploited and exploited peat bogs and moors and heathlands land cover classes); semi-natural areas (including natural grasslands, sparsely vegetated, transitional woodland and scrub and bare rocks land cover classes), artificial surfaces (including artificial and green urban areas land cover classes) and marshes (Table 2.18),
- mixed, conifers and broadleaved forests (Table 2.19).

Detailed CORINE coverage for each catchment is provided in the associated CD-Rom (Appendix 1/Summary catchment descriptive variables).

Twenty-three catchments had more than 60% of their catchment area covered with pasture, while seven had more than 60% coverage with peatlands. For thirty-eight catchments, more than 60% of their area comprised agricultural land covers.

Table 2.17: Land cover types based on CORINE dataset 1989/90 updated by forestry coverage, 1998, showing proportion of arable; improved, unimproved and mixed grasslands (resp. HPG, LPG and MG) and mixed agriculture (Mixed Agri.) (Total peatlands), expressed as % of the total catchment area. Total pasture (HPG + LPG + MG) and Total agricultural area (Total Agri. = Total pasture + Mixed Agri. + Arable) are also provided.

ID	Catchment	Arable	HPG	LPG	MG	Total Pasture	Mixed Agri.	Total Agri.
1	Achryane	0	10	9	3	22	0	22
2	Acrow	0	0	0	0	0	0	0
3	Aillbrak	0	7	2	0	9	59	68
4	Atedaun	0	22	9	12	43	6	49
5	Ballyallia	0	44	11	0	56	22	78
6	Ballybeg	0	22	0	30	52	0	52
7	Ballycar	0	64	5	0	69	0	69
8	Ballycullinan	0	7	9	22	38	29	68
9	Ballydoolavan	0	0	11	54	66	14	80
10	Ballyeighter	0	24	0	20	44	0	44
11	Ballyleann	0	12	0	33	45	53	98
12	Ballyteige	0	22	9	12	43	6	49
13	Black-Kilk	0	85	0	0	85	0	85
14	Black-Dro	0	1	0	9	10	0	10
15	Bridget	0	54	3	7	63	14	78
16	Bunny	0	25	2	1	28	6	34
17	Burke	0	0	98	0	98	1	99
18	Castle	0	30	15	19	65	1	65
19	Caum	0	0	0	0	0	53	53

Table 2.17 (continued)

ID Catchment	Arable	HPG	LPG	MG	Total Pasture	Mixed Agri.	Total Agri.
20 Clonlea	0	51	29	0	80	0	80
21 Cloonmackan	0	0	41	0	41	1	42
22 Cloonsnaghta	0	0	54	41	96	0	96
23 Cullaun	0	36	7	11	54	4	59
24 Cullaunyheeda	0	25	17	15	57	11	68
25 Curtins	0	0	11	18	29	68	97
26 Doolough	0	3	20	0	23	5	28
27 Doon	0	25	15	20	60	1	61
28 Dromoland	0	35	0	0	35	0	35
29 Dromore	0	0	0	16	16	0	16
30 Drumcullaun	0	4	21	9	35	26	60
31 Druminure	0	0	0	31	31	0	31
32 Eanagh	0	0	39	12	51	16	67
33 Effernan	0	0	3	28	32	43	75
34 Farrihy	0	88	0	0	88	0	88
35 Finn	0	32	5	0	38	8	46
36 Garvillaun	0	0	28	38	66	0	66
37 Gash	0	56	15	5	76	1	77
38 George	0	23	0	53	76	0	76
39 Girroga	0	46	0	0	46	0	46
40 Goller	0	2	29	0	32	0	32
41 Gortaganniv	0	20	70	0	90	10	100
42 Gorteen	0	0	4	3	7	2	8
43 Gortglass	0	0	48	24	73	7	80
44 Graney	0	7	3	17	26	3	29
45 Inchichronan	0	9	13	13	35	12	47
46 Inchiquin	0	18	10	4	32	8	40
47 Keagh	0	0	0	0	0	0	0
48 Kilgory	0	40	7	30	77	6	82
49 Killone	0	3	0	72	75	0	75
50 Knockalough	0	50	1	0	51	18	69
51 Knockerra	0	0	97	3	100	0	100
52 Lickeen	0	0	43	2	45	18	63
53 Lisnahan	0	96	0	0	96	0	96
54 Luirk	0	38	1	1	40	0	40
55 Luogh	0	0	0	0	0	0	0
56 Moanmore	0	0	18	0	18	10	27
57 Mooghna	0	14	17	32	63	0	63
58 More	0	67	0	0	67	0	67
59 Morgans	0	0	8	2	10	90	100
60 Muckanagh	1	49	13	3	65	6	71
61 Muckinish	0	20	0	0	20	0	20
62 Naminna	0	0	0	0	0	0	0
63 O'Briens Big Lou	0	0	0	55	55	2	57
64 O'Grady	0	24	18	23	65	2	68
65 Rask	0	24	0	0	24	0	24
66 Rosconnell	0	0	70	2	72	0	72
67 Rosroe	0	23	16	0	39	0	39
68 Rushaun	0	40	0	38	78	22	100
69 Tullabrack	0	17	83	0	100	0	100

Table 2.18: Land cover types based on CORINE dataset 1989/90 updated by forestry coverage, 1998, showing proportion of total peatlands, semi-natural areas, artificial surfaces and marshes, expressed as % of the total catchment area.

ID	Catchment	Total Peatlands	Semi-Natural Areas	Artificial Surfaces	Marshes
1	Achryane	69	0	0	0
2	Acrow	75	5	0	0
3	Aillbrak	32	0	0	0
4	Atedaun	4	39	0	0
5	Ballyallia	0	5	0	2
6	Ballybeg	0	9	0	0
7	Ballycar	0	18	0	0
8	Ballycullinan	2	8	0	0
9	Ballydoolavan	12	0	0	0
10	Ballyeighter	4	45	0	0
11	Ballyleann	0	2	0	0
12	Ballyteige	4	38	0	1
13	Black-Kilk	10	3	0	0
14	Black-Dro	0	11	0	0
15	Bridget	0	5	0	0
16	Bunny	0	59	0	1
17	Burke	0	0	0	0
18	Castle	14	2	0	0
19	Caum	35	8	0	0
20	Clonlea	0	9	0	0
21	Cloonmackan	10	20	0	0
22	Cloonsnaghta	0	4	0	0
23	Cullaun	7	27	0	1
24	Cullaunyheeda	8	9	0	0
25	Curtins	0	0	0	0
26	Doolough	49	0	0	0
27	Doon	18	2	0	0
28	Dromoland	0	0	21	0
29	Dromore	0	4	0	0
30	Drumcullaun	24	8	0	0
31	Druminure	69	0	0	0
32	Eanagh	15	0	0	0
33	Effernan	3	0	0	3
34	Farrihy	12	0	0	0
35	Finn	0	32	0	0
36	Garvillaun	0	34	0	0
37	Gash	0	0	13	0
38	George	0	17	0	0
39	Girroga	0	18	2	0
40	Goller	64	0	0	0
41	Gortaganniv	0	0	0	0
42	Gorteen	34	0	0	0
43	Gortglass	1	2	0	0
44	Graney	31	2	0	0
45	Inchichronan	16	19	0	0
46	Inchiquin	2	52	0	0
47	Keagh	99	0	0	0
48	Kilgory	5	2	0	0

Table 2.18 (continued)

ID	Catchment	Total Peatlands	Semi-Natural Areas	Artificial Surfaces	Marshes
49	Killone	0	0	0	0
50	Knockalough	0	17	0	0
51	Knockerra	0	0	0	0
52	Lickeen	18	0	0	0
53	Lisnahan	0	4	0	0
54	Luirk	0	59	0	0
55	Luogh	100	0	0	0
56	Moanmore	72	0	0	0
57	Mooghna	32	0	0	0
58	More	33	0	0	0
59	Morgans	0	0	0	0
60	Muckanagh	12	11	0	2
61	Muckinish	0	80	0	0
62	Naminna	36	0	0	0
63	O'Briens Big Lou	10	0	0	25
64	O'Grady	11	5	0	0
65	Rask	0	76	0	0
66	Rosconnell	18	0	0	0
67	Rosroe	0	24	0	0
68	Rushaun	0	0	0	0
69	Tullabrack	0	0	0	0

Table 2.19: Land cover types based on CORINE dataset 1989/90 updated by forestry coverage, 1998, showing proportion of mixed, conifer and broadleaved forests, expressed as % of the total catchment area.

ID	Catchment	Mixed forest	Conifer forest	Broadleaf forest
1	Achryane	0	9	0
2	Acrow	0	20	0
3	Aillbrak	0	0	0
4	Atedaun	0	1	4
5	Ballyallia	3	0	10
6	Ballybeg	1	1	25
7	Ballycar	0	0	0
8	Ballycullinan	0	9	8
9	Ballydoolavan	3	5	0
10	Ballyeighter	3	0	1
11	Ballyleann	0	0	0
12	Ballyteige	0	1	5
13	Black-Kilk	0	0	0
14	Black-Dro	3	0	31
15	Bridget	1	0	5
16	Bunny	0	0	1
17	Burke	1	0	1
18	Castle	1	13	2
19	Caum	0	4	0
20	Clonlea	0	0	0
21	Cloonmackan	0	18	0
22	Cloonsnaghta	0	0	0

Table 2.19 (continued)

ID	Catchment	Mixed forest	Conifer forest	Broadleaf forest
23	Cullaun	0	0	3
24	Cullaunyheeda	3	2	4
25	Curtins	0	3	0
26	Doolough	0	15	0
27	Doon	1	14	2
28	Dromoland	23	5	17
29	Dromore	5	0	42
30	Drumcullaun	0	6	0
31	Druminure	0	0	0
32	Eanagh	0	17	1
33	Effernan	0	13	0
34	Farrihy	0	0	0
35	Finn	0	0	0
36	Garvillaun	0	0	0
37	Gash	0	0	3
38	George	0	0	7
39	Girroga	0	0	34
40	Goller	0	0	0
41	Gortaganniv	0	0	0
42	Gorteen	3	47	8
43	Gortglass	0	0	0
44	Graney	0	35	1
45	Inchichronan	0	9	4
46	Inchiquin	0	2	4
47	Keagh	0	1	0
48	Kilgory	1	1	3
49	Killone	0	0	6
50	Knockalough	0	0	0
51	Knockerra	0	0	0
52	Lickeen	0	7	1
53	Lisnahan	0	0	0
54	Luirk	0	0	1
55	Luogh	0	0	0
56	Moanmore	0	0	0
57	Mooghna	0	5	0
58	More	0	0	0
59	Morgans	0	0	0
60	Muckanagh	0	0	1
61	Muckinish	0	0	0
62	Naminna	2	53	0
63	O'Briens Big Lou	0	5	2
64	O'Grady	0	14	2
65	Rask	0	0	1
66	Rosconnell	0	8	2
67	Rosroe	0	0	4
68	Rushaun	0	0	0
69	Tullabrack	0	0	0

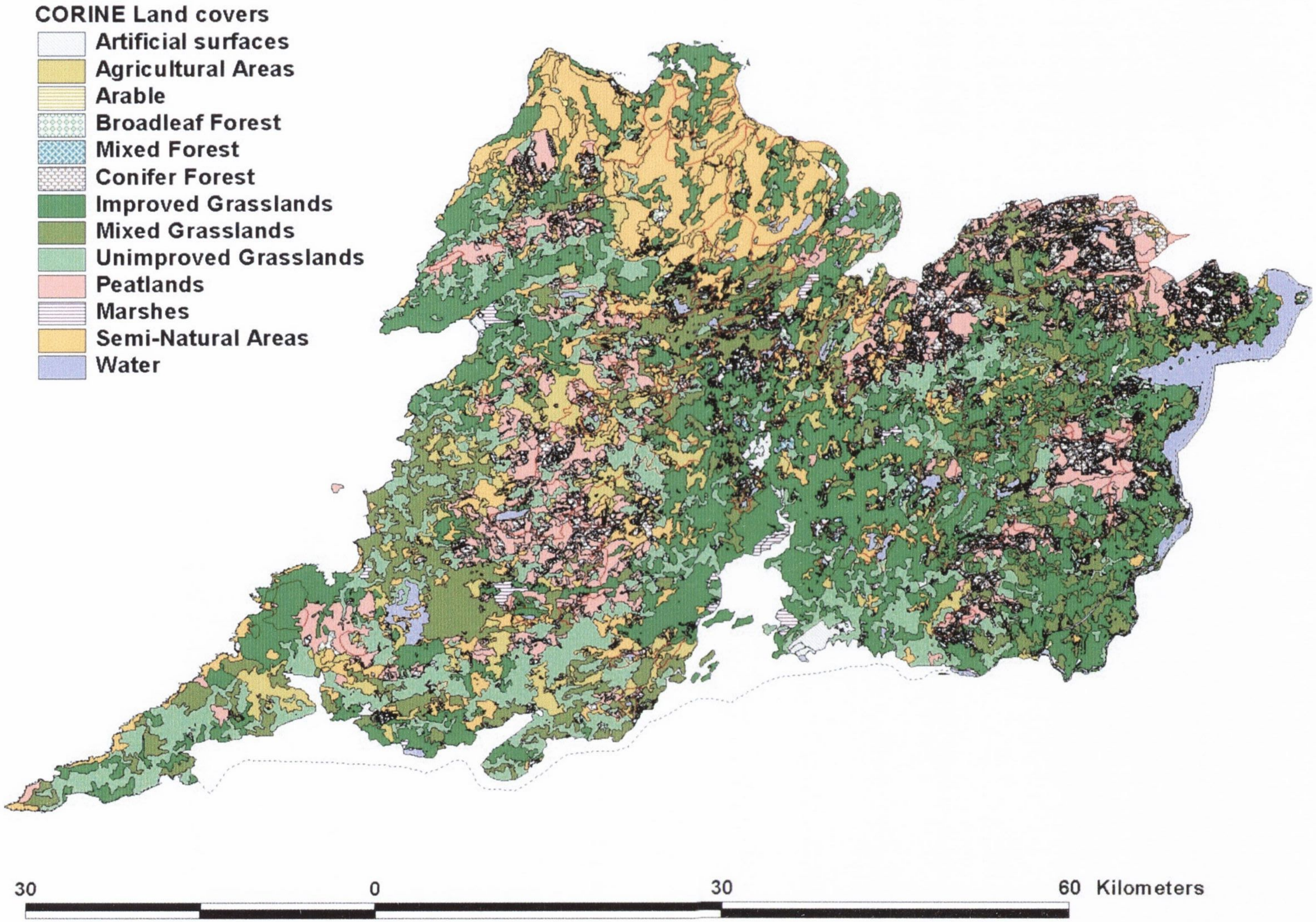

Figure 2.21: Land cover distribution based on the CORINE coverage 1989/90 updated by FIPS data, 1998, also showing outlines of catchment boundaries

The occurrence of carboniferous limestone was negatively correlated (n=69) with total peatlands (r=-0.45; p<0.01) and conifer forests (r=-0.25; p<0.05); while positively correlated (n=69, p<0.01) with high productivity grasslands (r=0.61) and broadleaf forests (r=0.62). Shales and similar rock types were positively correlated with total peatlands (r=0.28, n=69, p<0.05), while negatively correlated (n=69, p<0.01) with high productivity grasslands (r=-0.56) and broadleaf forests (r=-0.67) (Figures 2.22 to 2.25).

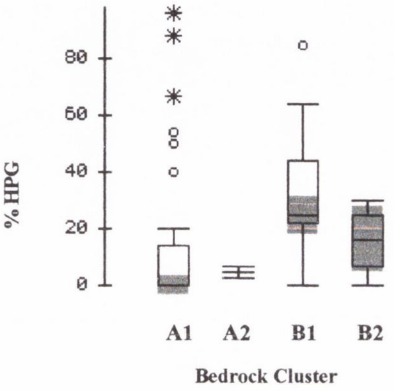

Figure 2.22: Distribution of % improved grasslands (HPG) among the different bedrock cluster types, as described in Table 2.7.

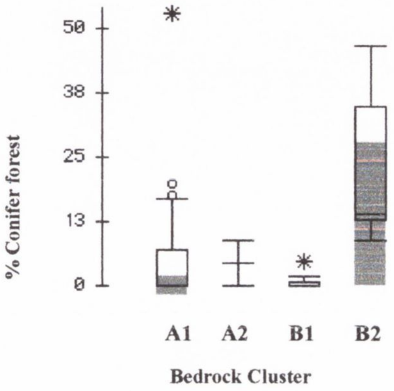

Figure 2.24: Distribution of % Conifer forest among the different bedrock cluster types, as described in Table 2.7.

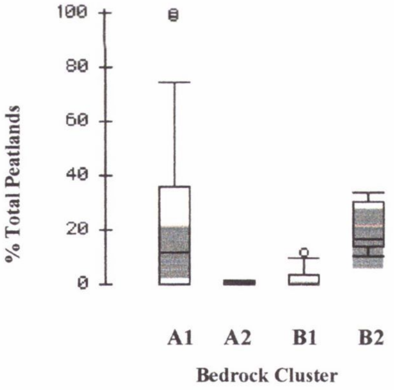

Figure 2.23: Distribution of % Total Peatlands among the different bedrock cluster types, as described in Table 2.7.

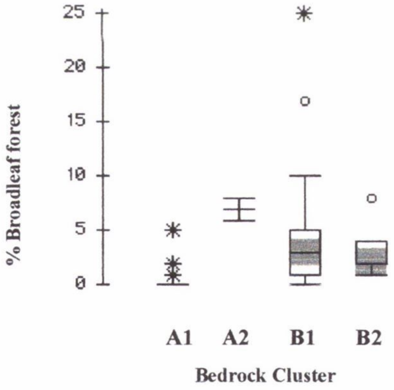

Figure 2.25: Distribution of % Broadleaf forest among the different bedrock cluster types, as described in Table 2.7.

Catchment land uses were significantly correlated (Spearman's Rank correlations, Table 2.20), with physical variables (topography and soil characteristics). Grasslands and broadleaf forests were usually associated with lower elevation, well drained soils, such as grey brown podzolics, brown earths and rendzinas and higher soil Morgan P levels; while peatlands and conifers were associated with greater elevation, steeper slope and poorly drained soils, such as peats, with lower soil Morgan P levels.

Table 2.20: Spearman's Rank correlation coefficients between catchment land uses (CORINE) and physical variables (n=69). Coefficients significant at p≤0.05 are in bold, and underlined if p≤0.01.

	Improved Grasslands	**Unimproved Grasslands**	**Mixed Grasslands**	**Total Grasslands**	**Mixed Agri.**	**Total Agri.**	**Mixed Forest**	**Conifer Forest**	**Broadleaf Forest**	**Total Peatlands**	**Semi-Natural Areas**
Mean Elevation	**-0.42**	0.12	0.03	**-0.39**	0.10	**-0.32**	-0.19	**0.50**	**-0.35**	**0.56**	-0.22
Mean Slope	-0.13	0.04	0.18	-0.13	0.10	-0.16	-0.10	**0.35**	0.03	0.13	0.04
Brown Earths	**0.39**	-0.17	0.18	0.20	0.01	0.10	**0.30**	-0.09	**0.52**	-0.29	0.31
Rendzinas	**0.27**	**-0.31**	0.07	-0.11	-0.11	-0.23	0.07	-0.18	**0.46**	-0.27	**0.57**
Grey Brown Podzolics	**0.54**	0.00	0.11	0.24	0.01	0.06	0.19	-0.02	**0.60**	-0.29	**0.33**
Peats	**-0.25**	0.18	**-0.27**	**-0.28**	0.10	-0.24	0.03	**0.40**	**-0.36**	**0.64**	**-0.41**
Gleys	-0.17	0.24	0.14	0.23	**0.29**	**0.43**	-0.12	0.06	-0.24	0.05	**-0.27**
Brown Podzolics	-0.06	**0.30**	0.12	0.09	0.18	0.16	-0.07	0.16	-0.17	0.13	-0.16
Podzols	-0.03	0.06	**0.27**	-0.05	0.08	-0.15	0.17	**0.48**	**0.27**	**0.27**	-0.05
Well drained soils	**0.62**	-0.24	0.05	0.21	-0.16	0.00	0.19	**-0.25**	**0.59**	**-0.47**	**0.51**
Poorly drained soils	**-0.48**	0.19	-0.11	-0.20	0.23	0.04	-0.14	**0.28**	**-0.54**	**0.50**	**-0.51**
Mean Soil P	**0.38**	-0.23	-0.06	0.05	-0.16	-0.05	0.12	-0.27	**0.47**	**-0.38**	**0.30**
Soil P Index	0.19	0.07	0.20	**0.34**	0.20	**0.42**	-0.01	-0.09	0.14	**-0.32**	0.02

Animal and Human densities

Animal densities in 2000 and human population densities in 2002 were estimated for each catchment, based on the Agricultural Census data of 2000 and Human Population Census of 2002 (Table 2.21) assuming the proportional distribution and density among DEDs. Cattle densities ranged between 0.04 cattle ha^{-1} for Lough Girroga to 2.14 cattle ha^{-1} for Lough Rosroe. Maximum sheep density was obtained for Lough Ballyeighter with 1.00 sheep ha^{-1}. Lough Ballyallia had the greatest human density with 3.30 people ha^{-1}. No significant correlations were found between sheep and human densities and catchment physical and hydrological variables. Cattle density was significantly positively correlated ($n=67$, $p<0.01$) with the occurrence of carboniferous limestone ($r=0.66$), while negatively correlated with shales and similar rock types ($r=-0.65$).

Table 2.21: Agricultural census data on cattle and sheep densities (CSO, 2000) and human population census data on human density (CSO, 2002)

ID	Catchment	Human density (/ha)	Cattle density (/ha)	Sheep density (/ha)
1	Achryane	0.17	0.99	0.07
2	Acrow	0.19	0.99	0.07
3	Aillbrak	0.24	1.41	0.11
4	Atedaun	0.11	0.86	0.34
5	Ballyallia	3.32	1.42	0.28
6	Ballybeg	0.94	1.03	0.36
7	Ballycar	0.24	1.50	0.28
8	Ballycullinan	0.16	1.09	0.33
9	Ballydoolavan	0.14	1.03	0.04
10	Ballyeighter	0.11	1.29	1.00
11	Ballyleann	0.12	0.60	0.07
12	Ballyteige	0.11	0.87	0.35
13	Black-Kilk	n/a	n/a	n/a
14	Black-Dro	0.02	0.16	0.00
15	Bridget	0.13	1.26	0.23
16	Bunny	0.07	0.73	0.46
17	Burke	0.23	0.85	0.00
18	Castle	0.15	1.02	0.26
19	Caum	0.13	0.69	0.00
20	Clonlea	0.39	1.49	0.32
21	Cloonmackan	0.10	0.55	0.00
22	Cloonsnaghta	0.13	0.68	0.09
23	Cullaun	0.12	0.94	0.51
24	Cullaunyheeda	0.29	1.39	0.32
25	Curtins	0.14	0.67	0.00
26	Doolough	0.11	0.50	0.00
27	Doon	0.12	1.02	0.25
28	Dromoland	1.14	1.16	0.14
29	Dromore	n/a	n/a	n/a
30	Drumcullaun	0.17	0.72	0.03
31	Druminure	0.21	0.94	0.00
32	Eanagh	0.20	1.16	0.28
33	Effernan	0.11	0.90	0.11

Table 2.21 (continued)

ID	Catchment	Human density (/ha)	Cattle density (/ha)	Sheep density (/ha)
34	Farrihy	0.13	1.15	0.01
35	Finn	0.29	1.78	0.33
36	Garvillaun	0.17	1.08	0.31
37	Gash	0.50	1.22	0.32
38	George	0.10	1.20	0.74
39	Girroga	n/a	0.04	0.00
40	Goller	0.15	1.03	0.19
41	Gortaganniv	0.23	0.82	0.00
42	Gorteen	0.51	0.77	0.46
43	Gortglass	0.22	1.11	0.00
44	Graney	0.07	0.45	0.02
45	Inchichronan	0.12	0.86	0.15
46	Inchiquin	0.07	0.74	0.25
47	Keagh	0.30	1.66	0.15
48	Kilgory	0.13	1.19	0.19
49	Killone	1.00	1.09	0.39
50	Knockalough	0.20	1.03	0.03
51	Knockerra	0.14	1.22	0.01
52	Lickeen	0.14	0.99	0.09
53	Lisnahan	0.16	1.51	0.00
54	Luirk	0.05	0.79	0.35
55	Luogh	0.27	1.30	0.10
56	Moanmore	0.11	0.78	0.00
57	Mooghna	0.13	1.29	0.00
58	More	0.12	0.97	0.05
59	Morgans	0.16	1.08	0.32
60	Muckanagh	0.14	0.98	0.55
61	Muckinish	0.16	1.64	0.35
62	Naminna	0.08	0.39	0.00
63	O'Briens Big Lou	0.16	0.59	0.23
64	O'Grady	0.14	0.82	0.11
65	Rask	0.17	0.72	0.18
66	Rosconnell	0.25	0.99	0.05
67	Rosroe	0.57	2.14	0.07
68	Rushaun	0.26	1.26	0.19
69	Tullabrack	0.22	1.70	0.00

Wastewater treatment plants and licensed industrial discharges

In 2000, County Clare had thirty-three wastewater treatment plants, located in the main towns of the county. However, untreated wastewater effluent was still discharged into coastal water in Kilkee and Kilrush. None of the wastewater treatment plants had nutrient removal and therefore only provided either primary or secondary treatment.

Potential point source nutrient pollution from wastewater treatment plant effluent discharges was limited in this study and only concerned a small number of catchments. Main potential point source of nutrient pollution was likely to occur by septic tank uses, as most catchments were located in rural areas. Based on their location and type of receiving water bodies, no licensed industrial effluent discharge in the county appeared likely to have an impact on the lake water chemistry of the catchments included in the study.

Six wastewater treatment plants discharging effluents directly into some of the studied lakes or inflowing streams nearby the lake inlet (Table 2.22) are likely to impact on the lake nutrient status; while five wastewater treatment plants, discharging into groundwater or inflowing streams, upstream of the main lake, are likely to have indirect effect in nutrient inputs into the studied lakes (Table 2.23). Clareabbey wastewater treatment plant, discharging into the River Fergus may also affect indirectly Lough Ballybeg, due to close proximity to the lake and the importance of groundwater in the catchment.

Farmland usages

Farmland usages were estimated for each catchment based on the Agricultural Census of 2000. They were divided into silage, permanent meadow, permanent hay and rough grazing (Table 2.24). For fifty-four catchments, 60% or more of their area were associated with agricultural activities (Total area farmed). A significant positive correlation was found between %Rough grazing and mean elevation ($r=0.27$, $n=67$, $p<0.05$). No other significant correlations were found between agricultural land uses (CSO) and catchment descriptive variables.

Table 2.22: List of wastewater treatment plants directly discharging into the studied lakes. Type of treatment, plant type and person equivalent (PE), agglomeration person equivalent (PE) and receiving water type are also listed.

Plant Name	Type of Treatment	Plant Type	Plant PE	Agglomeration PE	Receiving Water	Affected Catchment
Corofin Waste Water Treatment Plant	Primary treatment	Imhoff Tank	n/a	400	Fergus River	Atedaun
(Hillcrest) Kilkishen Waste Water Treatment Plant	Secondary Treatment	Biological Disc	100	100	Local Stream	Clonlea
(Plunket Drive) Kilkishen Waste Water Treatment Plant	Secondary Treatment	Biological Disc	100	100	Local Stream	Clonlea
No. 2 Kilkishen Waste Water Treatment Plant	Secondary Treatment	Extended Aeration	100	100	Local Stream	Clonlea
Newmarket-on-Fergus Waste Water Treatment Plant	Secondary treatment	Extended Aeration	3181	1940	Lough Gash	Gash
Crusheen Waste Water Treatment Plant	Primary treatment	Septic Tank	200	400	Local Stream to Inchichronan Lough	Inchichronan

Table 2.23: List of wastewater treatment plants potentially affecting the studied lakes. Type of treatment, plant type and person equivalent (PE), agglomeration person equivalent (PE) and receiving water type are also listed.

Plant Name	Type of Treatment	Plant Type	Plant PE	Agglomeration PE	Receiving Water	Catchment Potentially affected
Connolly Waste Water Treatment Plant	Secondary Treatment	Conventional Aeration	60	100	Aughaghanna River	Drumcullaun
Inagh Waste Water TreatmentPlant	Secondary Treatment	Extended Aeration	600	500	Inagh River	Druncullaun
Toonagh Waste Water Treatment Plant	Secondary Treatment	RBC	60	60	Groundwater	Ballycullian, Ballyallia
Ruan Waste Water Treatment Plant	Secondary Treatment	Biological Filtration	60	60	Groundwater	Dromore, Ballyteige
Kilfenora Waste Water Treatment Plant	Secondary Treatment	Conventional Aeration	1200	370	Groundwater	Inchiquin

Table 2.24: Agricultural census data (CSO, 2000) on silage, permanent hay and rough grazing, expressed as % of drainage area. Sum of all pasture and total area farmed are also provided.

ID	Catchment	Total Area Farmed (%)	Pasture (%)	Silage (%)	Hay (%)	Rough Grazing (%)
1	Achryane	74	30	6	22	16
2	Acrow	78	36	6	23	13
3	Aillbrak	84	39	8	27	8
4	Atedaun	68	31	3	12	19
5	Ballyallia	89	48	5	24	7
6	Ballybeg	73	45	6	18	4
7	Ballycar	91	59	4	20	8
8	Ballycullinan	72	42	3	21	4
9	Ballydoolavan	70	34	5	22	7
10	Ballyeighter	100	34	1	20	46
11	Ballyleann	41	21	3	11	3
12	Ballyteige	68	31	3	12	19
13	Black-Kilk	100	100	n/a	n/a	n/a
14	Black-Dro	8	4	1	3	0
15	Bridget	83	49	4	25	2
16	Bunny	57	25	2	10	19
17	Burke	69	37	7	19	6
18	Castle	62	36	3	14	4
19	Caum	63	26	8	18	11
20	Clonlea	81	46	4	20	5
21	Cloonmackan	57	24	5	15	13
22	Cloonsnaghta	46	24	3	13	5
23	Cullaun	67	32	3	14	17
24	Cullaunyheeda	84	49	5	23	4
25	Curtins	64	31	7	15	10
26	Doolough	47	19	6	12	9
27	Doon	62	36	3	14	4
28	Dromoland	68	39	5	17	0
29	Dromore	100	100	n/a	n/a	n/a
30	Drumcullaun	62	31	6	15	9
31	Druminure	81	43	12	17	7
32	Eanagh	74	45	3	21	5
33	Effernan	60	36	1	18	1
34	Farrihy	59	31	4	21	2
35	Finn	100	70	4	24	9
36	Garvillaun	72	43	3	21	5
37	Gash	69	41	2	16	3
38	George	79	41	2	20	16
39	Girroga	2	1	0	1	0
40	Goller	74	35	8	14	16
41	Gortaganniv	67	35	7	19	6
42	Gorteen	51	31	6	12	2
43	Gortglass	100	42	7	33	31
44	Graney	37	17	3	9	6
45	Inchichronan	54	29	3	14	8
46	Inchiquin	64	29	3	9	23
47	Keagh	98	44	9	33	10
48	Kilgory	79	46	4	23	3
49	Killone	78	48	6	19	4
50	Knockalough	72	34	7	19	10
51	Knockerra	75	40	11	19	5

Table 2.24 (continued)

ID	Catchment	Total Area Farmed (%)	Pasture (%)	Silage (%)	Hay (%)	Rough Grazing (%)
52	Lickeen	84	45	11	15	13
53	Lisnahan	78	36	14	28	0
54	Luirk	67	26	2	9	25
55	Luogh	80	46	6	24	1
56	Moanmore	44	23	4	14	3
57	Mooghna	87	45	11	21	9
58	More	70	32	7	18	11
59	Morgans	71	42	3	21	5
60	Muckanagh	64	34	4	14	11
61	Muckinish	90	37	3	19	0
62	Naminna	39	15	3	12	11
63	O'Briens Big Lou	38	24	5	9	2
64	O'Grady	54	31	3	15	2
65	Rask	70	27	2	9	29
66	Rosconnell	74	41	6	20	6
67	Rosroe	100	71	4	30	4
68	Rushaun	81	48	4	21	6
69	Tullabrack	91	48	8	29	6

II-6 Discussion

This study included sixty-nine catchments located in County Clare, Ireland. They covered about 53% of the county area and presented a wide range of catchment and drainage areas. Catchment descriptive variables, such as topography, geology, soils, hydrology and land uses were collated and spatially analysed by using Geographic Information System. It provided the foundation for a comprehensive database on water chemistry for the county and assessment of impact of variations in land use types on water quality among catchments located in a fairly restricted geographical region.

Some catchments were covered by underlying karstified bedrock aquifers and were part of the Fergus catchment. The close linkages between surface water and groundwater in such areas mean that lake and river catchments cannot be defined solely on the basis of surface topographic divides, but must take groundwater inputs and outputs into consideration. Nevertheless, variables such as bedrock geology and soil types may be geographically similar. Miscalculations of catchment and drainage areas incurred when using topographic divides might lead to errors when estimating hydrological parameters, such as flushing rate and retention time (Free, 2002). Karst groundwater flow may transfer water between surface catchments (Figures 2.26 to 2.27) (Coxon and Drew, 2000; Kilroy, 2001). In addition, groundwater inputs may have an important influence on some chemical parameters, such as phosphorus concentrations; colour and conductivity (Lucey *et al*, 1999; Mc Dowel and Lickens, 1988; Pierzynski *et al*, 2000; Kilroy, 2001). Groundwater impacts on water chemistry are assessed in Chapter 3.

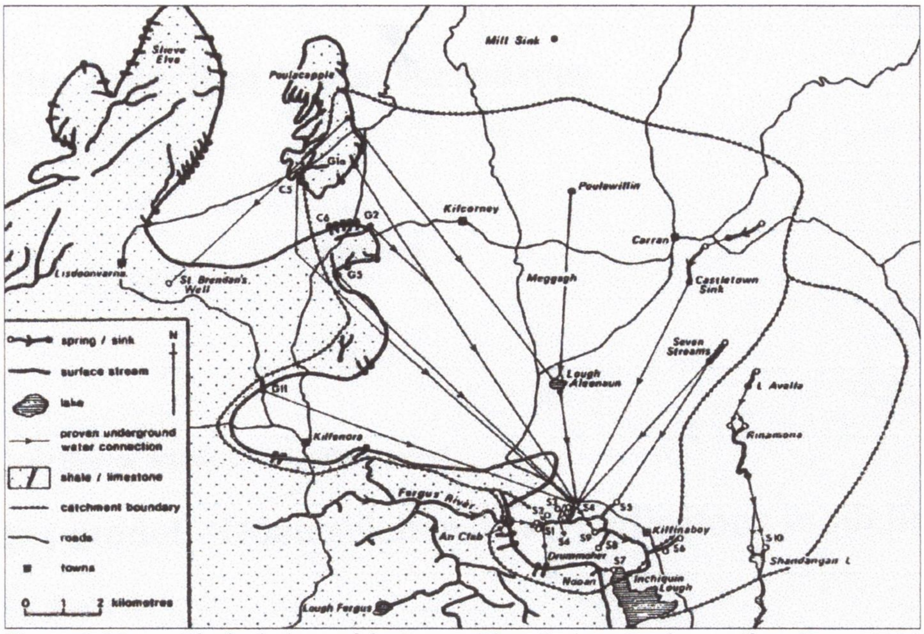

Figure 2.26: The hydrology of the Fergus River Springs Catchment (from Drew, 1988)

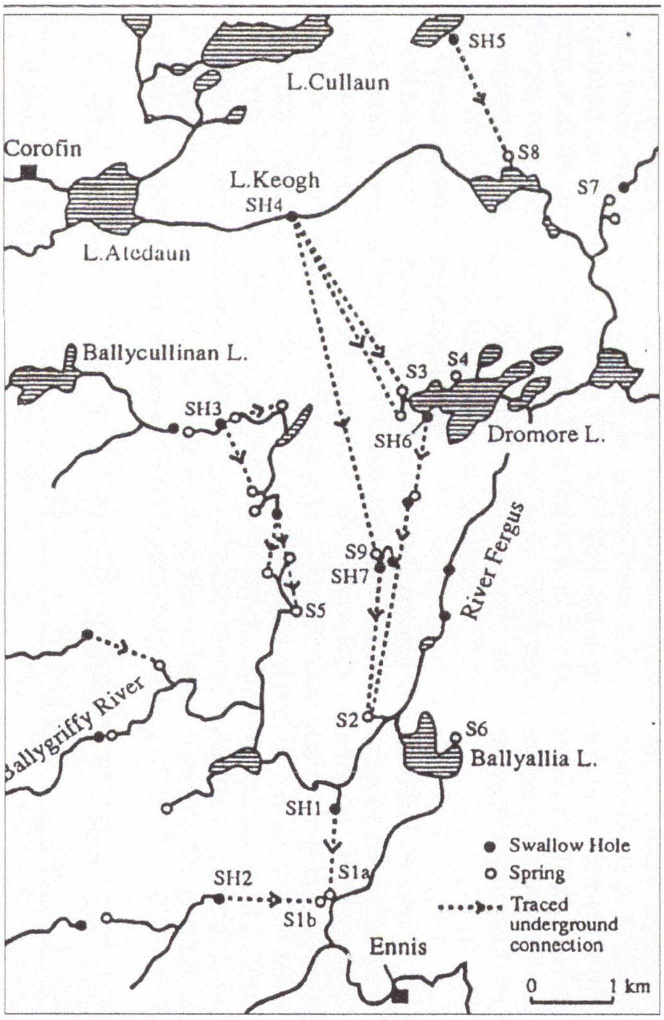

Figure 2.27: Springs, swallow holes and underground connections in the Lower Fergus Catchment (from Coxon and Drew, 1999)

When looking at interrelationships between catchment descriptive variables, several significant correlations were found between the occurrence of carboniferous limestones or shales and similar rock types in the catchments and other descriptive variables. Nevertheless, owing to the natural variability in bedrock geology composition, the reliability of such relationships is uncertain owing to skewed distribution of the bedrock types. Spearman's Rank correlations were used when identifying correlations between variables which were not normally distributed (Fowler *et al*, 1998). Another way to tackle that problem is to differentiate catchments based on their bedrock types when plotting significant correlations between other descriptive variables.

Many of the catchment characteristics were significantly correlated (Spearman's Rank correlation coefficients $r \geq 0.25$; $p \leq 0.05$; $n=69$). These interrelationships are important because when relating catchment descriptive variables to lake ecological variables, some variables may act as a substitute for other catchment characteristics. In addition, when looking at relationships between catchment descriptive variables and water chemistry (Chapter 3) or identifying empirical relationships between catchment land uses and in-lake nutrient status (Chapters 4), catchment characteristics that are strongly significantly correlated may not be used together as explanatory parameters in multiple regression models (Petrucelli *et al*, 1999; Fowler *et al*, 1998).

Characteristics of the physical environment, such as topography and bedrock geology, influence the catchment morphological and hydrological variables and may impact on lake water chemistry and ecology (Wetzel, 2001). Catchment and drainage areas increased with the intensity of the relief present. Lakes lying on carboniferous limestones and old red sandstones had greater catchment and drainage areas, greater lake surface areas, volumes and shoreline and were associated with lower catchment elevation and lake altitude. In contrast, lakes lying on shales and similar rock types had lower catchment and drainage areas, lower lake surface areas, volumes and shorelines and were associated with higher elevation and lake altitude. In addition, catchments lying on carboniferous limestones had a greater proportion of upstream lakes than those lying on shales and sandstones. The presence of upstream lakes in the catchment can have an impact on nutrient loss, particulate fractions and influence seasonal patterns of lake chemistry (Zhou *et al*, 2000; Rasmussen *et al*, 1989).

As expected, annual rainfall levels recorded among the studied catchments over the monitoring period were greater for catchments with higher elevation and slope (Goodale *et al*, 1998; Black, 1996). The difference in annual mean rainfall between 2000 and 2001, with an average decrease of 418 mm between the two years, may affect lake water chemistry, as lower loads of particulate fractions and nutrients from the catchments are likely to be associated with lower precipitation.
GIS spatial interpolation functions to derive rainfall surface over the studied catchments were used in previous studies (Daly *et al*, 2000; Irvine *et al*, 2001; Bhuyan *et al*, 2003), but the accuracy of

the catchment rainfall estimates could be questioned. Such methods may not take into account the influence of specific topographic features on rainfall distribution and is highly dependant on the location or height of the weather stations from which the rainfall measurements are derived. Climate data exists as measurements at discrete points and many different methods have evolved to generate regional maps from point data. Interpolation methods include Thiessen polygons (Thiessen, 1911), inverse distance interpolations, optimal interpolations or kriging (Dingman *et al*, 1988; Bacchi and Kottegoda, 1995). Other approaches (Daly *et al*, 1994) used measured climate data and elevation to establish or derive climate-elevation relationships. Simple regression equations relating climate to grid position and elevation have also been used to summarise the spatial variation in the climatic data (Goodale *et al*, 1998). The most accurate way to draw precipitation contour map is to use isohyetal lines, which take into account the influence of the topography (Fetter, 2001). However, this method is time consuming and needs to be applied separately for each catchment.

In County Clare, the most important factors influencing soil formation are topography, climate and geological parent material (Finch *et al*, 1971). Catchment lying on carboniferous limestone had greater coverage by well/moderately drained soils such as brown earths, grey brown podzolics and rendzinas, with higher soil Morgan P levels, while shales and similar rock types were associated with poorly/imperfectly drained soils such as peats and gleys, with lower soil Morgan P levels.

Land use distribution among the catchments reflects the influence of the physical environment (Heritage Council, 2000; Finch *et al*, 1971). Pasture and total peatlands were the main CORINE land covers recorded among the catchments. CORINE peatlands category (O'Sullivan, 1992) was associated with catchments lying on shales and similar rock types, with higher elevation and presenting greater coverage by peat soils. Pasture was associated with catchments with lower elevation and low peat soils coverage. Broadleaf forests were associated with underlying carboniferous limestones, lower elevation and the occurrence of brown earths, rendzinas and grey brown podzolics.

There were some discrepancies observed between CORINE land covers and farmland usages from Agricultural Census of 2000. Differences observed between the two databases may be originally incurred by the way they were both generated: CSO statistics describing agricultural land uses relying on farm surveys, while CORINE describes land cover types based on the interpretation of satellite imagery. Despite not differentiating any farmland usage among the pasture category, the CORINE data may be more useful as they are geographically correct (land covers determined within the catchment boundaries). The CORINE dataset provides a spatially accurate pattern of the biophysical land occupation throughout the whole catchment, although it did not distinguish specific land usage directly. The Census of Agriculture summarises actual land usage. However, the data only cover portion of the catchments that were farmed and the data are not location specific (Irvine *et al*, 2001). Farmland usage was estimated for each catchment assuming the equal distribution of activities and animal densities within each DED. This may lead to errors owing to the natural patchiness of farming intensity and population density. This could generate inaccuracies especially for small catchments, where agricultural land use estimates may be inferred by land uses from outside their catchment.

The year in which data have been published is not important for some datasets such as bedrock geology, soils or topography. For others, especially land cover coverage, using up-to-date data is important. In order to reduce any inaccuracies, the initial CORINE coverage was updated by the forestry coverage (FIPS, 1998). A more recent CORINE coverage was produced in 2000 but was not available at the time of the data processing.

Soil Morgan P coverage was produced on 10 by 10 km-basis, which would be very inaccurate for very small catchments owing to the high variability and natural patchiness of soil chemical properties, but more accurate datasets were not available. The access to an accurately geocoded database of soil P levels would be of considerable value for agricultural and environmental research. Integration of the soil P test values of the farms under REPS as part of the Land Parcel Identification System GIS database developed by the Department of Agriculture would provide an efficient and highly accurate coverage of soil P test values at a national scale (Daly *et al*, 2000).

Finally, there may be some mis-location of features or spatial distortions, as different digital coverages were used, each of them issuing initially from different sources. For example, topography and water features related coverages were based on OSI paper maps at 1:50,000; while bedrock geology datasets had for initial source the Geological Survey of Ireland solid geology maps at 1:100,000. The soil coverage was produced initially based on one-inch paper maps. CORINE datasets coverage was derived from 1:100,000 scale data. Comparison between the different coverages (Geology, soils, CORINE and manually digitised water features) for the common category “Water” estimated the maximum distortion to be up to 100 m-200 m, verifying the findings of Heritage Council (2000). Major distortions were corrected by manually editing and correcting some features of the coverage, especially in the case of the small-scale study carried out in Lough Lickeen (Chapter 5).

III-1 Introduction

Standing waters (lakes, meres, pools and ponds) are an important component of the aquatic environment and have suffered a variety of impacts, the most significant of which have been acidification and eutrophication (Wetzel, 2001).

Progressive acidification associated with deposition of rain and particulates (wet and dry deposition) enriched in mineral acids is a problem in some lakes with low buffering capacity. The presence of dissolved salts from the catchment affect the potential of surface waters to buffer against increases in $[H^+]$. In non-carbonate terrain, such as in areas of crystalline rocks or quartz sandstones, this buffering capacity is rapidly exhausted and free H^+ ions create a progressive acidification of the lake (Chapman, 1996; Lucey *et al*, 1999; Wetzel, 2001). In Ireland, eutrophication is, however, the commonest form of pollution threatening the water quality of lakes. It is caused by increased input of nutrients, principally phosphorus, compared with natural background levels. Eutrophication results in increased open water production of planktonic forms of algae and Cyanobacteria, and in shallower areas, macrophytes and algae on and near shorelines. In freshwater, phosphate concentrations and probably to a lesser extent, nitrogen compounds, are the primary regulators of algal, Cyanobacterial and other aquatic plant growth. In extreme conditions, such as hypertrophic lakes, plant growth can be limited by other factors such as poor light penetration, high colour, silica exhaustion and trace element availability (Cole, 1975; Wetzel & Lickens, 1991; Flanagan, 1992; Lucey *et al*, 1999).

Johnes *et al* (1998) identified two approaches to lake classification:
- spatial state scheme, used to place bodies of water into categories against defined limits;
- state-changed scheme, which measures the degree to which the system has changed with respect to individual or groups of variables, from some predetermined baseline.

In this chapter, lakes will be classified using spatial state schemes, based on nutrient-related variables (total phosphorus, chlorophyll-*a*) as described in a modified trophic status classification based on the OECD (1982) scheme (Lucey *et al*, 1999), or pH and alkalinity to measure the acidity, as described in the ECE scheme (Premazzi and Chiaudani, 1992). Such schemes are designed to distribute a set of data into groups, which have statistical coherence and ecological meaning. They cannot, however, make any allowance for natural variability and their use in defining environmental impacts is, therefore, limited (Johnes *et al*, 1998).

Over the period 2000-2001, sixty-nine lakes were monitored on a three tier-sampling basis. Seasonal variations ($n \geq 7$ samples /year) were assessed for twelve lakes (high frequency monitoring – HFM); four time-sampling per annum was carried out for eighteen lakes over a one year-period (medium frequency monitoring – MFM), while single summer samples were taken for thirty-nine more lakes (low frequency monitoring – LFM). A full range of chemical analyses was carried out on the samples. Secchi disc measurement of transparency and a single assessment of summer stratification were carried out during the summer for the lakes included in the high frequency monitoring, by measuring vertical profiles of temperature and dissolved oxygen.

This chapter presents the results of the monitoring carried out in 2000-2001 on the sixty-nine study lakes. Seasonal variations among the most frequently sampled lakes and potential influence of groundwater on lake water chemistry were assessed. Correlations between lake ecological variables and catchment physical and hydrological parameters were assessed. Relationships with land use will be dealt with in Chapter 4.

Over 2000-2001, 20% of the total of lakes in the county, estimated at 358 (Kennelly, 1997), were sampled. This was the first time that such coverage of lakes was monitored in the county. Up until 2000, limnological study of the lakes in the county, with the exception of Lough Derg, which has been part of a seasonal sampling frequency programme since 1995 and of a few lakes, sampled intensively as part of one-off research programmes (Allott, 1986, 1990; Irvine *et al*, 2001), has been of low intensity and quite sporadic (Appendix 2 – Table 1).

III-2 Methods

III-2.1 Three-tier sampling

As part of the high frequency monitoring, ten lakes were sampled eight times in 2000 and 2001. An additional two lakes (Loughs Castle and Killone) was added for 2001 and one lake (Lough Keagh), for which the access was particularly difficult, was moved to the medium frequency monitoring. Twenty lakes from the medium frequency monitoring were sampled four times per year either in 2000 or 2001. Sixty lakes were also sampled once during the summer either in 2000 or 2001, as part of the low frequency monitoring (Table 3.1). Owing to Foot and Mouth disease in 2001, sampling was cancelled in March 2001 and only partially carried out in April 2001. Lakes from the medium frequency monitoring, that were not sampled in April 2001 were sampled in October 2001.

Table 3.1: Intensity of sampling for the 69 lakes sampled between March 2000 and October 2001. Total numbers of samples taken over the monitoring period are given and type of monitoring regime is provided (HFM: high monitoring frequency; MFM: medium monitoring frequency; LFM: low monitoring frequency).

Lakes	Month Sampled in 2000	Month Sampled in 2001	Total Samples 2000-01	Monitoring regime
Achryane	8	8	2	LFM
Acrow	4, 6, 7, 9		4	MFM
Aillbrack	8	8	2	LFM
Atedaun	4, 6, 7, 9		4	MFM
Ballyallia	4, 6, 7, 9		4	MFM
Ballybeg	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Ballycar	4, 6, 7, 9		4	MFM
Ballycullinan	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Ballydoolavan		8	1	LFM
Ballyeighter		8	1	LFM
Ballyleann	4, 6, 7, 9		4	MFM
Ballyteige	9	8	2	LFM
Black-Dro		8	1	LFM
Black-Kilk	8		1	LFM
Bridget	8		1	LFM
Bunny	8		1	LFM
Burke	4, 6, 7, 9		4	MFM
Castle	4, 6, 7, 9	4,5,6,7,8,9,10	11	HFM
Caum	8	8	2	LFM
Clonlea	8	4,6,8,9	5	MFM
Cloonmackan	4, 6, 7, 9	8	5	MFM
Cloonsnaghta	4, 6, 7, 9		4	MFM
Cullaun	4, 6, 7, 9	8	5	MFM
Cullaunyheeda	3,4,5,6,7,8,9,10	1,5,6,7,8,9,10	15	HFM
Curtins	8	8	2	LFM
Doolough	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Doon		4, 6, 8, 9	4	MFM
Dromoland		8	1	LFM
Dromore	3,4,5,6,7,8,9,10	1,5,6,7,8,9,10	15	HFM
Drumcullaun	8		1	LFM
Druminure	8	8	2	LFM
Eanagh		8	1	LFM
Effernan	8	8	2	LFM
Farrihy		8	1	LFM
Finn	8		1	LFM
Garvillaun	8	8	2	LFM
Gash		8	1	LFM
George		8	1	LFM
Girroga	9	8	2	LFM
Goller		8	1	LFM
Gortaganniv	8	8	2	LFM
Gorteen		8	1	LFM
Gortglass	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Graney	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Inchichronan	8	4, 6, 8, 9	5	MFM
Inchiquin	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Keagh	3,4,5,6,7,8,9,10	1, 4, 6, 8, 9	13	HFM

Table 3.1 (continued)

Lakes	Month Sampled in 2000	Month Sampled in 2001	Total Samples 2000-01	Monitoring regime
Kilgory		8	1	LFM
Killone		5,6,7,8,9,10	6	HFM
Knockalough	8	4, 6, 8, 9	5	MFM
Knockerra	8		1	LFM
Lickeen	3,4,5,6,7,8,9,10	1,4,5,6,7,8,9,10	16	HFM
Lisnahan	8	6, 8, 9, 10	5	MFM
Luirk		8	1	LFM
Luogh	8	8	2	LFM
Moanmore		6, 8, 9, 10	4	MFM
Mooghna	8	8	2	LFM
More	8		1	LFM
Morgans	8	8	2	LFM
Muckanagh	8	4, 6, 8, 9	5	MFM
Muckinish	9		1	LFM
Naminna	8	6, 8, 9, 10	5	MFM
O'Briens	8		1	LFM
O'Grady		8	1	LFM
Rask		8	1	LFM
Rosconnell		8	1	LFM
Rosroe		6, 8, 9, 10	4	MFM
Rushaun	8		1	LFM
Tullabrack	8		1	LFM

III-2.2 Sampling techniques

Samples for water chemistry were collected with a weighted plastic container thrown from the bank side and retrieved, after sinking about 1 m, using an attached rope; with the exception of the summer (July) when samples from the most intensively studied lakes were collected from mid-water. One sample was taken for each lake.

According to Chapman (1996), if only one sample is taken, it should be located at the deepest part of the lake, where oxygen deficits are likely to be the greatest. Lakes or reservoirs can be subject to several influences that cause water quality to vary from place to place and from time to time. Where feeder streams and effluents enter lakes or reservoirs there may be local areas where the incoming water is concentrated, because it has not yet mixed with the main water body (Bartram and Balance, 1996). Nevertheless, owing to logistical and financial constraints, lake samples had to be taken from the shore near the lake outlet, where the water was assumed to be reasonably mixed and representative of the lake. This assumption is tested in Chapter 5 for Lough Lickeen, where samples were taken from the shore, mid-lake and at the lake outlet.

Water samples, vertical profiles of temperature and oxygen, and Secchi disc measurements of transparency were taken in July from mid-lake for the high frequency monitoring, except for Lough

Keagh and Doolough where the access with the boat was impracticable. Vertical profiles of oxygen and temperature were taken at 1-2m intervals using a portable WTW OXI 196 meter.

Near-shore water temperatures were recorded and at least 1l of water was filtered by using a hand pump and passed through Whatmann GF/C 47mm filter papers. Used filter papers were subsequently stored in centrifuge tubes containing 10 ml of methanol for later extraction of phytoplankton chlorophyll-*a*, following the method of the Standing Committee of Analysts (1980).

Samples of unfiltered water were stored in 5l-polyethylene bottles, which were rinsed three times with surface water before sampling; while filtered water samples were stored into 2l-brown glass bottles, which were initially acid washed with a solution of 50% HCl, and then rinsed three times with filtered water at each sampling. In addition, each lake was attributed specific sampling containers.

Owing to the number of lakes sampled and the location of the sampling sites (western Ireland), the delay for processing in the laboratory (Centre for the Environment, Trinity College Dublin) was up to a maximum of three days. Filtering and initial processing of the chlorophyll-*a* samples were carried out immediately after sampling at each site.

III-2.3 Analytical techniques

pH, alkalinity and conductivity

Using unfiltered water, measurements were made of conductivity using a WTW LF96 conductivity meter. pH was determined on 50 ml of unfiltered and unstirred water samples using a Jenway 3030 pH-meter, with a Reagecon combination pH electrode (GCF11). It was preliminarily calibrated with Reagecon buffers of pH 4 and 7. High-level alkalinity (50 ml unfiltered sample) was determined by titration with H_2SO_4 (0.01M) to pH 4.5 using a Metrohm-Herisau E 485 burette (E485) (Clesceri *et al*, 1998). Low-level alkalinity was determined by Gran titration on 100 ml of unfiltered samples to four end points between pH 4.3 and 3.8 (Mackereth *et al*, 1989).

Colour, turbidity and total dissolved organic carbon

Colour was determined on samples of filtered water, passed through Whatman GF/C 47 mm filters and measured at 455 nm with a HACH DR2000 spectrophotometer. De-ionised water was used as a blank and readings were adjusted for any difference between cuvettes (HACH, 1991). Results were expressed as mg l^{-1} PtCo. Turbidity was measured with a HACH 2100P turbidity meter on unfiltered samples (Clesceri *et al*, 1998).

Total Dissolved Organic Carbon (TDOC) was determined on filtered samples with a Shimadzu TOC 5000-A. After purging with acid (to remove inorganic carbon), the TDOC is measured by thermo-catalytic oxidation of carbon to carbon dioxide and subsequent analysis in a non-dispersive infrared gas analyser.

Nitrogen

Nitrate and nitrite in freshwater, and seawater, can be analysed on filtered samples by Flow Injection Analysis (FIA Tecator 5020, 5032, 5007). Nitrate and nitrite are both measured colorimetrically following reaction with sulphanilamide and napthylethylenediamine dihydrochloride to form a pink azo dye. Nitrate is first converted to nitrite by reduction on a cadmium column. Total nitrogen (TN) was determined on unfiltered samples by alkaline persulphate digestion followed by flow injection analysis (Clesceri *et al*, 1998; Koroleff, 1983b) Ammonia (sum of NH_3 and NH_4) reacts with hypochlorite and sodium salicylate at approximately pH 12.6 in the presence of a catalyst (sodium nitroprusside) to form a coloured compound that is related to indophenol blue. The compound is blue but appears green against the yellow colour of the reagent blank. The absorbance is measured spectrophotometrically at 662 nm (Standing Committee of Analysts; 1981).

Phosphorus

According to Cole (1975), the best figure to use in quantifying phosphorus in a body of water is total phosphorus, including sestonic as well as dissolved values. Total phosphorus (TP) was therefore used to characterise phosphorus status of lakes and determined on unfiltered samples by acid persulphate digestion (Eisenreich *et al*, 1975) followed by reaction with molybdate and measured spectrophotometrically at 882 nm after colourimetric reaction with ascorbic acid (Murphy and Riley, 1962).

Silicates

The determination of dissolved silicon compounds in natural waters is based on the formation of a yellow silicomolybdic acid when an acid sample is treated with molybdate solution, which is reduced to an intensely coloured blue complex. It was then measured by spectrophotometry at 810 nm using a Shimadzu UV-1601 spectrophotometer (Koroleff, 1983a).

Phytoplankton chlorophyll-*a*

Chlorophyll-*a* (Chl a) was determined by spectrophotometry at 665 and 750 nm, using a Shimadzu UV-1601 spectrophotometer, after methanol extraction (samples boiled at 72°C for one minute and centrifuged at 3500 rpm for eight minutes) (Standing Committee of Analysts, 1980).

Analyses for silicates and ammonia were only carried out for the most intensively monitored lakes. Total dissolved organic carbon was determined at least once for each lake in 2000 and on every sample on 2001.

Quality control

pH, conductivity, alkalinity, turbidity, colour, TDOC and chlorophyll-*a* were determined on one replicate. All other analyses were carried out using two replicates.

Working standards from which ranges of standard solutions were prepared, were made up fresh on the day of analysis. Reagents were kept in cold storage (4°C) and where solutions were unstable, prepared fresh on the day of analysis. All standards and reagents were prepared volumetrically in grade A flasks.

Quality control solutions were used to control the quality of the analyses. For pH, a control solution of pH = 4.00 +/- 0.03 was used and for turbidity, a quality control sample of 5.20 NTU. For TP, TN, NO_3-N and NH_4-N, the quality control solution contained concentrations of respectively 25.0 µg l^{-1}, 1.00 mg l^{-1}, 1.00 mg l^{-1} and 0.1 mg l^{-1}. The quality control solution for silicates contained 1 mg l^{-1} and for TDOC 20 mg l^{-1}. Every quality control was run several times during each analysis.

III-2.4 Lake classification schemes

Nutrient scheme

Trophic status of the lakes was assessed following the modification of the OECD (1982) scheme used by the Irish *Environmental Protection Agency*, and which is now incorporated in Local Government Regulations (DELG, 1998). Under the original OECD (1982) scheme, a lake is classified into one of several trophic categories based on an overall assessment of mean concentrations of total phosphorus, maximum concentrations of chlorophyll-*a* and range of recorded transparency usually using a Secchi disc. The scheme requires that mean values of total phosphorus reflect seasonal averages and contains as an underlying assumption that phytoplankton populations primarily determine lake transparency. The widespread influence of peat and the colour that its drainage waters bring into lakes make the later assumption invalid for many Irish lakes. In addition, DELG Regulations (1998) require that the total phosphorus averages be based on at least ten samples taken in a 12 consecutive month-period or on at least fifteen samples taken in a 24 month-period. It is for these reasons that maximum chlorophyll-*a* is often the adopted scheme.

Based on the modified OECD (1982) scheme (Lucey *et al,* 1999), currently used to assess trophic status in Irish lakes, a maximum value of less than 8 µg chlorophyll-*a* l^{-1} classifies a lake as 'oligotrophic' and signifies negligible impairment of water quality. A 'mesotrophic' classification is assigned to lakes that have maximum concentrations of chlorophyll-*a* recorded between 8 and 25 µg l^{-1}. Impairment of a lake is considered as 'very little' under this category. Lakes, which have a maximum concentration of chlorophyll-*a* equal or greater than 25 µg l^{-1} are considered as 'eutrophic' and are deemed to have undergone impairment of water quality (Table 3.2).

Table 3.2: Trophic classification scheme according to chlorophyll-*a* and TP concentrations, as proposed by OECD (1982)

Trophic category	Mean Chl a ($\mu g\ l^{-1}$)	Maximum Chl a ($\mu g\ l^{-1}$)	Mean TP ($\mu g\ l^{-1}$)
Ultra-oligotrophic	< 1.0	< 2.5	< 4
Oligotrophic	< 2.5	< 8.0	< 10
Mesotrophic	2.5-8	8-25	10-35
Eutrophic	8-25	25-75	35-100
Hypertrophic	> 25	> 75	> 100

Acidity scheme

The Economic Commission for Europe (ECE) has devised a classification system for ecological quality, which includes five quality classes based on pH and alkalinity (Table 3.3) (Premazzi and Chiaudani, 1992).

Table 3.3: ECE scheme for the classification of the ecological quality of lakes by acidity (Premazzi and Chiaudani, 1992)

Class	pH	Alkalinity $mg\ l^{-1}\ CaCO_3$	Class interpretation
I	9.0-6.5	> 200	Buffering capacity very good
II	6.5-6.3	200-100	Buffering capacity good
III	6.3-6.0	100-20	Buffering capacity weak but keeps the acidity at levels suitable for most fish
IV	6.0-5.3	20-10	Buffering capacity is exceeded, leading to levels of acidity, which affect the development of spawn
V	< 5.3	< 10	Buffering capacity absent and the acidity is toxic for fish species

III-2.5 Groundwater influence on lake water chemistry

In karstic areas, the water chemistry of lakes is highly dependant on the surface water-groundwater relationships. The trophic status of groundwater-fed lakes is controlled by the nutrient content of the inflowing groundwater (Coxon and Drew, 1999). Karst aquifers are particularly vulnerable to contamination owing to a number of factors including the presence of an epikarstic zone and the existence of both conduit and diffuse flow within the aquifer, but a particularly critical factor is the occurrence of point recharge. Surface water contaminants (both natural and anthropogenic) may enter the aquifer via sinking streams, while the rapid transfer through the aquifer by conduit flow and lack of attenuation means that groundwater contaminants may in turn be discharged into surface waters (Coxon and Drew, 2000).

The best way to assess the influence of groundwater inputs on the lake water chemistry would be to compare variations in chemical concentrations in the lake and in the surface drainage network. Unfortunately, it was not possible to simultaneously measure the chemistry of the inflowing and out-flowing streams during the monitoring. Based on the bedrock geology data, aquifer vulnerability mapping and the Fergus catchment delineation work (Deakin, 2000; Coxon and Drew, 1999; Drew, 1990; Kilroy, 2001), lakes that were likely to be influenced by groundwater inputs were identified. Looking at their catchment network drainage density and variations in alkalinity, conductivity, colour and total dissolved solids can provided an indication on the influence of underlying aquifers and sub-surface flows on water chemistry (Coxon and Drew, 1999; Kilroy, 2001).

III-2.6 Statistical analyses

Summary statistics were calculated using *DataDesk 6.0* on the water chemistry results and expressed as mean, minimum and maximum concentrations. 95% confidence intervals (95% CI) were calculated on the means based on the sample size (n) and standard deviation (SD). For $n > 30$, 95% CI were calculated as: Mean ± 1.96*SE, with SE = SD / $n^{0.5}$; while for $n < 30$, 95% CI were calculated as: Mean ± SE * t, with t, coefficient of the t-distribution at $p=0.05$ (Fowler *et al*, 1998). pH averages were calculated based on the arithmetic scale using $[H^+] = 10^{-pH}$.

Interrelationships between chemical variables and relationships with catchment descriptive variables were assessed by carrying out Spearman's Rank correlations with *DataDesk 6.0*. Principal component and cluster analyses were carried out using *Primer 5* software.

Owing to changes in the monitoring programme and restrictions that followed the outbreak of Foot and Mouth Disease in 2001, the initial three-tier sampling frequency regime was altered and gave more complex sampling frequency patterns over the monitoring period 2000-01 (Appendix 2 – Tables 2 to 4). High frequency monitoring (HFM) included twelve lakes that were sampled on a monthly basis for at least one of the two monitoring years. Such monitoring frequency complies with the requirements of the DELG (1998) Nutrient Regulations. Medium frequency monitoring (MFM) included eighteen lakes, that were sampled at least four times during one of the two years; while low frequency monitoring (LFM) included thirty-nine lakes, that were sampled only once during the summer.

For the most frequently monitored lakes (HFM), influence of the different sampling regimes on the accuracy of the averages 2000-01 of the chemical variables was assessed by comparing the means based on n=15-16 samples ± 95% confidence interval and estimated means based on the other seasonal spread of sampling frequency regimes.

III-3 Results

III-3.1 Physical variables

For the lakes included in the high frequency monitoring, temperature and dissolved oxygen vertical profiles were measured once during the summer. These measurements only give an indication of the occurrence of stratification at a given time in the year and specific sampling conditions (wind, temperature) (Moss, 1992), which is subject to short-term changes in many Irish lakes. When change in temperature per metre was greater than 1 °C, the lake was considered as stratified, with presence of a thermocline (Horne and Goldman, 1994). Detailed results of vertical profiles carried out in July 2000 and 2001 are given in Appendix 2 (Table 5 to 16) and in the associated CD-Rom (Appendix 2/Vertical profiles).

Oxygen depletion in the hypolimnion in Loughs Ballybeg, Ballycullinan, Inchiquin and Killone in both July 2000 and July 2001 was indicative of some long duration of summer stratification. (Figures 3.1 to 3.8). Loughs Dromore, Gortglass, Graney and Lickeen showed signs of stratification and DO_2 depletion in 2000 but not in 2001 (Figures 3.9 to 3.16), while no tendency to summer stratification was observed in Loughs Cullaunyheeda and Castle.

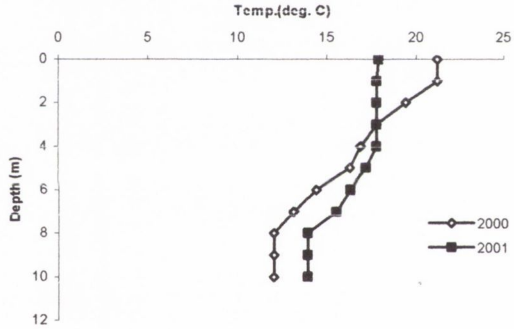

Figure 3.1: Lough Ballybeg – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

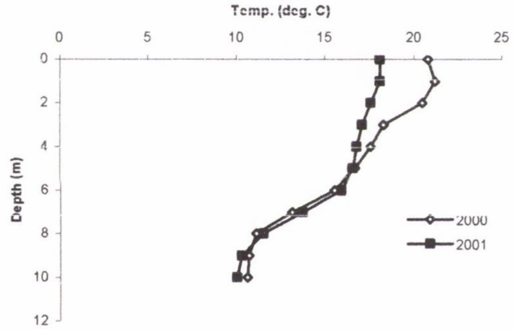

Figure 3.3: Lough Ballycullinan - T (°C) / Depth (m) vertical profile – July 2000 and July 2001

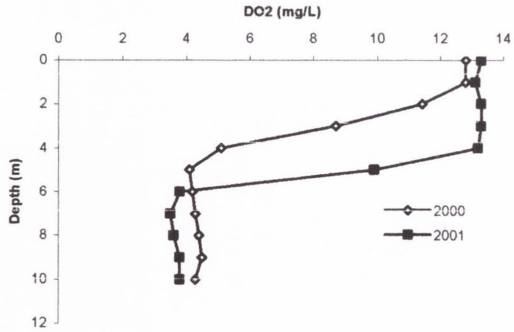

Figure 3.2: Lough Ballybeg – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

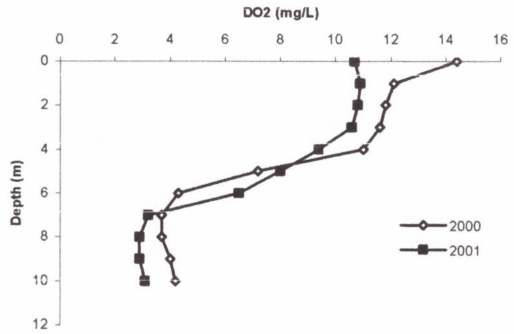

Figure 3.4: Lough Ballycullinan – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

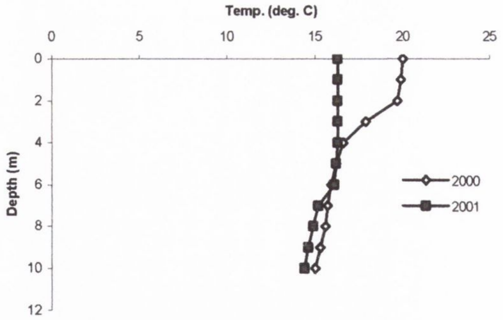

Figure 3.5: Lough Inchiquin – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

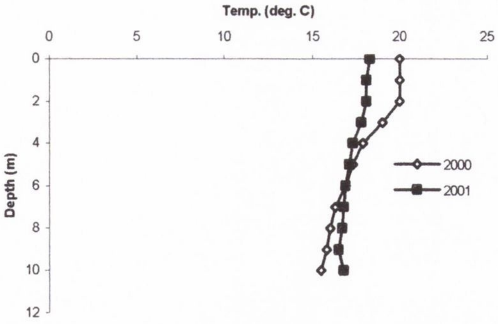

Figure 3.9: Lough Dromore – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

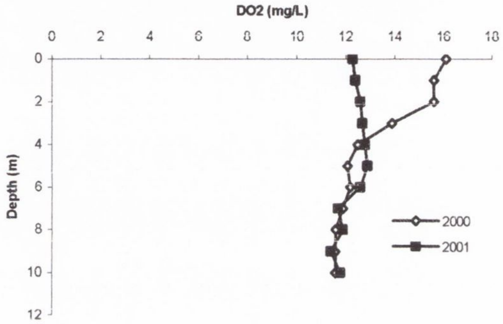

Figure 3.6: Lough Inchiquin – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

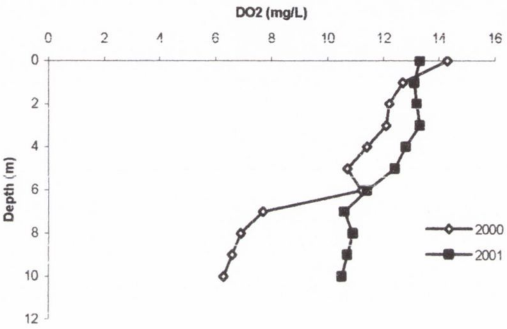

Figure 3.10: Lough Dromore – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

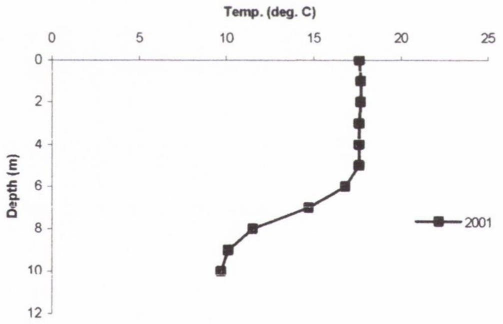

Figure 3.7: Lough Killone – T (°C) / Depth (m) vertical profile – July 2001

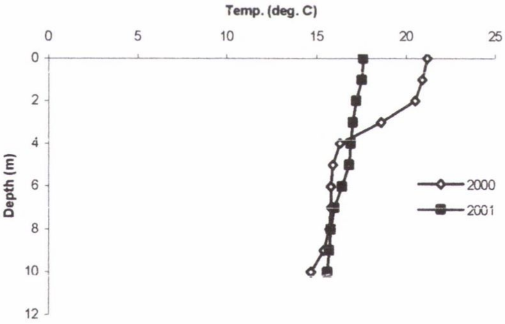

Figure 3.11: Lough Gortglass – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

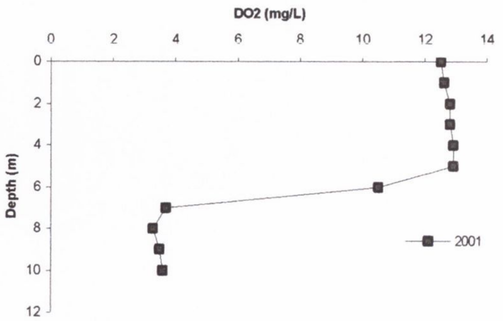

Figure 3.8: Lough Killone – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2001

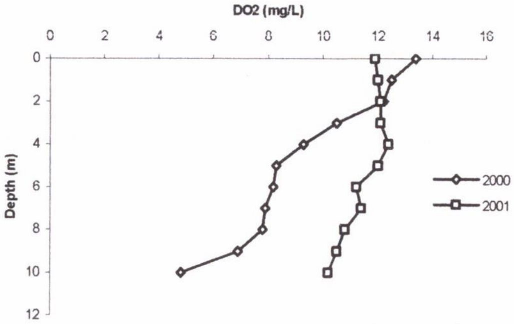

Figure 3.12: Lough Gortglass – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

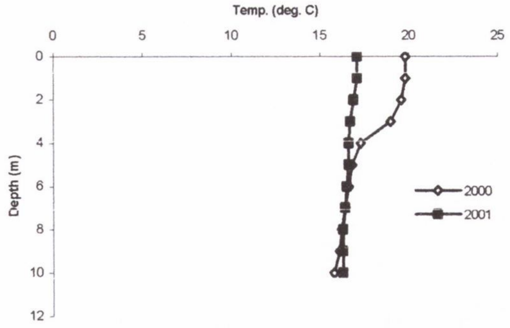

Figure 3.13: Lough Graney – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

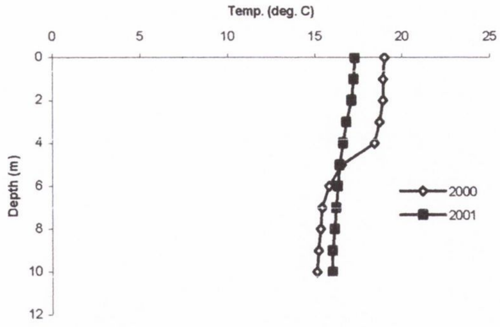

Figure 3.15: Lough Lickeen – T (°C) / Depth (m) vertical profile – July 2000 and July 2001

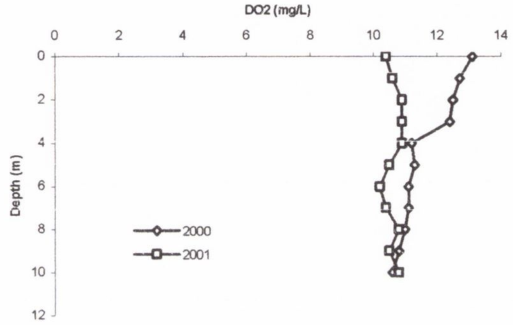

Figure 3.14: Lough Graney – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

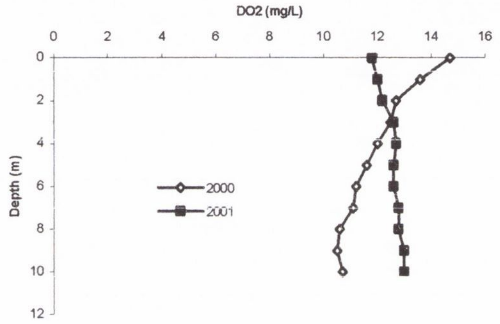

Figure 3.16: Lough Lickeen – DO_2 (mg l^{-1}) / Depth (m) vertical profile – July 2000 and July 2001

Lake transparency measured by Secchi-depth, ranged from 0.4 m (Lough Ballybeg) to 3.2 m (Lough Cullaunyheeda) in July 2000, while it ranged from 1.0 m (Doolough) to 3.7 m (Lough Cullaunyheeda) in July 2001. Combined Secchi depth measurements from July 2000 and July 2001 were significantly negatively correlated ($n=18$, $p<0.05$) with Log (Turbidity) ($r=-0.53$), and chlorophyll-*a* concentrations ($r=-0.54$).

III-3.2 Chemical variables

Overview of the monitoring results

In-lake concentrations of nitrate-nitrogen (NO_3-N), total nitrogen (TN), total phosphorus (TP), phytoplankton chlorophyll-*a* (Chl a); as well as pH, alkalinity (Alk.), conductivity (Cond.), colour and turbidity (Turb.) were analysed on each occasion. In-lake concentrations of ammonium-nitrogen (NH_4-N) and silicates (SiO_4-Si) were assessed on seven occasions for the lakes included in the high frequency monitoring. In-lake concentrations of total dissolved organic carbon (TDOC) were assessed at least once for each lake in 2000 and on every occasion in 2001. Details of the monthly results obtained for each lake are available in the associated CD-Rom (Appendix 2/TTS

Monitoring Results). Among the sixty-nine lakes monitored, monthly results covered a wide range of concentrations (Table 3.4).

Table 3.4: Summary of the monthly results obtained for the 69 lakes monitored between March 2000 and October 2001. Total number of analyses (Count) and unit systems are shown. Minimum (Min), maximum (Max) and range of results are also provided for each variable, as well as mean based on all the results.

	Unit	Count	Min	Max	Range	Mean
Temp.	°C	177	1.0	22.0	21.0	15.0
NH_4-N	mg l^{-1}	73	0.00	0.39	0.39	0.03
NO_3-N	mg l^{-1}	303	0.00	0.81	0.81	0.09
TN	mg l^{-1}	303	0.15	3.38	3.23	0.72
TDOC	mg l^{-1}	183	2.4	56.8	54.4	9.1
TP	µg l^{-1}	303	4.3	695.3	691.0	34.6
SiO_4-Si	mg l^{-1}	73	0.04	5.06	5.02	1.50
Chla	µg l^{-1}	303	0.1	148.5	148.4	11.8
pH		303	5.37	9.48	4.11	6.94
Alk.	mg $CaCO_3$ l^{-1}	303	-0.2	291.6	291.8	88.1
Cond.	µS cm^{-1}	303	68.0	14840.0	14772.0	302.9
Colour	PtCo	303	0	417	417	52
Turb.	NTU	303	0.3	70.1	69.8	4.8

M-ANOVA (Multivariate ANalysis Of VAriance) results, carried out on the monthly results (Table 3.5), showed that surface temperature, in-lake nitrate (NO_3-N) concentrations, Log(TP), conductivity and Log(Turbidity) were significantly influenced ($p \leq 0.01$) by the sampling month. The type of catchment bedrock (based on the bedrock cluster groups listed in Table 2.7) also had a significant influence ($p \leq 0.01$) on Log(TP), alkalinity, conductivity and Log(Colour). Chlorophyll-*a* levels, Log(TP), alkalinity, conductivity, Log (Colour) and Log(Turbidity) were significantly different among lakes ($p \leq 0.01$). Finally, characteristics of soils in the catchment (based on the soil cluster groups listed in Table 2.8) significantly influenced ($p \leq 0.01$) the alkalinity and conductivity results.

Table 3.5: Overview of p-values obtained for M-ANOVA carried out on the monthly results, with independent factor: Year, month, bedrock, soil and lake. Dependant variables are temperature (X_1), Log(NH_4-N) (X_2), NO_3-N (X_3), Log(TN) (X_4), Log(TDOC) (X_5) Log(TP) (X_6), SiO_4-Si (X_7), Chla (X_8), pH (X_9), Alk. (X_{10}), Cond. (X_{11}), Log(Colour) (X_{12}) and Log(Turb) (X_{13}).

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
Year	0.80	0.59	0.59	0.89	0.99	0.50	0.09	0.36	0.15	0.69	0.29	0.11	0.72
Month	0.00	0.12	0.00	0.06	0.13	0.02	0.43	0.22	0.39	0.40	0.00	0.75	0.01
Bedrock	0.83	0.92	0.02	0.49	0.21	0.00	0.13	0.33	0.19	0.00	0.00	0.01	0.03
Soil	0.60	0.77	0.25	0.93	0.37	0.02	0.13	0.70	0.13	0.00	0.00	0.62	0.53
Lake	0.83	0.85	0.08	0.02	0.04	0.00	0.10	0.01	0.07	0.00	0.00	0.01	0.00

Seasonal variations among high frequency monitored lakes

Twelve lakes (HFM) were sampled on a monthly basis between March and October 2000, in January 2001 and from April to October 2001. Winter months were underrepresented, but the sampling was designed to catch maximum productivity period in the lakes, with the assumption that lake winter chemistry was less variable. Mid-winter (e.g. January 2001) sampling was done to measure possible maximum concentrations of TP and TN.

The bedrock geology of the catchments included in the HFM sampling was representative of the county geology; with four catchments (Loughs Ballybeg, Cullaunyheeda, Dromore and Inchiquin) mainly with carboniferous limestones, four (Loughs Gortglass, Keagh, Lickeen and Doolough) with shales and similar rock types, two (Loughs Ballycullinan and Killone) with mixed geology limestones/shales and two (Loughs Castle and Graney) with old red sandstones and Silurian quartzite. In addition, groundwater connections to surface network drainage are likely to influence lake hydrology and water chemistry for Loughs Ballybeg, Ballycullinan, Dromore and Inchiquin (Chapter 2, Sections II-4 & II-5.2). Peat soils represented the main soil type in Lough Keagh and Doolough catchments (>70%) and were also found in Loughs Castle, Cullaunyheeda, Graney and Lickeen catchments (c.a. 30%).

- Monthly variations in pH, alkalinity and conductivity

Based on M-ANOVA results carried out on the monthly results obtained for the twelve HFM lakes, recorded pH were significantly different ($p \leq 0.01$) among sampling months and among lakes. Alkalinity levels were also found to be significantly different ($p \leq 0.01$) among lakes while conductivity levels were significantly different ($p \leq 0.01$) between 2000 and 2001, between sampling months and, finally, among lakes. As expected, variations in alkalinity and conductivity were positively correlated for Loughs Ballybeg ($r=0.93$, $p<0.01$, $n=15$), Castle ($r=75$, $p<0.05$, $n=11$) and Dromore ($r=0.72$, $p<0.05$, $n=15$), as conductivity levels are influenced by in-lake concentrations of calcium carbonate.

Alkalinity covered a large range, with a tendency for minima over the summer and maxima over the winter (Figure 3.17), in Loughs Ballybeg, Inchiquin, Dromore and Ballycullinan, with a maximum alkalinity range of 122 mg $CaCO_3$ l^{-1} found in Lough Ballybeg, and to a lesser extent in Loughs Cullaunyheeda, Killone and Castle (Figure 3.18). Smaller ranges of variations in alkalinity and increase over the spring and summer were observed for Loughs Lickeen, Keagh, Graney, Gortglass and Doolough (Figure 3.19)

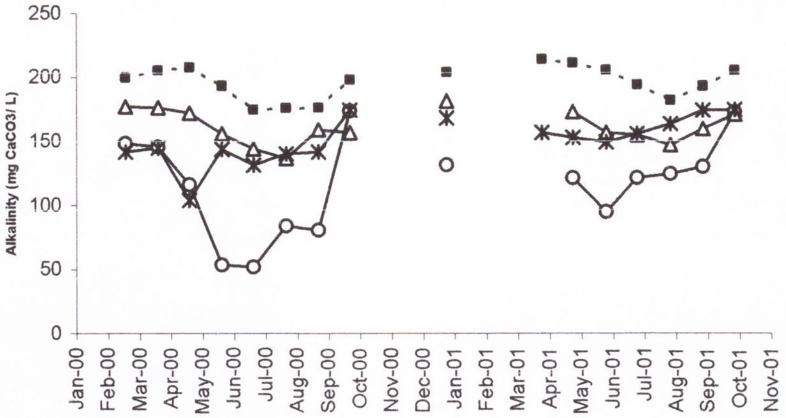

Figure 3.17: Monthly variations in alkalinity (mg $CaCO_3$ l^{-1}) observed between March 2000 and October 2001 in Loughs Ballybeg (—○—), Ballycullinan (--■--), Dromore (—Δ—) and Inchiquin (—*—).

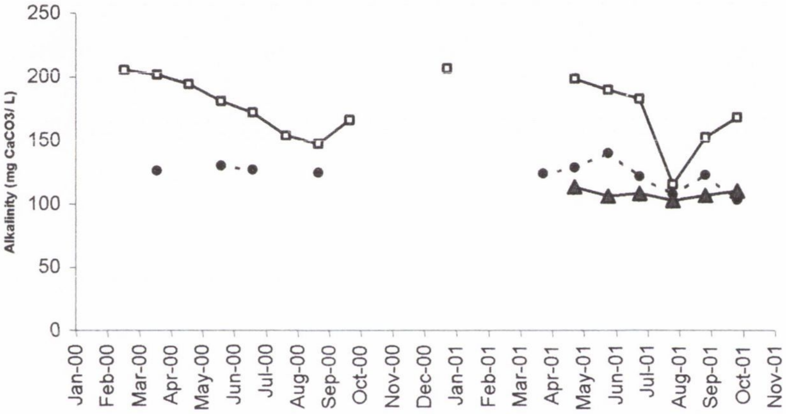

Figure 3.18: Monthly variations in alkalinity (mg $CaCO_3$ l^{-1}) observed between March 2000 and October 2001 in Loughs Castle (--•--), Cullaunyheeda (—□—) and Killone (—▲—).

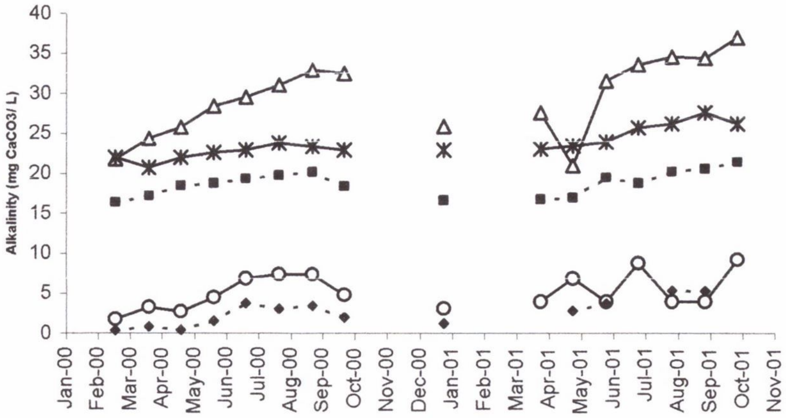

Figure 3.19: Monthly variations in alkalinity (mg $CaCO_3$ l^{-1}) observed between March 2000 and October 2001 in Doolough (—○—), Loughs Gortglass (--■--), Graney (—Δ—), Keagh (--♦--) and Lickeen (—*—).

Greater ranges in seasonal variations in alkalinity were recorded mainly for lakes likely to be influenced by groundwater. Similar patterns of increasing pH over the spring and summer and associated decrease in alkalinity levels were observed in hard water lakes, such as Loughs Ballybeg, Ballycullinan, Cullaunyheeda, Dromore and Inchiquin. Greater variations were observed for Lough Ballybeg (Figure 3.20), as alkalinity and pH levels during the summer are likely to be also influenced by the more acidic inflow from Lough Killone, as groundwater inputs would be likely to be reduced. In these lakes, the increase in pH was usually associated with an increase in chlorophyll-*a* concentrations (Figure 3.21). Much smaller range of variations in alkalinity were observed for softer lakes, such as Loughs Castle, Gortglass, Graney, Keagh, Killone and Doolough (Figure 3.22).

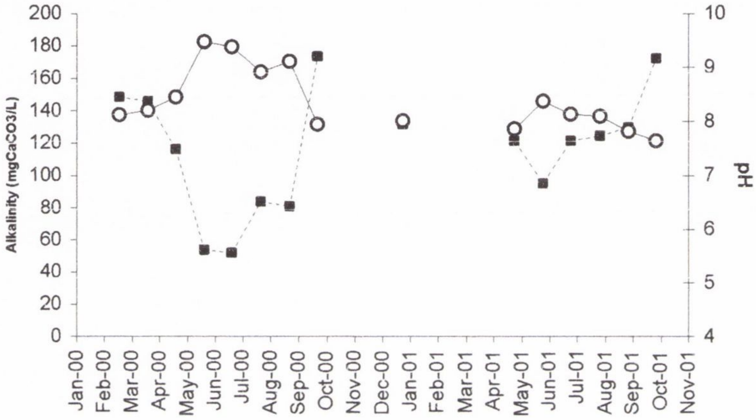

Figure 3.20: Seasonal variations of pH (—○—) and Alkalinity (mg $CaCO_3$ l^{-1}) (--■--) recorded in hard water lakes, as illustrated for Lough Ballybeg between March 2000 and October 2001.

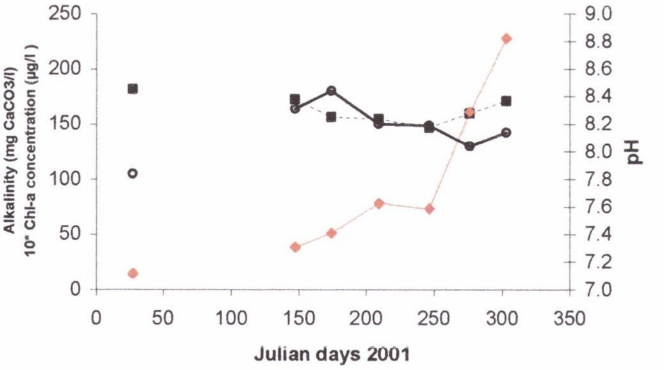

Figure 3.21: Seasonal variations of pH (—○—), alkalinity (mg $CaCO_3$ l^{-1}) (--■--) and chlorophyll-*a* concentrations (—◆—) recorded in hard water lakes, illustrated for Lough Dromore in 2001.

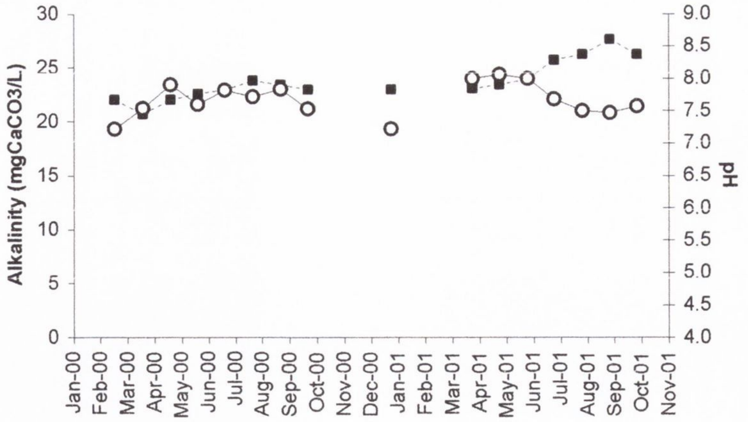

Figure 3.22: Seasonal variations of pH (—○—) and Alkalinity (mg $CaCO_3$ l^{-1}) (--■--) recorded in soft water lakes, as illustrated for Lough Lickeen between March 2000 and October 2001.

Based on M-ANOVA results, variations in pH, alkalinity and conductivity were significantly different ($p \leq 0.01$) among lakes within different bedrock and soil clusters. Significant variations ($p \leq 0.01$) in alkalinity were found between lakes likely to be influenced by groundwater and lakes with no groundwater. Alkalinity ranges were positively correlated with % carboniferous limestone ($r=0.87$, $p<0.01$, $n=2$); while negatively correlated with % shales and similar rock types ($r=-0.73$, $p<0.05$, $n=12$) in the catchments.

- Monthly variations in colour and TDOC

Based on M-ANOVA results, variations in lake colour were significantly different ($p<0.01$) among sampling month and lakes. Monthly variations in colour showed a general decreasing trend over spring reaching minimum values during the summer and increasing over the winter in Loughs Cullaunyheeda, Gortglass, Graney, Keagh and Lickeen (Figure 3.23) and Loughs Castle, Killone and Doolough (Figure 3.24). No clear seasonal trend and lower colour values were observed among the lakes likely to be influenced by groundwater (Figure 3.25).

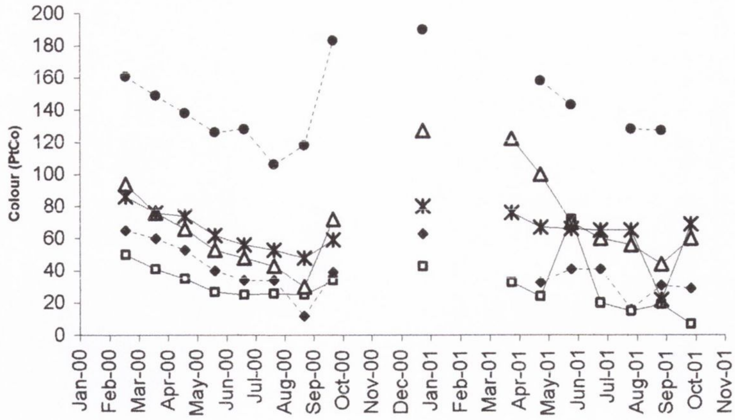

Figure 3.23 Monthly variations in colour (PtCo) recorded between March 2000 and October 2001 in Loughs Cullaunyheeda (--♦--), Gortglass (—□—), Graney (—Δ—), Keagh (--○--) and Lickeen (—*—).

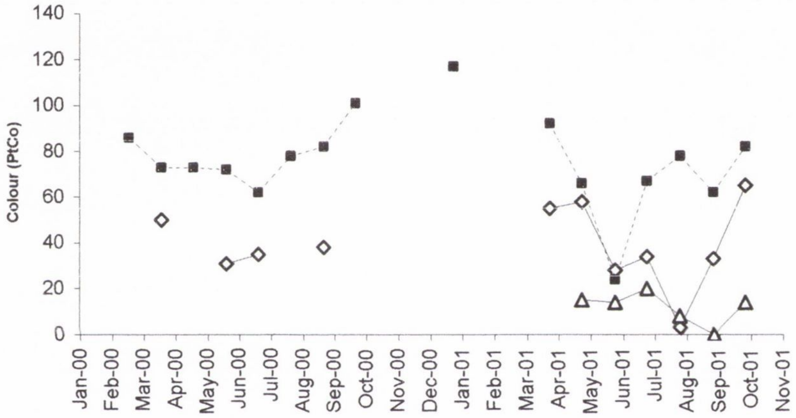

Figure 3.24: Monthly variations in colour (PtCo) recorded between March 2000 and October 2001 in Loughs Castle (—◇—), Killone (—Δ—) and Doolough (--■--).

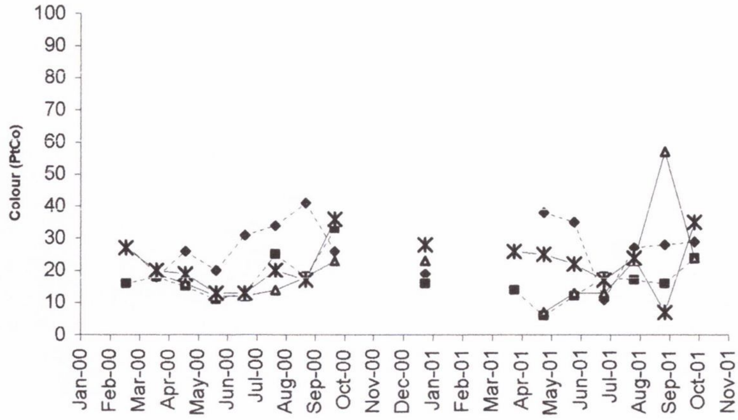

Figure 3.25: Monthly variations in colour (PtCo) recorded between March 2000 and October 2001 in Loughs Ballybeg (--♦--), Ballycullinan (--■--), Dromore (Δ) and Inchiquin (*).

The main trend of decrease in colour during the spring and summer is mainly the result of adsorption onto surfaces or cleavage by UV irradiation, sedimentation and possible co-precipitation of organic matter by calcium carbonate (Steinberg and Muenster, 1985). Sedimentation and photolysis processes have been shown experimentally to reduce colour during the summer (Engstrom, 1987; Tipping and Woof, 1983), but will only be important if sufficient time is available for these processes to take place. In addition, the production and release of colour from the catchment is seasonal. Colour is stored in the catchment during the summer through increased microbial activity and may then be released following precipitation in autumn (Naden and McDonald, 1989). In 2000, most lakes recorded an increase in colour in September, which was usually associated with greater increase in monthly rainfall. Lough Graney recorded the greatest range in colour variation (97 PtCo) over the monitoring period (Figure 3.26).

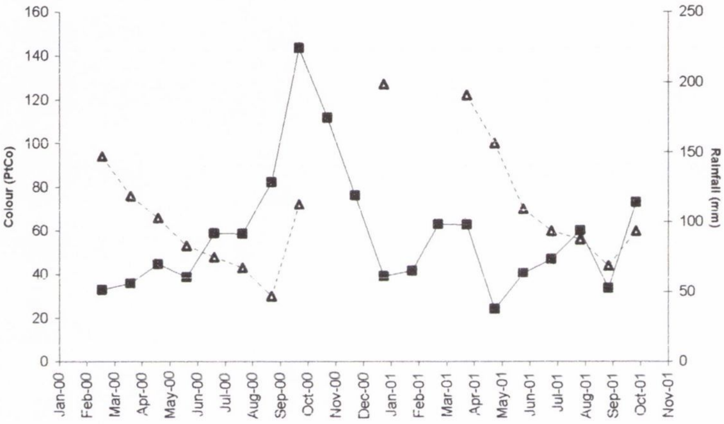

Figure 3.26: Variations in Colour (PtCo) (--Δ--) and Rainfall (mm) (—■—) in Lough Graney, between March 2000 and October 2001.

Recorded TDOC concentrations were low during the monitoring period (usually <10 mg l^{-1}). An increase from April to October was observed in Loughs Ballycullinan, Castle, Inchiquin and Dromore (Figure 3.27). A mid-season peak in TDOC was recorded for Doolough, Loughs Graney, Gortglass, Killone and Lickeen (Figure 3.28). No variations were observed in TDOC concentrations recorded in Loughs Ballybeg and Cullaunyheeda.

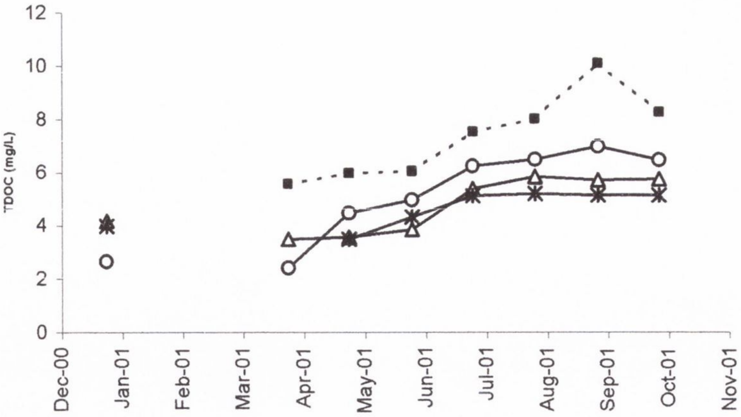

Figure 3.27: Variations in total dissolved organic carbon (mg l^{-1}) in 2001 for Loughs Ballycullinan (—○—), Castle (--■--), Inchiquin (—Δ—) and Dromore (—*—).

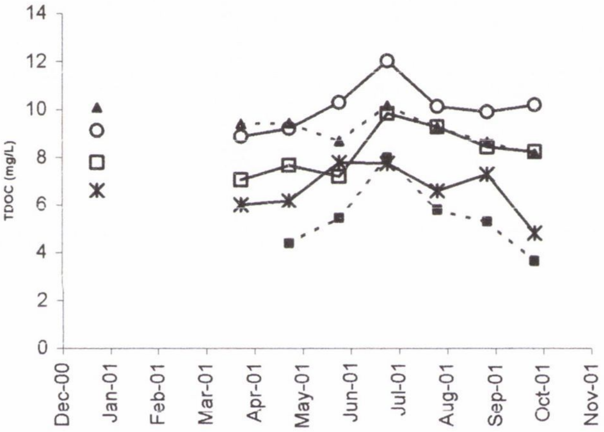

Figure 3.28: Variations in total dissolved organic carbon (mg l^{-1}) in 2001 for Doolough (—□—), Loughs Lickeen (—○—), Killone (--■--), Graney (--▲--) and Gortglass (—*—).

- Seasonal patterns of nutrients

Nutrient concentrations were quite variable between years and among lakes. Based on M-ANOVA results, no significant differences were found in NH_4-N, NO_3-N and TN concentrations between years or among lakes. However, concentrations of NO_3-N were significantly different ($p \leq 0.01$) among sampling months. There was a tendency for in-lake TN minimum concentrations to occur during the summer, and maximum during the winter in Loughs Castle, Cullaunyheeda, Dromore and Gortglass (Figure 3.29). Loughs Graney, Inchiquin, Keagh, Killone, Lickeen and Doolough showed more complex variations with mid-season peaks (Figure 3.30). Notable increase from spring to winter in TN concentration was observed in Lough Ballybeg in 2000, but not in 2001. In Lough Ballycullinan, there was a moderate mid-summer to winter increase in 2001 (Figure 3.31).

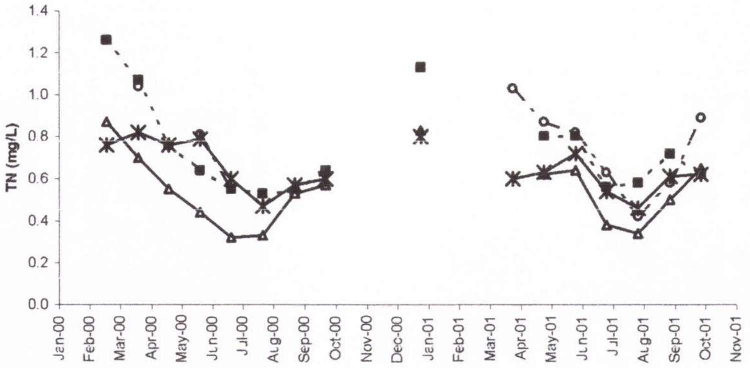

Figure 3.29: Monthly variations in in-lake TN concentrations (mg l^{-1}) between March 2000 and October 2001 in Loughs Castle (---○---), Cullaunyheeda (--■--), Dromore (—Δ—) and Gortglass (—*—).

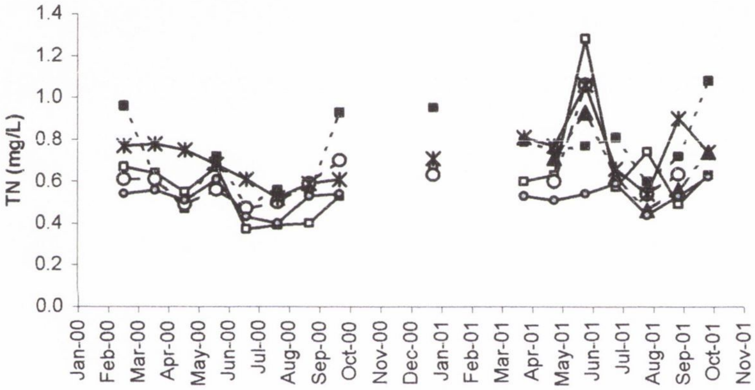

Figure 3.30: Monthly variations in in-lake TN concentrations (mg l^{-1}) between March 2000 and October 2001 in Doolough (—○—), Loughs Graney (—□—), Inchiquin (--■--), Keagh (---○---), Killone (--▲--) and Lickeen (—*—). TN maximum (3.38 mg l^{-1}) reached in January 2001 in Doolough was not included for clarity.

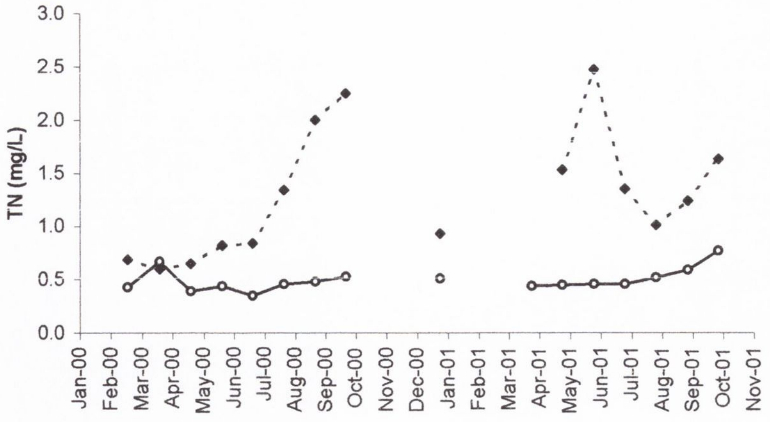

Figure 3.31: Monthly variations in in-lake TN concentrations (mg l^{-1}) between March 2000 and October 2001 in Loughs Ballybeg (--♦--) and Ballycullinan (—○—).

Recorded NH_4-N concentrations were generally low (< 0.05 mg l^{-1}). Greater concentrations were recorded for Loughs Ballycullinan, Ballybeg, Killone, Castle and Cullaunyheeda, with a maximum value of 0.39 mg l^{-1} found in Lough Castle in October 2001. NO_3-N levels were also low and showed a tendency to reach minimum values during the summer. Ratios of NO_3-N/TN were, in general, low and minimum during the summer. These trends appeared related to rainfall patterns (Figures 3.32 and 3.33). Ratios were maximum in Loughs Inchiquin and Castle.

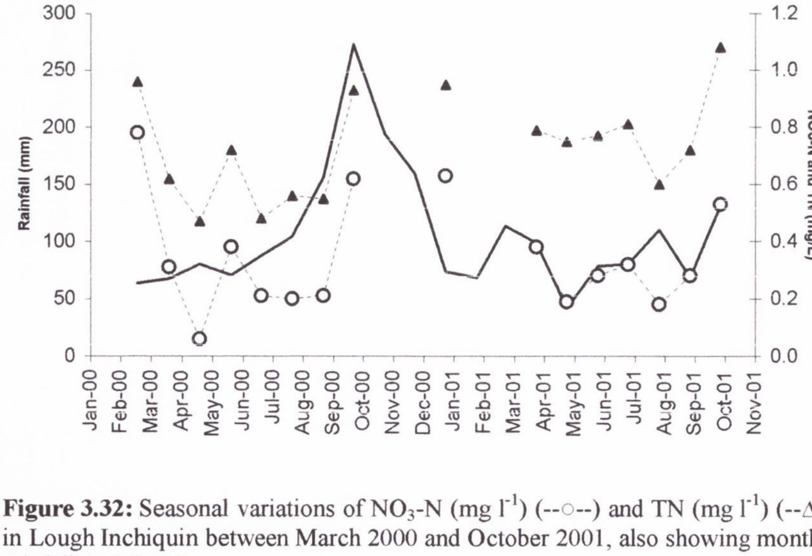

Figure 3.32: Seasonal variations of NO_3-N (mg l^{-1}) (--○--) and TN (mg l^{-1}) (--Δ--) in Lough Inchiquin between March 2000 and October 2001, also showing monthly rainfall (—) (mm).

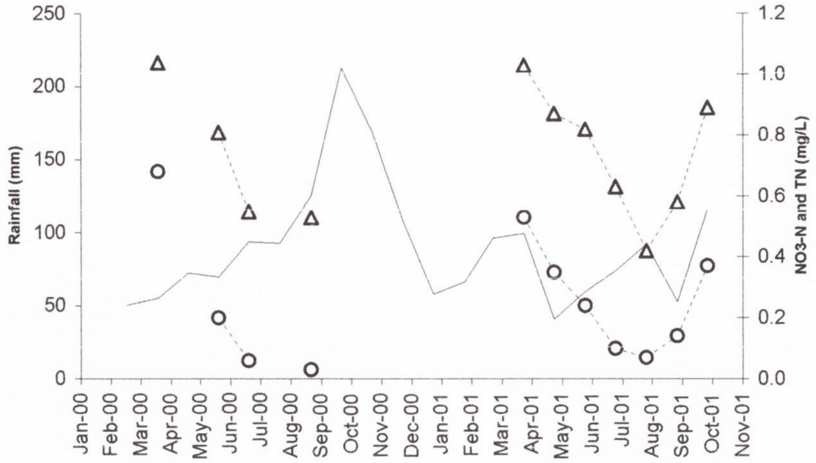

Figure 3.33: Seasonal variations of NO_3-N (mg l^{-1}) (--○--) and TN (mg l^{-1}) (--Δ--) in Lough Castle between March 2000 and October 2001, also showing monthly rainfall (—) (mm).

Similar complex variations were observed in in-lake TP concentrations, with summer minimum and winter maximum for Loughs Cullaunyheeda, Doolough, Gortglass and Killone (Figure 3.34). Loughs Ballybeg and Dromore had increasing TP concentrations from March to October (only in 2000 for Lough Ballybeg) (Figure 3.35), while more complex variations with mid-season peaks were observed for Loughs Ballycullinan, Castle, Graney, Inchiquin, Keagh and Lickeen (Figure 3.36).

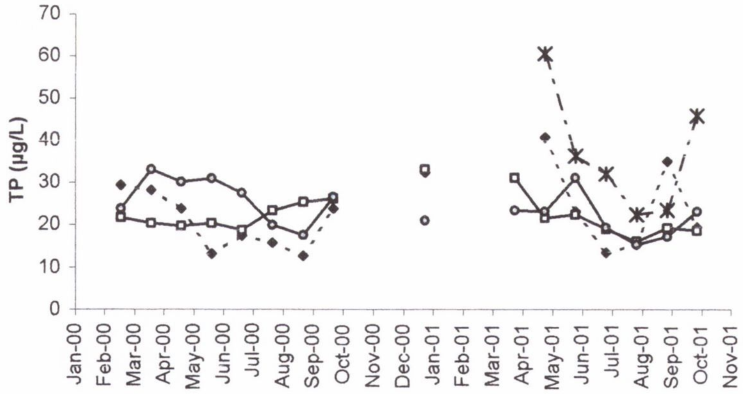

Figure 3.34: Monthly variations in in-lake TP concentrations (µg l^{-1}) between March 2000 and October 2001 in Loughs Cullaunyheeda (--♦--), Doolough (—□—), Gortglass (—○—) and Killone (--*--).

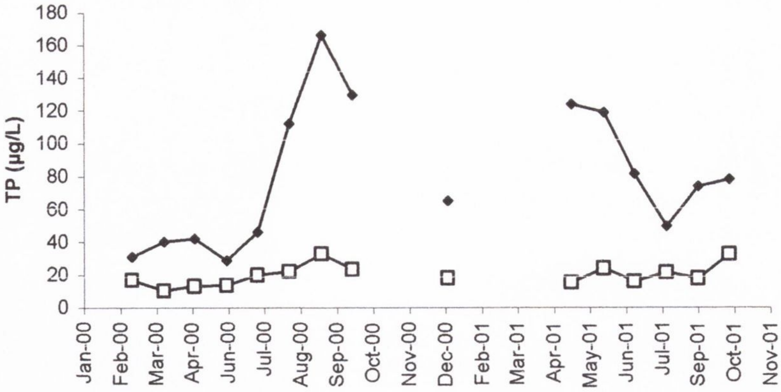

Figure 3.35: Monthly variations in in-lake TP concentrations (μg l^{-1}) between March 2000 and October 2001 in Loughs Ballybeg (—♦—) and Dromore (—□—).

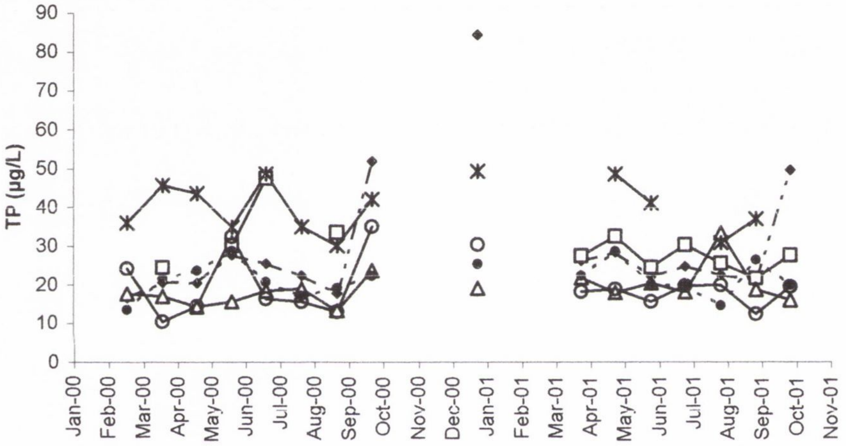

Figure 3.36: Monthly variations in in-lake TP concentrations (μg l^{-1}) between March 2000 and October 2001 in Loughs Ballycullinan (--♦--), Castle (—□—), Graney (—Δ—), Inchiquin (—○—), Keagh (—*—) and Lickeen (---●---)

No significant differences in TP concentrations were found between sampling years and among sampling months (M-ANOVA, $p<0.05$). However, significantly different ($p\leq0.01$) TP concentrations among HFM lakes were found. Variations in TP concentrations were also significantly different ($p\leq0.01$) among lakes belonging to different bedrock or soil clusters (as described in Tables 2.7 and 2.8).

Variations of in-lake TN and TP concentrations were significantly positively correlated for Loughs Ballybeg ($r=0.91$, $p<0.01$, $n=15$); Cullaunyheeda ($r=0.77$, $p<0.01$, $n=15$); Gortglass ($r=0.66$, $p<0.05$, $n=16$) and Inchiquin ($r=0.58$, $p<0.05$, $n=16$). Lough Ballybeg recorded an important decrease in both TP and TN concentrations during the winter months, reflecting the influence of lower rainfall from October 2000 to January 2001 and dilution effect of groundwater recharge during the winter months (Figure 3.37).

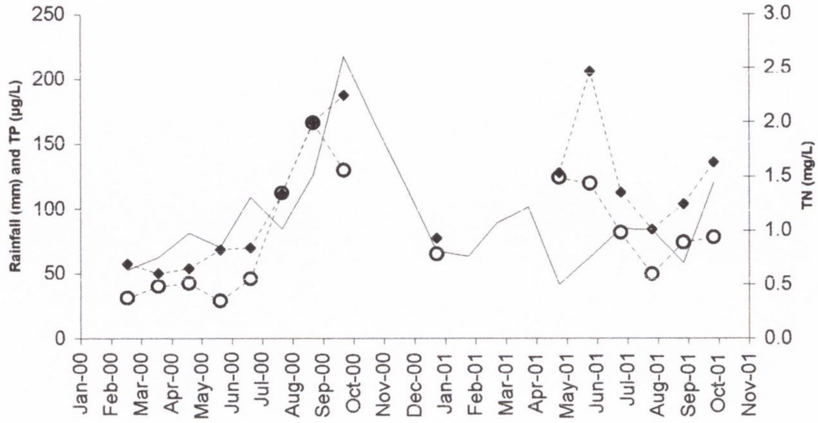

Figure 3.37: Seasonal variations of in-lake TN (mg l^{-1}) (--♦--) and TP (µg l^{-1}) (--○--) in Lough Ballybeg, between March 2000 and October 2001. Also showing variations in catchment rainfall (mm) (—).

In hard water lakes, precipitation of calcite occurs when there is an uptake of CO_2 or HCO_3^- by phytoplankton or by other plants. This causes an increase in pH and leads to over saturation of calcite. Dissolved phosphate can then coprecipitate with calcite during crystal growth (Hartley *et al*, 1997; Danen-Louwerse *et al*, 1995; Dittrich *et al*, 1997). Substantial precipitation of PO_4^{3-} only occurs when the pH is above 8.5 (Otsuki and Wetzel, 1972). Simultaneous decrease in alkalinity and in-lake TP concentrations were recorded in Lough Ballybeg from May to July 2000 (Figure 3.38) and in Lough Cullaunyheeda from April to July 2000 (Figure 3.39), all of which had pH levels ≥8.5.

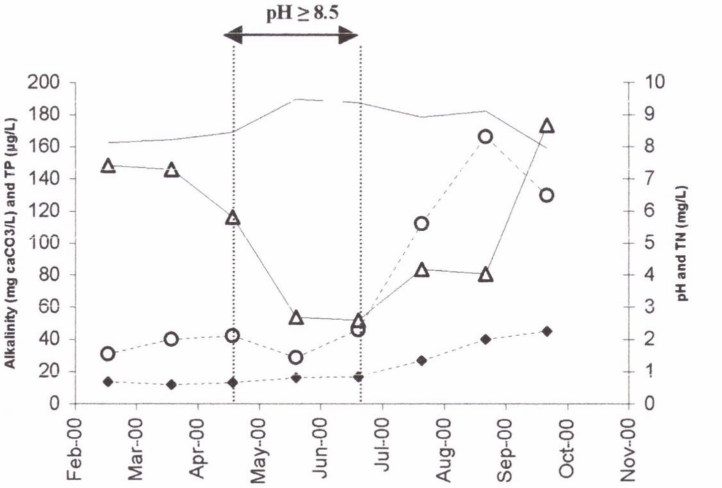

Figure 3.38: Potential signs of phosphate co-precipitation with calcite in Lough Ballybeg, showing variations in alkalinity (–Δ–), pH ( ), TN (mg l^{-1}) (---♦---) and TP (µg l^{-1}) (---○---) concentrations.

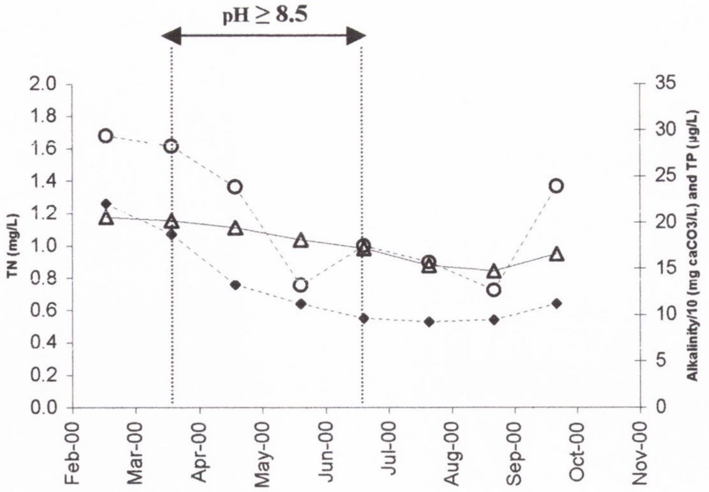

Figure 3.39: Potential signs of phosphate co-precipitation with calcite in Lough Cullaunyheeda, showing variations in alkalinity (Δ), TN (mg l^{-1}) (---♦---) and TP (µg l^{-1}) (---○---) concentrations.

Limitation of algal growth by nitrogen is thought to take place if the ratio of NO_3-N and NH_4-N to PO_4-P is less than 10 by weight (Horne and Goldman, 1994; Irvine *et al*, 2001). The N/P ratio was estimated based on the in-lake TN and TP concentrations. Ratios presented complex seasonal patterns of variations between March 2000 and October 2001. Potential nitrogen limitation was only observed in Lough Ballycullinan in January 2001, with a ratio of six. However, in-lake TN concentrations recorded in January 2001 were similar to levels recorded throughout the year. Maximum NO_3-N and TP concentrations were recorded that month. Low ratios of TN:TP recorded that month could be explained by increased P concentrations (Figure 3.40).

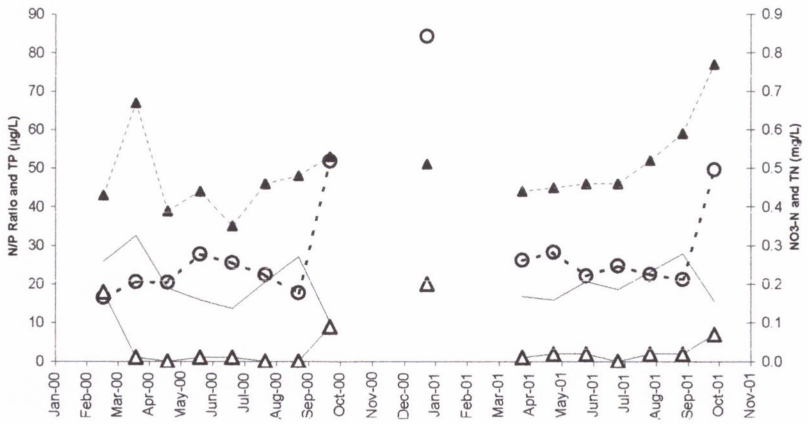

Figure 3.40: N/P ratio (—) variations in Lough Ballycullinan between March 2000 and October 2001, also showing variations in in-lake concentrations in TP (--○--) (µg l^{-1}), TN (--▲--) and NO_3-N (--Δ--) (mg l^{-1}).

Other nutrients such as SiO_4-Si could also limit algal growth. Measurements of in-lake SiO_4-Si were not frequent enough to allow assessment of monthly variations. In general, levels were variables ranging from 0.04 mg l^{-1} to a maximum value of 5.1 mg l^{-1} recorded in Lough Ballybeg in May 2001.

- Variations in chlorophyll-*a*:

Phytoplankton chlorophyll-*a* concentration was very variable among lakes and years (Figure 3.41 to 3.43). Maximum chlorophyll-*a* did not always occur during the summer months and some lakes had secondary peaks of chlorophyll-*a* concentrations during the year. Based on M-ANOVA results, no significant differences in chlorophyll-*a* levels were found between sampling years and among sampling months. Bedrock and soil types also did not appear to significantly influence lake chlorophyll-*a* concentrations.

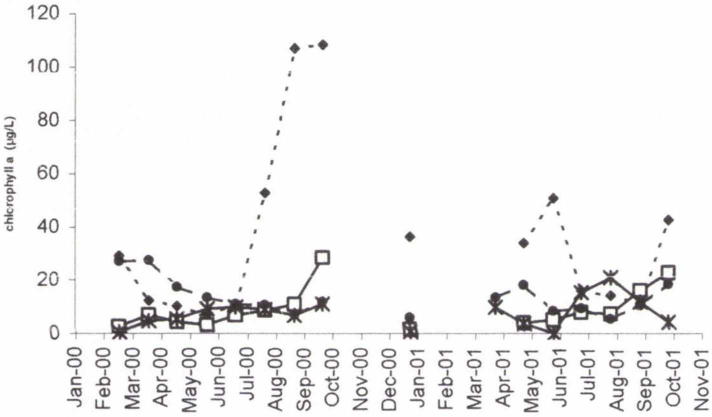

Figure 3.41: Variations in phytoplankton chlorophyll-*a* (µg l^{-1}) between March 2000 and October 2001 for Loughs Ballybeg (--♦--), Dromore (—□—), Gortglass (---●---) and Graney (—*—).

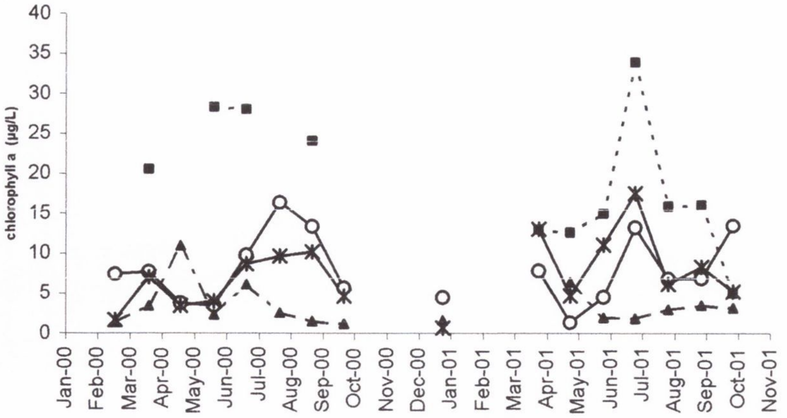

Figure 3.42: Variations in phytoplankton chlorophyll-*a* (µg l^{-1}) between March 2000 and October 2001 for Loughs Ballycullinan (—○—), Castle (---■---), Cullaunyheeda (--▲--) and Doolough (—*—).

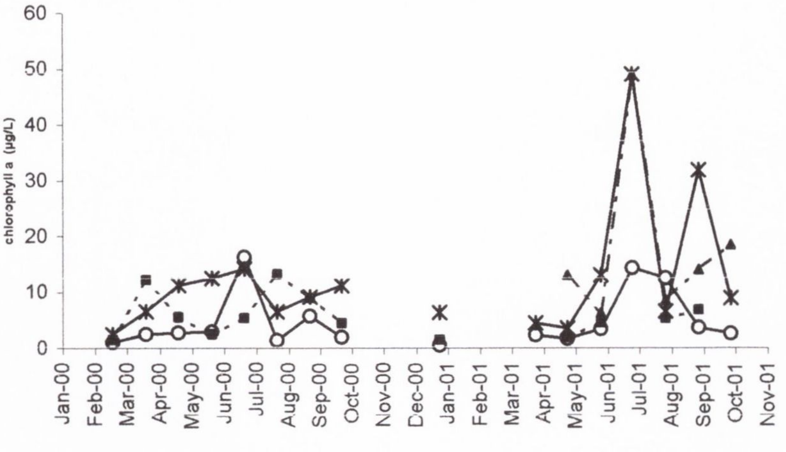

Figure 3.43: Variations in phytoplankton chlorophyll-*a* ($\mu g\ l^{-1}$) between March 2000 and October 2001 for Loughs Inchiquin (—○—), Keagh (---■---), Killone (---▲---) and Lickeen (—*—).

Variations of in-lake chlorophyll-*a* concentrations were correlated with in-lake nutrient concentrations and turbidity (Table 3.7).

Table 3.7: Spearman's Rank correlation coefficients between chlorophyll-*a* concentrations and other chemical variables. n=16 for Loughs Ballycullinan, Doolough, Gortglass, Graney and Lickeen; n=15 for Loughs Ballybeg, Cullaunyheeda and Dromore, n=13 for Lough Keagh, n=11 for Lough Castle, n=6 for Lough Killone. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

	NO_3-N	TN	TP	Turb.
Ballybeg	0.22	0.77**	0.81**	0.78**
Ballycullinan	-0.35	0.22	-0.22	0.15
Castle	-0.56	-0.45	0.32	-0.36
Cullaunyheeda	-0.02	-0.02	0.23	0.46
Doolough	-0.57*	-0.26	-0.05	0.06
Dromore	-0.32	-0.32	0.54	0.48
Gortglass	0.10	0.51	0.58*	0.68*
Graney	-0.66*	-0.42	0.32	0.23
Inchiquin	-0.43	-0.47	-0.29	-0.03
Keagh	-0.39	-0.35	-0.27	0.37
Killone	0.17	-0.14	0.09	0.26
Lickeen	-0.53	-0.08	0.13	0.47

Influence of the monitoring frequency

The effect of the total number of samples taken and of sampling months on the observed monitoring means 2000-01 of the different chemical variables among the lakes included in the high frequency monitoring, was assessed by recalculating the means based on the different combinations of HFM sampling occasions, as described in Table 3.1 and Appendix 2, Table 2. Results are presented in Table 17, Appendix 2.

Overall, most recalculated means (>96%) of chemical variables based on the different seasonal spreads of HFM monitoring were within 95% CI of the observed monitoring means 2000-01. More variations were observed when applying the seasonal spread of monitoring HFM n=6 (e.g. Lough Killone), especially for conductivity. This resulted mainly from the difference in lake chemistry observed between 2000 and 2001 (Appendix 2 – Tables 18 to 21).

The accuracy of the monitoring means obtained for the MFM lakes was assessed by comparing the monitoring means 2000-01 and means recalculated applying the different seasonal spreads of MFM monitoring (described in Table 3.1 and Appendix 2, Table 3) for the lakes included in the high frequency monitoring. Results are presented in Table 22, Appendix 2. More variation was observed between means of the different chemical variables calculated based on the HFM monitoring results or when applying the different seasonal spreads of MFM monitoring, especially for the conductivity results. 20% of the means calculated for the HFM lakes, applying the different seasonal spreads of MFM monitoring, were outside the intervals of observed monitoring means 2000-01 ± 95% CI.

Variability in the accuracy of the monitoring means 2000-01 is to be expected, owing to natural variability (annual and seasonal) in lake water chemistry, the influence of sampling conditions and the complexity of the monitoring frequency regimes used during the monitoring 2000-01. Means were more representative of the annual seasonal variations in lake water chemistry when more samples were taken evenly distributed over the monitoring period. Difficulties related to spread and frequency of seasonal monitoring is common in sampling programmes. In order to simplify the processing and statistical analyses of the data, high and medium frequency monitoring datasets were processed together. Nevertheless, distinction between high and medium frequency was made when interpreting maximum chlorophyll-*a* concentrations. Low frequency monitoring data, based on one or two summer samples, were treated separately, as they were not representative of the overall means for 2000-01 in the lakes.

Monitoring means of pH, alkalinity and conductivity

Based on the ECE acidity scheme (Premazzi and Chiaudani, 1992), most of the lakes included in the monitoring were classified as Class I based on their pH averages, while they were distributed between Class II and III based on their alkalinity levels (Table 3.8).

Table 3.8: Classification by acidity of the lakes based on the ECE scheme (Premazzi and Chiaudani, 1992)

Class	pH	No. Lakes	Alkalinity mg $CaCO_3$ l^{-1}	No. Lakes
I	9.0-6.5	64	> 200	5
II	6.5-6.3	1	200-100	24
III	6.3-6.0	3	100-20	24
IV	6.0-5.3	1	20-10	10
V	< 5.3	0	< 10	6

Lower pH, alkalinity and conductivity values were usually recorded among catchments lying on shales and similar rock types and associated with poorly drained soils, such as peats; while higher values were recorded among catchments lying on carboniferous limestone and associated with well drained soils. In addition, higher conductivity values were recorded at proximity of the sea, such as Loughs Luirk, Rask and Muckinish and Black (near Kilkee).

Among the HFM-MFM lakes ($n \geq 4$ sampling occasions), mean pH ± 95% CI ranged from 5.46 ± 0.21 (Lough Acrow) to 8.35 ± 0.15 (Lough Cullaunyheeda), while mean alkalinity ± 95% CI ranged from 0.0 ± 0.5 (Lough Acrow) to 213.6 ± 14.1 mg $CaCO_3$ l^{-1} (Lough Clonlea). Lough Naminna recorded the lowest mean conductivity (72.4 ± 8.4 $\mu S\ cm^{-1}$), while the maximum mean (436.8 ± 48.7 $\mu S\ cm^{-1}$) was recorded in Lough Ballycar (Table 3.9).

Table 3.9: Mean 2000-01 pH, alkalinity (mg $CaCO_3$ l^{-1}) and conductivity ($\mu S\ cm^{-1}$) among the lakes included in the high and medium frequency monitoring. Total number of samples (n) and 95% CI (in italics) are also given.

Lakes	n	pH	*95% CI*	Alk.	*95% CI*	Cond.	*95% CI*
Acrow	4	5.46	*0.21*	0.0	*0.5*	82.3	*7.3*
Atedaun	4	8.01	*0.34*	135.4	*44.7*	334.5	*83.0*
Ballyallia	4	8.18	*0.21*	157.7	*30.6*	381.8	*57.7*
Ballybeg	16	8.13	*0.32*	116.6	*20.8*	299.4	*39.5*
Ballycar	4	8.14	*0.08*	186.0	*18.3*	436.8	*48.7*
Ballycullinan	16	8.04	*0.09*	196.3	*6.9*	422.1	*17.6*
Ballyleann	4	7.75	*0.19*	44.9	*4.5*	182.0	*8.0*
Burke	4	7.76	*0.34*	47.9	*3.8*	183.5	*12.1*
Castle	11	8.04	*0.13*	123.3	*6.9*	284.5	*18.5*
Clonlea	5	8.17	*0.29*	213.6	*14.1*	428.6	*16.8*
Cloonmackan	5	7.35	*0.08*	14.9	*3.0*	119.8	*10.6*
Cloonsnaghta	4	7.21	*0.08*	12.7	*2.1*	130.5	*4.6*
Cullaun	5	8.29	*0.10*	126.0	*77.7*	347.4	*48.1*
Cullaunyheeda	15	8.35	*0.15*	175.8	*14.3*	394.6	*24.3*
Doolough	16	6.88	*0.13*	5.1	*1.2*	94.0	*6.2*
Doon	4	7.68	*0.40*	76.7	*13.3*	180.3	*32.8*
Dromore	15	8.15	*0.09*	161.4	*7.3*	363.7	*21.7*
Gortglass	16	7.42	*0.07*	18.7	*0.8*	131.4	*5.2*
Graney	16	7.66	*0.10*	29.5	*2.5*	115.5	*6.4*

Table 3.9 (continued)

Lakes	n	pH	*95% CI*	Alk.	*95% CI*	Cond.	*95% CI*
Inchichronan	5	8.01	*0.22*	134.7	*12.6*	306.8	*39.3*
Inchiquin	16	8.21	*0.12*	151.0	*9.8*	342.3	*18.7*
Keagh	13	6.14	*0.25*	2.6	*1.0*	104.9	*8.0*
Killone	6	8.26	*0.30*	107.9	*3.8*	265.7	*16.8*
Knockalough	5	7.75	*0.29*	25.2	*4.6*	130.2	*18.3*
Lickeen	16	7.59	*0.14*	23.7	*1.0*	139.3	*5.3*
Lisnahan	5	7.85	*0.22*	46.8	*1.9*	317.6	*46.8*
Moanmore	4	7.08	*0.23*	15.5	*2.7*	156.8	*17.3*
Muckanagh	5	8.27	*0.15*	155.9	*50.5*	334.6	*67.2*
Naminna	5	6.38	*0.27*	1.7	*1.1*	72.4	*8.4*
Rosroe	4	8.21	*0.20*	151.9	*17.7*	344.3	*37.8*

When looking at the relationship between mean pH and alkalinity among HFM-MFM lakes (n=30) (Figure 3.44), acidic catchments (n=13) showed low to moderate buffering capacity against acidification (Alkalinity <100mg $CaCO_3$ l^{-1}). Any decrease in pH would result in decrease in alkalinity level. Calcareous catchments (n=11) had good buffering capacity (Alkalinity >100mg $CaCO_3$ l^{-1}). Four lakes (Loughs Acrow, Naminna, Keagh Doolough) showed poor buffering capacity against acidification (Alkalinity <10mg $CaCO_3$ l^{-1}). All were upland peatland catchments, with conifer forests comprising 15 to 53% of the catchment area, except for Lough Keagh.

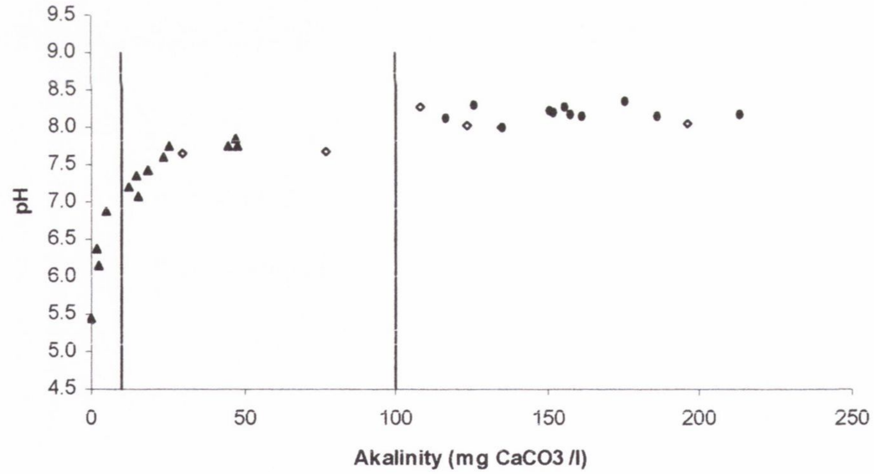

Figure 3.44: Comparison between means alkalinity and pH among the HFM-MFM lakes (n=30) monitored in 2000-01. Lakes are differentiated among acidic (▲, n=13), calcareous (●, n=11) and other types of bedrock (◊, n=6), as described in Table 2.7. The limit values of alkalinity = 10 and 100 mg $CaCO_3$ l^{-1} are also shown by the black lines.

Among the LFM lakes (n≤2 sampling occasions), values recorded during the summer (or summer average if n=2) for pH ranged from 6.14 (Lough Ballydoolavan) to 8.81 (Lough Finn), and from 2.3 (Lough Luogh) to 291.6 mg $CaCO_3$ l^{-1} (Lough Luirk) for alkalinity. Summer conductivity values ranged from 101.7 µS cm^{-1} (Lough Achryane) to 14840 µS cm^{-1} (Lough Muckinish) (Table 3.10).

Table 3.10: Mean 2000-01 pH, alkalinity (mg CaCO$_3$ l^{-1}) and conductivity (µS cm^{-1}) among the lakes included in the low frequency monitoring. Total number of samples (n) and 95% CI (in italics) are also given.

Lakes	n	pH	*95% CI*	Alk.	*95% CI*	Cond.	*95% CI*
Achryane	2	7.00	*0.70*	8.5	*13.0*	101.7	*118.2*
Aillbrack	2	7.40	*0.38*	11.3	*29.2*	129.0	*242.0*
Ballydoolavan	1	6.14		14.8		101.8	
Ballyeighter	1	8.07		80.4		191.0	
Ballyteige	2	7.94	*0.19*	116.3	*318.9*	324.5	*400.2*
Black Dro	1	8.10		147.6		307.0	
Black-Lis	1	7.61		93.4		3010.0	
Bridget	1	8.26		192.1		433.0	
Bunny	1	8.34		100.4		265.0	
Caum	2	6.73	*0.64*	17.9	*10.9*	106.0	*127.1*
Curtins	2	7.97	*5.08*	54.4	*60.7*	176.0	*216.0*
Dromoland	1	8.09		179.8		515.0	
Drumcullaun	1	7.65		42.3		171.0	
Druminure	2	7.38	*0.32*	20.1	*34.8*	119.0	*177.9*
Eanagh	1	7.30		34.4		119.0	
Effernan	2	7.30		22.4		145.0	
Farrihy	1	7.27		102.0		514.0	
Finn	1	8.81		65.4		216.0	
Garvillaun	2	7.63	*1.08*	67.4	*43.5*	197.0	*228.7*
Gash	1	7.64		233.2		485.0	
George	1	8.26		160.6		330.0	
Girroga	2	8.15	*0.38*	202.5	*34.3*	434.5	*222.4*
Goller	1	6.66		15.0		104.0	
Gortaganniv	2	7.92	*1.84*	88.1	*5.8*	229.0	*317.7*
Gorteen	1	7.44		54.0		174.0	
Kilgory	1	8.05		184.4		363.0	
Knockerra	1	7.43		19.8		154.0	
Luirk	1	7.88		291.6		581.0	
Luogh	2	6.23	*2.92*	2.3	*16.5*	150.5	*374.8*
Mooghna	2	7.42	*1.33*	46.8	*81.8*	176.5	*184.2*
More	1	7.47		23.6		156.0	
Morgans	2	7.47	*3.18*	43.0	*50.3*	171.5	*196.9*
Muckinish	1	8.09		148.8		14840.0	
O'Briens	1	8.30		158.2		394.0	
O'Grady	1	7.44		64.4		158.0	
Rask	1	7.75		226.8		964.0	
Rosconnell	1	7.91		25.8		107.0	
Rushaun	1	7.85		69.7		206.0	
Tullabrack	1	7.14		13.8		165.0	

Catchment descriptive variables and mean pH, alkalinity and conductivity were also intercorrelated (Table 3.11). For both sampling frequency regimes (HFM-MFM and LFM), catchments with low elevation, covered mainly by underlying carboniferous limestone and associated with well/moderately drained soils, such as brown earths, rendzinas and grey brown podzolics, were associated with higher mean pH, alkalinity and conductivity. On the other hand, catchments lying at higher elevation, covered by underlying shales and similar rocks and associated with poorly/imperfectly drained soils, such as peats, were associated with lower mean pH, alkalinity and conductivity (Figures 3.45 to 3.47). Two-sample t-tests showed that mean pH, alkalinity and conductivity recorded between catchments with 0 and 100% of carboniferous limestone and then between catchments with 0 and 100% of shales and similar rock types were, respectively, significantly different ($\alpha=0.05$, $p\leq0.001$).

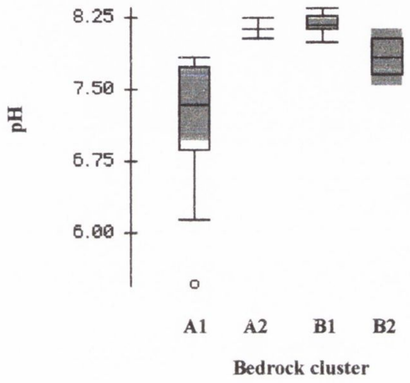

Figure 3.45: Distribution of mean in-lake pH recorded in the HFM-MFM lakes (n=30) monitored in 2000-01 among the different catchment bedrock types, as described in Table 2.7.

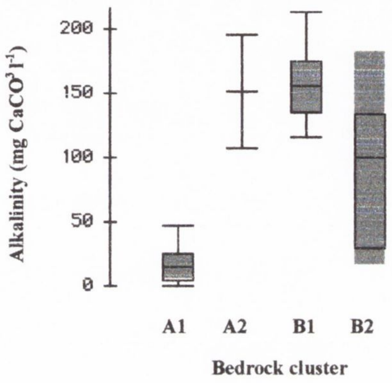

Figure 3.46: Distribution of mean in-lake alkalinity (mg $CaCO_3$ l^{-1}) recorded in the HFM-MFM lakes (n=30) monitored in 2000-01 among the different catchment bedrock types, as described in Table 2.7.

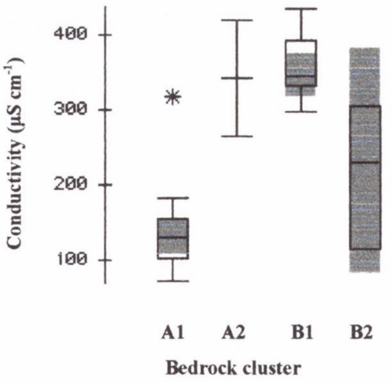

Figure 3.47: Distribution of mean in-lake conductivity (µS cm^{-1}) recorded in the HFM-MFM lakes (n=30) monitored in 2000-01 among the different catchment bedrock types, as described in Table 2.7.

Table 3.11: Spearman's Rank correlation coefficients between mean pH, alkalinity and conductivity 2000-01 with catchment descriptive variables. Sampling frequency regimes: HFM-MFM (n=30) and LFM (n=39) are differentiated. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ are by **.

		pH		**Alkalinity**		**Conductivity**	
		HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM
Topography	Log(Catchment Area)	0.44*	0.23	0.50**	0.41*	0.39*	0.19
	Log(Drainage Area)	0.40*	0.21	0.46*	0.40*	0.36	0.55**
	Minimum elevation	-0.62**	-0.59**	-0.64**	-0.74**	-0.63**	-0.66**
	Log(Maximum elevation)	-0.37	-0.19	-0.33	-0.17	-0.40*	-0.10
	Mean elevation	-0.63**	-0.54**	-0.58**	-0.51**	-0.66**	-0.53**
Bedrock	Carboniferous limestone	0.81**	0.68**	0.89**	0.77**	0.87**	0.75**
	Shales and similar rock	-0.72**	-0.65**	-0.78**	-0.75**	-0.69**	-0.70**
Soils	Well/Moderate drainage	0.83**	0.62**	0.81**	0.71**	0.78**	0.69**
	Poor/Imperfect drainage	-0.64**	-0.64**	-0.58**	-0.70**	-0.57**	-0.73**
	S1	0.83**	0.62**	0.81**	0.71**	0.78**	0.69**
	S2	-0.01	-0.44**	0.09	-0.46**	0.06	-0.50**
	S4	-0.46*	-0.53**	-0.50**	-0.63**	-0.55**	-0.53**
	Minimum soil Morgan P levels	0.17	0.06	0.33	0.28	0.40*	0.15
	Maximum soil Morgan P levels	0.64**	0.45**	0.61**	0.51**	0.59**	0.53**
	Mean soil Morgan P levels	0.66**	0.36*	0.68**	0.50**	0.71**	0.19
	Brown earths	0.53**	0.32	0.38*	0.51**	0.36	0.19
	Rendzinas	0.47*	0.49**	0.51**	0.52**	0.50*	0.51**
	Grey brown podzolics	0.73**	0.54**	0.79**	0.64**	0.76**	0.51**
	Peats	-0.46*	-0.53**	-0.50**	-0.63**	-0.55**	-0.53**
	Gleys	-0.01	-0.44**	0.09	-0.46**	0.06	-0.50**
	Brown podzolics	-0.07	-0.33	-0.13	-0.45**	-0.18	-0.34*
Bathymetry	Log(Lake Area)	0.37	0.29	0.35	0.23	0.20	0.35*
	Log(Lake Volume)	0.45*	0.28	0.27	0.22	0.15	0.11
	Log(lake mean depth)	0.49*	0.17	0.23	0.20	0.20	0.18
	Lake altitude	-0.61**	-0.57**	-0.67**	-0.74**	-0.64**	-0.75**
	Log(Lake shoreline)	0.38*	0.31	0.39*	0.26	0.24	0.03
	Dl	0.34	0.27	0.44*	0.23	0.33	0.35*

Monitoring means of colour, turbidity and total dissolved organic carbon

Among the lakes included in the monitoring, twenty-nine were highly coloured (≥50 PtCo) and thirty-seven had low dissolved organic carbon (≤10 mg TDOC l^{-1}). Higher colour and TDOC were usually recorded among lakes covered with poorly drained soils, such as peats. Among the HFM-MFM lakes, mean colour ± 95% CI ranged from 10 ± 8 (Lough Cullaun) to 209 ± 105 mg PtCo l^{-1} (Lough Moanmore) and turbidity from 0.7 ± 0.4 (Lough Cullaun) to 16.2 ± 9.4 NTU (Lough Ballybeg). Mean TDOC concentrations ranged from 4.3 (Lough Ballyallia) to 23.3 mg l^{-1} (Lough Moanmore) (Table 3.12).

Table 3.12: Means 2000-01 colour (mg PtCo l^{-1}), turbidity (NTU) and TDOC (mg l^{-1}) among the lakes included in the high and medium frequency monitoring. Total number of samples (n), number of TDOC analyses (n_{TDOC}) and 95% CI (in italics) are also given.

Lakes	n	Colour	*95% CI*	Turb	*95% CI*	n_{TDOC}	TDOC	*95% CI*
Acrow	4	65	*10*	2.0	*0.8*	1	6.7	
Atedaun	4	30	*29*	3.3	*6.8*	1	4.6	
Ballyallia	4	21	*9*	1.8	*1.0*	1	4.3	
Ballybeg	16	31	*10*	16.2	*9.4*	9	9.3	*6.6*
Ballycar	4	31	*2*	1.4	*1.4*	1	7.9	
Ballycullinan	16	17	*3*	1.8	*0.5*	10	5.2	*1.1*
Ballyleann	4	29	*10*	3.5	*2.0*	1	7.3	
Burke	4	38	*14*	3.8	*5.4*	1	7.0	
Castle	11	39	*12*	3.5	*0.7*	8	7.3	*1.3*
Clonlea	5	27	*11*	14.1	*13.8*	4	8.5	*0.6*
Cloonmackan	5	45	*11*	5.9	*2.3*	2	9.2	*3.4*
Cloonsnaghta	4	77	*3*	1.6	*0.4*	1	9.4	
Cullaun	5	10	*8*	0.7	*0.4*	2	4.5	*2.7*
Cullaunyheeda	15	39	*9*	4.2	*3.8*	9	15.0	*12.1*
Doolough	16	76	*11*	2.4	*0.5*	10	7.5	*1.2*
Doon	4	76	*55*	4.9	*3.1*	1	9.0	
Dromore	15	20	*6*	6.1	*9.8*	9	5.8	*1.9*
Gortglass	16	31	*8*	3.7	*1.1*	10	6.7	*0.7*
Graney	16	70	*15*	3.8	*0.7*	10	9.0	*0.7*
Inchichronan	5	34	*11*	4.0	*2.5*	4	8.3	*2.4*
Inchiquin	16	22	*4*	1.2	*0.3*	10	4.7	*0.8*
Keagh	13	143	*15*	2.6	*0.7*	7	12.6	*1.5*
Killone	6	12	*7*	4.3	*2.4*	6	5.4	*1.5*
Knockalough	5	44	*14*	2.3	*0.7*	4	9.5	*1.3*
Lickeen	16	64	*8*	3.7	*0.9*	10	9.8	*0.7*
Lisnahan	5	36	*17*	5.1	*6.8*	4	11.0	*0.9*
Moanmore	4	209	*105*	10.5	*13.1*	1	23.3	
Muckanagh	5	15	*15*	1.5	*1.0*	4	8.4	*1.9*
Naminna	5	41	*11*	1.3	*0.4*	4	5.5	*1.5*
Rosroe	4	13	*20*	1.9	*1.4*	1	10.6	

Summer values recorded for the LFM lakes, ranged from 0 (Lough Dromoland) to 417 mg PtCo l^{-1} (Lough Ballydoolavan) for colour; 0.71 (Lough Bunny) to 63.1 NTU (Lough Black (near Kilkee)) for turbidity and from 4.4 (Lough Luirk) to 29.5 mg l^{-1} (Lough Ballydoolavan) for TDOC (Table 3.13).

Table 3.13: Means 2000-01 colour (mg PtCo l^{-1}), turbidity (NTU) and TDOC (mg l^{-1}) among the lakes included in the low frequency monitoring. Total number of samples (n), number of TDOC analyses (n_{TDOC}) and 95% CI (in italics) are also given.

Lakes	n	Colour	*95% CI*	Turb	*95% CI*	n_{TDOC}	TDOC	*95% CI*
Achryane	2	61	*0*	6.6	*27.7*	1	8.2	
Aillbrack	2	26	*133*	1.4	*5.6*	1	9.5	
Ballydoolavan	1	417		46.4		1	29.5	
Ballyeighter	1	3		1.4		1	8.7	
Ballyteige	2	36	*140*	2.5	*9.2*	1	7.5	
Black Dro	1	16		5.4		1	5.4	
Black-Lis	1	151		63.1				
Bridget	1	34		2.8				
Bunny	1	8		0.7				
Caum	2	186	*51*	17.2	*198.9*	1	19.7	
Curtins	2	75	*362*	11.6	*124.1*	1	13.8	
Dromoland	1	0		2.7		1	5.2	
Drumcullaun	1	149		3.8				
Druminure	2	97	*70*	6.4	*5.2*	1	13.9	
Eanagh	1	75		3.0		1	13.4	
Effernan	2	60		4.5		1	14.2	
Farrihy	1	153		40.4		1	21.1	
Finn	1	9		5.6				
Garvillaun	2	50	*89*	2.4	*3.1*	1	10.1	
Gash	1	25		8.5		1	7.4	
George	1	14		1.1		1	7.3	
Girroga	2	13	*57*	1.1	*3.8*	1	6.4	
Goller	1	205		23.7		1	22.2	
Gortaganniv	2	50	*146*	2.7	*7.4*	1	13.6	
Gorteen	1	26		6.7		1	8.0	
Kilgory	1	20		1.3		1	10.3	
Knockerra	1	31		2.1				
Luirk	1	17		2.5		1	4.4	
Luogh	2	143	*718*	2.2	*9.5*	1	13.7	
Mooghna	2	87	*165*	5.0	*24.8*	1	10.5	
More	1	66		1.1				
Morgans	2	115	*133*	1.9	*4.6*	1	16.6	
Muckinish	1	6		3.2				
O'Briens	1	28		1.5				
O'Grady	1	168		1.1		1	14.6	
Rask	1	6		0.7		1	5.6	
Rosconnell	1	111		20.0		1	13.3	
Rushaun	1	76		5.8				
Tullabrack	1	102		2.2				

Lakes that were likely to have their water chemistry influenced by groundwater inputs usually recorded lower mean colour, turbidity and TDOC concentrations over the monitoring period. Mean colour, turbidity and TDOC concentrations were correlated among each other and with mean pH, alkalinity and conductivity (Table 3.14). Higher colour values were associated with more acidic water, and lower colour values with more alkaline lakes.

Table 3.14: Spearman's Rank correlation coefficients between mean colour, turbidity and TDOC, with means pH, alkalinity and conductivity. n=30 for HFM-MFM and n=39 for LFM. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

	Colour		**Log(Turbidity)**		**TDOC**	
	HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM
Log(Turbidity)	0.21	0.49**	1.00	1.00		
TDOC	0.56**	0.90**	0.42*	0.44**	1.00	1.00
pH	-0.72**	-0.72**	0.00	-0.36*	-0.17	-0.68**
Alkalinity	-0.72**	-0.63**	-0.01	-0.26	-0.25	-0.66**
Conductivity	-0.73**	-0.58**	-0.03	-0.22	-0.22	-0.64**

Mean colour, Log(turbidity) and TDOC concentrations were significantly correlated (n=30 for HFM-MFM, n=28 for LFM TDOC averages and n=39 for LFM colour averages and Log(turbidity); $p<0.05$) with several catchment descriptive variables (Table 3.15). For both sampling frequency regimes (HFM-MFM and LFM), catchments with higher elevation, covered with shales and similar rocks and associated with poorly/imperfectly drained soils such as peats (Figure 3.48), were associated with higher mean colour and TDOC concentrations; while catchments associated with well/moderately drained soils, such as brown earths, rendzinas and grey brown podzolics recorded lower means. Mean colour recorded between catchments covered by 0 and 100% carboniferous limestone were significantly different, as were means recorded between catchments covered by 0 and 100% shales and similar rock types (Two-samples t-test, $\alpha=0.05$, $p<0.05$) (Figure 3.49).

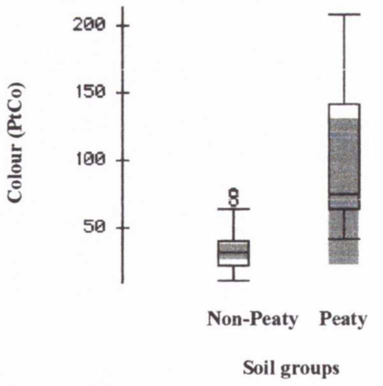

Figure 3.48: Distribution of mean colour (PtCo) recorded in the HFM-MFM lakes (n=30) monitored in 2000-01 between peaty and non-peaty catchments.

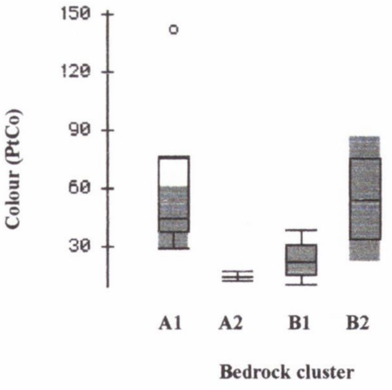

Figure 3.49: Distribution of mean colour (PtCo) recorded in the HFM-MFM lakes (n=30) monitored in 2000-01 among the different catchment bedrock types, as described in Table 2.7.

Table 3.15: Spearman's Rank correlation coefficients between mean colour, Log(turbidity) and TDOC concentrations 2000-01 with catchment descriptive variables. Sampling frequency regimes: HFM-MFM (n=30) and LFM (n=39 for colour and Log(turbidity), n=28 for TDOC) are differentiated. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

		Colour		**Log(Turbidity)**		**TDOC**	
		HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM
Topography	Minimum elevation	0.52**	0.49**	-0.24	0.11	0.23	0.50*
	Mean elevation	0.58**	0.32	-0.26	-0.06	-0.04	0.20
	Log(Maximum slope)	-0.03	-0.12	-0.19	-0.22	-0.38*	-0.15
Bedrock	Carboniferous limestone	-0.70**	-0.66**	-0.06	-0.34*	-0.25	-0.66**
	Shales and similar rock	0.49*	0.64**	0.00	0.34*	0.17	0.62**
Soils	Well/Moderate drainage	-0.77**	-0.77**	-0.12	-0.43*	-0.49*	-0.77**
	Poor/Imperfect drainage	0.60**	0.79**	0.16	0.42*	0.28	0.76**
	S1	-0.77**	-0.77**	-0.12	-0.43*	-0.49*	-0.77**
	S2	-0.04	0.68**	0.28	0.33	-0.06	0.65**
	S4	0.71**	0.51**	-0.02	0.35*	0.38*	0.52**
	Minimum soil Morgan P levels	-0.21	-0.20	0.44*	0.15	0.18	-0.28
	Maximum soil Morgan P levels	-0.50**	-0.26	0.04	-0.13	-0.16	-0.37
	Mean soil Morgan P levels	-0.54**	-0.32	0.25	-0.04	0.02	-0.32
	Brown earths	-0.48*	-0.14	0.05	-0.17	-0.41*	-0.27
	Rendzinas	-0.64**	-0.65**	-0.15	-0.35*	-0.59**	-0.67**
	Grey brown podzolics	-0.53**	-0.42*	-0.11	-0.28	-0.15	-0.49*
	Peats	0.71**	0.51**	-0.02	0.35*	0.38*	0.52**
	Gleys	-0.04	0.68**	0.28	0.33	-0.06	0.65**
Bathymetry	Lake altitude	0.52**	0.48**	-0.27	0.11	0.20	0.50*
	DI	-0.44*	-0.23	-0.04	-0.09	-0.20	-0.01

Nutrients: mean NO_3-N, TN and TP concentrations

Among the thirty lakes included in the high and medium frequency monitoring, mean 2000-01 NO_3-N concentrations were usually low and ranged from 0.00 ± 0.01 (Lough Ballyleann) to 0.35 ± 0.35 mg l^{-1} (Lough Inchiquin). Mean TN concentrations ranged from 0.34 ± 0.21 (Lough Naminna) to 1.29 ± 0.33 mg l^{-1} (Lough Ballybeg) (Table 3.16). Ratios NO_3-N/TN, calculated based on means 2000-01, were generally low and ranged from 0.00 for Loughs Ballyleann and Moanmore to 0.47 for Lough Inchiquin. Higher mean concentrations of NO_3-N and NO_3-N/TN ratios were usually recorded for the lakes likely to have their water chemistry influenced by groundwater inputs. Mean TP concentrations covered a wide range: 8.2 ± 1.7 (Lough Muckanagh) to 79.0 ± 23.3 μg l^{-1} (Lough Ballybeg) (Table 3.16). Limitation of algal growth by nitrogen is thought to take place if the ratio of NO_3-N and NH_4-N to PO_4-P is less than 10 by weight (Horne and Goldman, 1994; Irvine *et al*, 2001). TN/TP ratios, calculated on the means 2000-01, were over 10. However, NO_3-N mean concentrations were very low in several lakes, suggesting that nitrogen may be a limiting factor for phytoplankton productivity.

Table 3.16: Mean 2000-01 NO_3-N (mg l^{-1}), TN (mg l^{-1}) and TP (μg l^{-1}) concentrations among the lakes included in the high and medium frequency monitoring. TN/TP and NO_3-N/TN ratios, total number of samples (n) and 95% CI (in italics) are also given.

Lakes	**n**	**NO_3-N**	*95% CI*	**TN**	*95% CI*	**TP**	*95% CI*	**TN/TP**	**NO_3-N/TN**
Acrow	4	0.01	*0.01*	0.39	*0.11*	29.8	*12.4*	13	0.01
Atedaun	4	0.17	*0.20*	0.58	*0.22*	36.7	*50.6*	16	0.29
Ballyallia	4	0.11	*0.31*	0.49	*0.35*	21.0	*6.6*	23	0.23
Ballybeg	16	0.08	*0.10*	1.29	*0.33*	79.0	*23.3*	16	0.06
Ballycar	4	0.04	*0.09*	0.72	*0.08*	35.3	*19.2*	20	0.06
Ballycullinan	16	0.04	*0.03*	0.50	*0.06*	30.1	*9.4*	16	0.08
Ballyleann	4	0.00	*0.01*	0.59	*0.16*	32.9	*23.2*	18	0.00
Burke	4	0.01	*0.01*	0.56	*0.17*	25.5	*10.0*	22	0.01
Castle	11	0.25	*0.14*	0.74	*0.14*	29.5	*4.7*	25	0.34
Clonlea	5	0.07	*0.12*	0.63	*0.16*	17.1	*14.2*	37	0.11
Cloonmackan	5	0.03	*0.07*	0.68	*0.08*	27.2	*3.3*	25	0.05
Cloonsnaghta	4	0.08	*0.14*	0.67	*0.17*	27.4	*5.5*	25	0.11
Cullaun	5	0.09	*0.16*	0.44	*0.16*	8.8	*4.1*	50	0.21
Cullaunyheeda	15	0.14	*0.14*	0.75	*0.13*	22.9	*4.8*	33	0.19
Doolough	16	0.08	*0.03*	0.70	*0.38*	22.3	*2.5*	32	0.11
Doon	4	0.23	*0.53*	0.84	*0.32*	28.0	*9.9*	30	0.27
Dromore	15	0.16	*0.12*	0.55	*0.10*	19.9	*3.6*	28	0.29
Gortglass	16	0.06	*0.04*	0.65	*0.06*	23.9	*2.9*	27	0.09
Graney	16	0.11	*0.05*	0.61	*0.11*	19.0	*2.5*	32	0.19
Inchichronan	5	0.13	*0.14*	0.65	*0.09*	22.1	*4.8*	30	0.20
Inchiquin	16	0.35	*0.11*	0.74	*0.10*	19.7	*3.9*	37	0.47
Keagh	13	0.04	*0.03*	0.61	*0.09*	40.2	*4.1*	15	0.06
Killone	6	0.01	*0.01*	0.67	*0.17*	36.8	*15.2*	18	0.02
Knockalough	5	0.01	*0.02*	0.65	*0.16*	22.4	*10.3*	29	0.02
Lickeen	16	0.07	*0.04*	0.72	*0.07*	21.5	*2.4*	33	0.09
Lisnahan	5	0.06	*0.17*	0.95	*0.34*	33.4	*20.0*	29	0.07
Moanmore	4	0.01	*0.02*	1.24	*0.83*	44.8	*15.6*	28	0.00
Muckanagh	5	0.08	*0.17*	0.67	*0.15*	8.2	*1.7*	82	0.11

Table 3.16 (continued)

Lakes	n	NO_3-N	*95% CI*	TN	*95% CI*	TP	*95% CI*	TN/TP	NO_3-N/TN
Naminna	5	0.02	*0.01*	0.34	*0.21*	11.5	*8.6*	29	0.05
Rosroe	4	0.01	*0.02*	0.68	*0.25*	14.1	*2.1*	48	0.02

Summer concentrations of NO_3-N recorded for the LFM lakes were low, with a maximum of 0.6 mg l^{-1} recorded for Lough Rask. TN concentrations ranged from 0.3 (Lough Bunny) to 2.7 mg l^{-1} (Lough Gash) (Table 3.17). NO_3-N/TN ratios were low, with a maximum of 0.6 obtained for Loughs Rask and Luirk. Higher summer concentrations of NO_3-N and NO_3-N/TN ratios were also usually recorded for the lakes likely to have their water chemistry influenced by groundwater inputs. The range of summer TP concentrations was very wide, from 6 (Lough Bunny) to 691 µg l^{-1} (Lough Black (near Kilkee)) (Table 3.17). Summer TN/TP ratios by weight were under the ratio of 10:1 for six lakes (ranging from 2 to 10), suggesting that N may have been a limiting factor for the phytoplankton growth at the time of sampling. They were associated with high in-lake TP concentrations ($\geq$76 µg l^{-1}), very low NO_3-N ($\leq$0.03 mg l^{-1}) and low TN concentrations (0.7 - 2.2 mg l^{-1}).

Table 3.17: Mean 2000-01 NO_3-N (mg l^{-1}), TN (mg l^{-1}) and TP (µg l^{-1}) concentrations among the lakes included in the low frequency monitoring. TN/TP and NO_3-N/TN ratios, total number of samples (n) and 95% CI (in italics) are also given.

Lakes	n	NO_3-N	*95% CI*	TN	*95% CI*	TP	*95% CI*	TN/TP Ratio	NO_3-N/TN Ratio
Achryane	2	0.00	*0.00*	0.55	*0.89*	21.9	*61.1*	25	0.00
Aillbrack	2	0.00	*0.00*	0.69	*1.97*	18.0	*10.5*	38	0.00
Ballydoolavan	1	0.00		1.31		167.2		8	0.00
Ballyeighter	1	0.00		0.79		12.1		65	0.00
Ballyteige	2	0.13	*0.51*	0.67	*1.21*	39.5	*4.2*	17	0.20
Black Dro	1	0.00		0.42		24.5		17	0.00
Black-Kilk	1	0.03		1.66		696.3		2	0.02
Bridget	1	0.01		0.47		24.9		19	0.02
Bunny	1	0.01		0.30		5.5		55	0.03
Caum	2	0.01	*0.06*	0.91	*0.38*	54.7	*236.9*	17	0.01
Curtins	2	0.02	*0.25*	0.92	*1.91*	45.6	*70.3*	20	0.02
Dromoland	1	0.00		0.31		8.0		39	0.00
Drumcullaun	1	0.16		0.91		54.5		17	0.18
Druminure	2	0.00	*0.00*	0.96	*2.03*	51.8	*113.3*	19	0.00
Eanagh	1	0.02		0.80		25.5		31	0.03
Effernan	2	0.00		0.66		28.4		23	0.00
Farrihy	1	0.10		2.20		423.3		5	0.05
Finn	1	0.02		1.00		33.3		30	0.02
Garvillaun	2	0.01	*0.06*	0.74	*0.00*	76.4	*83.4*	10	0.01
Gash	1	0.46		2.73		245.3		11	0.17
George	1	0.01		0.40		9.3		43	0.03
Girroga	2	0.00	*0.00*	0.43	*0.57*	9.5	*16.9*	45	0.00
Goller	1	0.00		1.21		54.6		22	0.00
Gortaganniv	2	0.01	*0.06*	0.80	*0.76*	55.5	*169.5*	14	0.01
Gorteen	1	0.01		0.86		11.7		73	0.01
Kilgory	1	0.00		0.54		18.8		29	0.00

Table 3.17 (continued)

Lakes	n	NO_3-N	*95% CI*	TN	*95% CI*	TP	*95% CI*	TN/TP Ratio	NO_3-N/TN Ratio
Knockerra	1	0.00		0.79		25.1		31	0.00
Luirk	1	0.12		0.36		32.1		11	0.33
Luogh	2	0.00	*0.00*	0.55	*2.22*	47.9	*185.7*	11	0.00
Mooghna	2	0.07	*0.06*	0.76	*0.19*	48.7	*102.0*	16	0.09
More	1	0.03		0.58		22.3		26	0.05
Morgans	2	0.01	*0.00*	1.11	*0.83*	142.3	*0.1*	8	0.01
Muckinish	1	0.28		0.49		12.4		39	0.57
O'Briens	1	0.02		0.60		12.1		50	0.03
O'Grady	1	0.08		0.83		47.7		17	0.10
Rask	1	0.59		1.04		11.2		93	0.57
Rosconnell	1	0.02		1.52		75.2		20	0.01
Rushaun	1	0.01		0.89		31.3		28	0.01
Tullabrack	1	0.01		1.03		99.5		10	0.01

Only a few significant correlations were found between mean NO_3-N, TN and TP concentrations and other lake chemical variables (Table 3.18). No significant correlations were found between mean NO_3-N and TN concentrations and catchment descriptive variables. Catchments with steeper slopes and covered with rendzinas were associated with higher Log(TP) and lower Log(TN/TP ratio), while catchments associated with poorly/imperfectly drained soils, such as peats, were associated with lower Log(TP) and higher Log(TN/TP ratio) among the HFM-MFM lakes (Table 3.19).

Silicates and ammonium-nitrogen mean concentrations

Silicates (SiO_4-Si) and ammonium-nitrogen (NH_4-N) were only analysed for the high frequency monitoring lakes. Mean 2000-01 SiO_4-Si concentrations were variable with mean concentrations greater than 2.0 mg l^{-1} for Loughs Cullaunyheeda, Ballybeg, Killone and Castle, which had the maximum mean SiO_4-Si concentration with 2.5 ± 3.7 mg l^{-1} (Table 3.20). Mean 2000-01 NH_4-N concentrations were also low (< 0.05 mg l^{-1}), except for Loughs Killone, Cullaunyheeda and Castle with a maximum mean NH_4-N concentration of 0.14 ± 0.54 mg l^{-1} for Lough Castle (Table 3.20).

Phytoplankton chlorophyll-*a* concentrations

Among the HFM-MFM lakes ($n \leq 4$), mean 2000-01 chlorophyll-*a* concentrations ranged from 2.5 ± 1.9 (Lough Muckanagh) to 36.2 ± 18.2 μg l^{-1} (Lough Ballybeg), with recorded in-lake maximum chlorophyll-*a* concentrations ranging from 11.0 μg l^{-1} in Lough Cullaunyheeda to 108.4 μg l^{-1} in Lough Ballybeg for the HFM lakes ($n \geq 6$), and from 4.1 μg l^{-1} in Lough Muckanagh to 42.5 μg l^{-1} in Lough Lisnahan for the MFM lakes (n=4-5) (Table 3.21). Among the LFM lakes, summer chlorophyll-*a* concentrations (n=1 sampling occasion) or mean summer concentrations (n=2 sampling occasions) ranged from 1.9 μg l^{-1} for Lough Aillbrack to 148.5 μg l^{-1} for Lough Ballydoolavan (Table 3.22).

Table 3.18: Spearman's Rank correlation coefficients between mean NO_3-N, TN and TP concentrations, TN/TP and NO_3-N/TN ratios and other lake chemical variables. n = 30 for HFM-MFM and n = 39 for LFM. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

	NO_3-N		**Log(TN)**		**Log(TP)**		**Log(TN/TP)**		**NO_3-N/TN**	
	HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM	HFM-MFM	LFM
pH	0.37	0.18	0.18	-0.46**	-0.32	-0.52**	0.40*	0.45**	0.38*	0.26
Alkalinity	0.39*	0.39*	0.03	-0.31	-0.21	-0.33	0.21	0.20	0.44*	0.45**
Conductivity	0.32	0.43*	0.06	-0.26	-0.13	-0.26	0.18	0.10	0.37	0.47**
Colour	-0.06	0.04	0.26	0.58**	0.29	0.77**	-0.14	-0.67**	-0.17	-0.06
Log(Turbidity)	0.01	0.05	0.38	0.55**	0.34	0.58**	-0.10	-0.45**	-0.10	-0.11
TDOC	-0.20	-0.12	0.60**	0.61**	0.19	0.67**	0.19	-0.44*	-0.32	-0.16

Table 3.19: Spearman's Rank correlation coefficients between means NO_3-N, Log(TP), Log(TN/TP ratio) and NO_3-N/TN 2000-01 with catchment descriptive variables. Sampling frequency regimes: HFM-MFM (n = 30) and LFM (n = 39) are differentiated. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

		NO_3-N		**Log(TP)**	**Log(TN/TP)**	**NO_3-N/TN**	
		HFM-MFM	LFM	HFM-MFM	HFM-MFM	HFM-MFM	LFM
Topography	Log(Maximum slope)	-0.14	0.06	0.47*	-0.44*	-0.19	0.08
	Mean slope	-0.02	0.14	0.41*	-0.40*	-0.06	0.15
Bedrock	Shales and similar rock	0.14	-0.39*	0.04	-0.04	0.10	-0.42*
Soils	Well/Moderate drainage	-0.06	0.34*	0.18	-0.20	-0.02	0.35*
	Poor/Imperfect drainage	0.22	-0.33	-0.41*	0.24	0.27	-0.31
	S1	-0.06	0.34*	0.18	-0.20	-0.02	0.35*
	S2	-0.04	-0.34*	0.28	-0.36	-0.03	-0.31
	S4	0.07	-0.21	-0.52**	0.42*	0.11	-0.24
	Rendzinas	0.14	0.19	0.39*	-0.42*	0.15	0.19
	Peats	0.07	-0.21	-0.52**	0.42*	0.11	-0.24
	Gleys	-0.04	-0.34*	0.28	-0.36	-0.03	-0.31

Table 3.20: Mean 2000-01 SiO_4-Si (mg l^{-1}) and NH_4-N (mg l^{-1}) concentrations for the lakes included in the high frequency monitoring. Total number of analyses (n) and 95% CI (in italics) are also given.

Lakes	n	NH_4-N	*95% CI*	SiO_4-Si	*95% CI*
Ballybeg	7	0.04	*0.06*	2.41	*1.66*
Ballycullinan	7	0.05	*0.05*	1.95	*1.25*
Castle	3	0.14	*0.54*	2.50	*3.69*
Cullaunyheeda	7	0.06	*0.10*	2.05	*1.47*
Doolough	7	0.01	*0.01*	0.90	*0.60*
Dromore	7	0.01	*0.01*	1.30	*0.95*
Gortglass	7	0.01	*0.01*	1.81	*1.04*
Graney	7	0.02	*0.0*	1.39	*1.15*
Inchiquin	7	0.02	*0.01*	0.93	*0.61*
Keagh	4	0.01	*0.01*	0.34	*0.23*
Killone	3	0.06	*0.20*	2.24	*4.19*
Lickeen	7	0.01	*0.01*	0.66	*0.71*

Table 3.21: Mean and maximum 2000-01 chlorophyll-*a* concentrations (µg l^{-1}) recorded among the lakes included in the high and medium frequency monitoring. Total number of samples (n) and 95% CI (in italics) are also given.

Lakes	n	Chla	*95% CI*	Max Chla
Acrow	4	8.1	*5.7*	13.0
Atedaun	4	5.8	*6.0*	11.0
Ballyallia	4	8.1	*4.3*	12.1
Ballybeg	16	36.2	*18.2*	108.4
Ballycar	4	9.4	*13.6*	20.9
Ballycullinan	16	7.9	*2.3*	16.4
Ballyleann	4	13.2	*6.8*	17.0
Burke	4	15.8	*22.0*	35.1
Castle	11	19.3	*5.7*	33.9
Clonlea	5	6.6	*8.1*	18.0
Cloonmackan	5	14.2	*3.6*	17.9
Cloonsnaghta	4	9.0	*2.4*	10.4
Cullaun	5	4.6	*3.9*	9.0
Cullaunyheeda	15	3.4	*1.4*	11.0
Doolough	16	7.3	*2.3*	17.5
Doon	4	9.2	*9.1*	17.2
Dromore	15	9.1	*4.3*	28.5
Gortglass	16	13.5	*3.6*	27.5
Graney	16	7.7	*3.0*	21.0
Inchichronan	5	9.9	*8.0*	17.2
Inchiquin	16	4.8	*2.6*	16.3
Keagh	13	5.7	*2.3*	13.3
Killone	6	18.2	*16.4*	48.9
Knockalough	5	7.7	*4.3*	13.4
Lickeen	16	12.4	*6.3*	49.0
Lisnahan	5	13.0	*20.5*	42.5
Moanmore	4	13.5	*15.3*	27.8
Muckanagh	5	2.5	*1.9*	4.1
Naminna	5	4.4	*1.3*	6.2
Rosroe	4	5.9	*4.4*	8.5

Table 3.22: Summer chlorophyll-*a* concentrations ($\mu g\ l^{-1}$) recorded among the lakes included in the low frequency monitoring. Total number of samples (n) and Chla range for n=2 are provided.

Lakes	n	Range Chla
Achryane	2	7.8-23.7
Aillbrack	2	1.8-1.9
Ballydoolavan	1	148.5
Ballyeighter	1	3.6
Ballyteige	2	9.0-9.1
Black Dro	1	15.7
Black-Lis	1	66.7
Bridget	1	8.3
Bunny	1	2.3
Caum	2	5.3-25.0
Curtins	2	16.3-50.2
Dromoland	1	5.4
Drumcullaun	1	3.0
Druminure	2	16.9-25.9
Eanagh	1	5.0
Effernan	2	5.5-14.5
Farrihy	1	46.7
Finn	1	10.3
Garvillaun	2	9.0-17.5
Gash	1	11.3
George	1	10.3
Girroga	2	4.3-4.9
Goller	1	40.8
Gortaganniv	2	17.0-23.9
Gorteen	1	15.4
Kilgory	1	5.4
Knockerra	1	6.6
Luirk	1	2.1
Luogh	2	2.1-7.3
Mooghna	2	11.2-15.1
More	1	7.8
Morgans	2	11.7-21.6
Muckinish	1	10.3
O'Briens	1	2.3
O'Grady	1	17.4
Rask	1	2.7
Rosconnell	1	62.7
Rushaun	1	18.5
Tullabrack	1	6.1

Log(mean Chla concentrations) was significantly correlated (n=30 for HFM-MFM, n=39 for LFM; $p<0.05$) with several catchment descriptive variables (Table 3.23). Catchments with smaller lake areas and volumes and covered with gley soils were associated with higher values of Log(mean Chla concentrations) for the HFM-MFM lakes.

Table 3.23: Spearman's Rank correlation coefficients between Log(mean Chla concentrations) with catchment descriptive variables. Sampling frequency regimes: HFM-MFM (n=30) and LFM (n=39) are differentiated. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

		HFM-MFM	LFM
Topography	Minimum slope	0.39*	-0.02
	Log(Maximum slope)	-0.05	-0.38*
Bedrock	Carboniferous limestone	-0.30	-0.39*
	Shales and similar rock	0.25	0.35*
Soils	Well/Moderate drainage	-0.17	-0.49**
	Poor/Imperfect drainage	0.12	0.51**
	S1	-0.17	-0.49**
	S2	0.46*	0.55**
	Minimum soil Morgan P levels	0.42*	0.03
	Rendzinas	-0.16	-0.38*
	Gleys	0.46*	0.55**
Bathymetry	Log(Lake Area)	-0.45*	-0.28
	Log(Lake Volume)	-0.39*	-0.33

No significant correlations were found between Log(Maximum Chla concentrations) and catchment descriptive variables among the HFM lakes (n=12) or the combined HFM-MFM lakes (n=30). For the eighteen lakes included in the medium frequency monitoring, catchments with greater minimum slope and covered with gleys, recorded greater Log(maximum Chla concentrations) (Table 3.24).

Table 3.24: Spearman's Rank correlation coefficients between Log(Maximum Chla concentrations) with catchment descriptive variables for the MFM lakes (n=18). Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

		MFM
Topography	Minimum slope	0.55*
Soils	S2	0.67**
	Gleys	0.67**

Relationships between mean and maximum chlorophyll-*a* concentrations and other chemical variables were investigated using Pearson's Product-Moment correlations, among HFM (n=12), MFM (n=18) and combined HFM-MFM (n=30) lakes. Significant correlations were obtained with Log(mean TP concentrations), Log(mean TN concentrations) and Log(mean colour) (Table 3.25). Log-linear regression models predicting mean and maximum chlorophyll-*a* concentrations were also assessed. Best fitting models were usually based on Log(Mean TP concentrations) (Table 3.26). Associated R^2 values were relatively low, owing to the probable influence of other variables on phytoplankton growth.

Table 3.25: Pearson's Product-Moment correlation coefficients between Log(mean Chla concentrations) (A) and Log(Max. Chla concentrations) (B) and Log(mean TN concentrations), Log(mean TP concentrations) and Log(mean Colour). Sampling frequency regimes: HFM (n=12), MFM (n=18) and combined HFM-MFM (n=30) are differentiated. Significant correlations with $p<0.05$ are indicated by * and with $p<0.01$ by **.

	HFM (n=12)		**MFM (n=18)**		**HFM-MFM (n=30)**	
	A	B	A	B	A	B
Log(TN)	0.52	0.62*	0.42	0.52*	0.46*	0.56**
Log(TP)	0.63*	0.57	0.80**	0.73**	0.71**	0.68**
Log(Colour)	-0.27	-0.28	0.55*	0.45	0.16	0.14

Table 3.26: Best fitting Log-Linear regressions models predicting in-lake variations in mean and maximum chlorophyll-*a* concentrations, with chlorophyll-*a* and mean TP concentrations in $\mu g\ l^{-1}$ and mean TN concentrations in $mg\ l^{-1}$.

	Monitoring	**Linear Regression Model**	**p**	**R^2**
Log(Chla)	HFM (n=12)	Log(Chla) = 1.01 * Log(TP) - 0.47	$p < 0.05$	0.40
	MFM (n=18)	Log(Chla) = 0.78 * Log(TP) - 0.15	$p < 0.0001$	0.64
	HFM-MFM (n=30)	Log(Chla) = 0.86 * Log(TP) – 0.255	$p < 0.0001$	0.50
Log(Max Chla)	HFM (n=12)	Log(Max Chla) = 1.74 * Log(TN) + 1.70	$p < 0.05$	0.38
	MFM (n=18)	Log(Max Chla) = 0.87 * Log(TP) - 0.02	$p < 0.001$	0.54
	HFM-MFM (n=30)	Log(Max Chla) = 0.98 * Log(TP) – 0.10	$p < 0.0001$	0.44

Influence of bedrock type and colour on the TP - chlorophyll-*a* relationship

For the HFM-MFM lakes, a significant positive correlation was obtained between Log(mean chlorophyll-*a* concentrations) and Log(mean TP concentrations) (r_p=0.71, $p<0.01$, n=30). Differentiating catchments based on their predominant bedrock type (Table 2.7) gave a stronger correlation for calcareous lakes (r_p=0.80, $p<0.01$, n=11), while no significant correlation was found for acidic lakes (r_p=0.44, n=13, ns) (Figure 3.50). In order to investigate the influence of colour on the relationship, lakes were also differentiated between low-colour (<50 PtCo) and high-colour (>50 PtCo). A strong significant positive correlation was found between Log(mean chlorophyll-*a* concentrations) and Log(mean TP concentrations) for the low-colour lakes (r_p=0.79, $p<0.01$, n=22), while no significant correlation was obtained for the high-colour lakes (r_p=0.07, n=8, ns) (Figure 3.51).

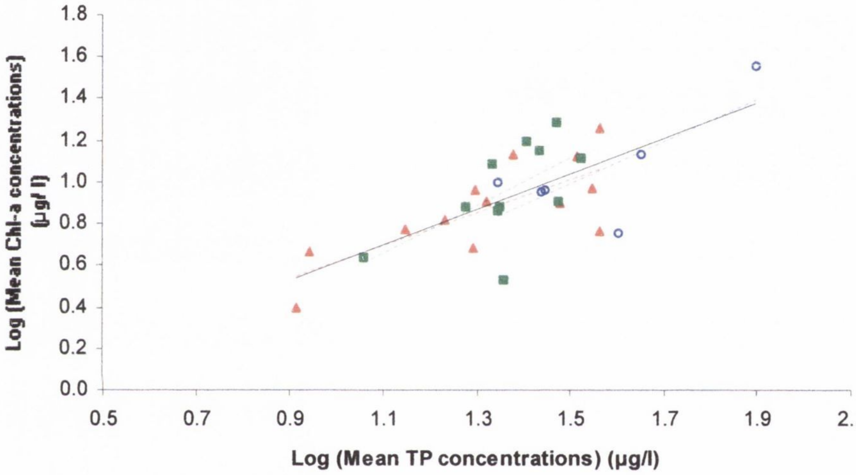

Figure 3.50: Comparison between Log (mean chlorophyll-*a* concentrations) (µg l^{-1}) and Log (mean TP concentrations) (µg l^{-1}) for the HFM-MFM lakes (n=30, r_p=0.71, $p<0.01$), also showing the linear regression line (R^2=0.50, df=28, —). Lakes are differentiated into acidic (▲, r_p=0.44, n=13, ns) with associated linear regression line (R^2=0.19, df=11, ----), calcareous (■, r_p=0.80, $p<0.01$, n=11) with associated linear regression line (R^2=0.64, df=9, ----) and other bedrock types (○, r_p=0.64, n=6, ns), with associated linear regression line (R^2=0.40, df=4, ----).

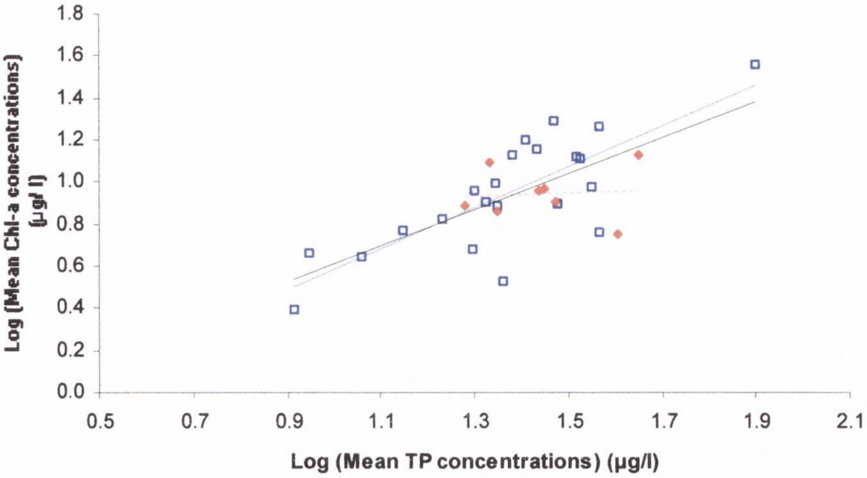

Figure 3.51: Comparison between Log (mean chlorophyll-*a* concentrations) (µg l^{-1}) and Log (mean TP concentrations) (µg l^{-1}) for the HFM-MFM lakes ($n=30$, $r_p=0.71$, $p<0.01$), also showing the linear regression line ($R^2=0.50$, $df=28$, —). Lakes are differentiated into low-colour (□, $r_p=0.79$, $p<0.01$, $n=22$) with associated linear regression line ($R^2=0.61$, $df=20$, ----) and high-colour lakes (◆, $r_p=0.07$, $n=8$, ns) with associated linear regression line ($R^2=0.01$, $df=4$, ----).

Influence of groundwater on the TP – chlorophyll-*a* relationship

The influence of groundwater on the ratios mean TP/mean chlorophyll-*a* and mean TP/maximum chlorophyll-*a* concentrations was assessed among the HFM-MFM lakes (n=30). Both ratios were found to be significantly greater for lakes that were likely to be influenced by groundwater (n=10, as listed in Table 2.5) (Two sample t-test, $p<0.05$, $\alpha=0.05$, Figures 3.52 and 3.53).

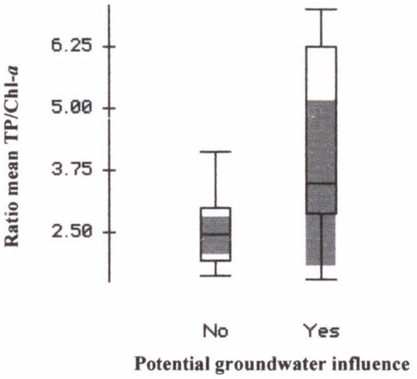

Figure 3.52: Distribution of the ratio mean TP/mean chlorophyll-*a* concentrations between lakes likely to be influenced by groundwater (Yes, n=10) and those without groundwater influence (No, n=20), for the HFM-MFM lakes (n=30).

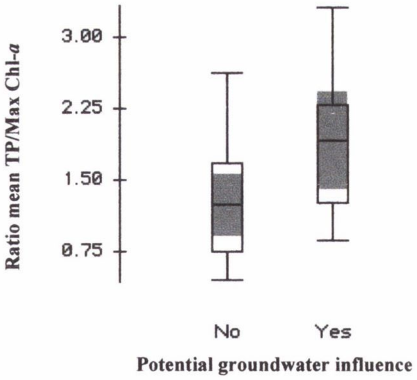

Figure 3.53: Distribution of the ratio mean TP/maximum chlorophyll-*a* concentrations between lakes likely to be influenced by groundwater (Yes, n=10) and those without groundwater influence (No, n=20), for the HFM-MFM lakes (n=30).

Lake trophic status

Lake trophic states were estimated based on the mean and maximum chlorophyll-*a* concentrations recorded over the monitoring period and mean 2000-01 TP concentrations, as described by the modified OECD (1982) scheme (Lucey *et al*, 1999). Among the thirty lakes included in the high and medium frequency monitoring, classifications of lakes into trophic states based on mean and maximum chlorophyll-*a* and mean TP concentrations (Table 3.27) were similar. Differences between the schemes were obtained for concentrations near class boundaries. Two lakes were found to be oligotrophic, nineteen mesotrophic; eight eutrophic and one hypertrophic. The distribution of lakes into trophic status classes, based on mean TP or maximum chlorophyll-*a* concentrations, overly simplifies the distribution of the in-lake mean TP (Figures 3.54 and 3.55) and maximum chlorophyll-*a* concentrations (Figures 3.56 and 3.57) recorded among the thirty lakes included in the high and medium frequency monitoring.

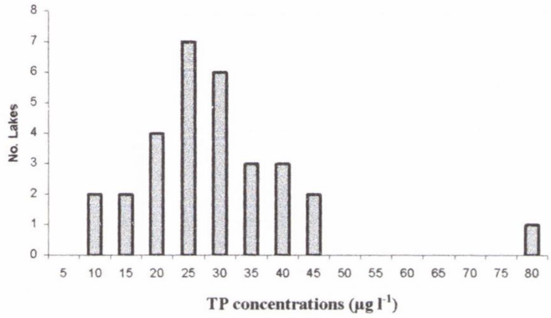

Figure 3.54: Distribution of mean TP concentrations 2000-01 recorded for the thirty HFM-MFM lakes, using an increment of 5 $\mu g\ l^{-1}$ TP.

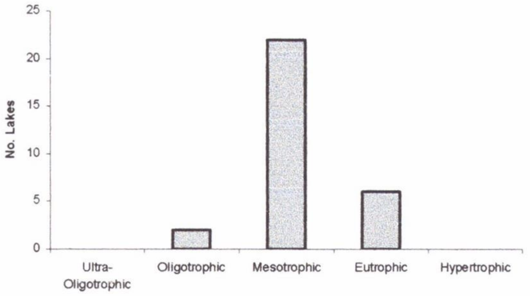

Figure 3.55: Distribution of the thirty HFM-MFM lakes, based on their trophic status, estimated using mean TP concentrations 2000-01.

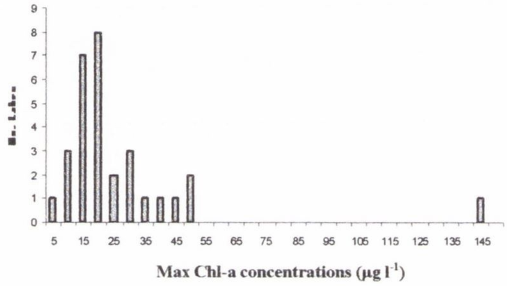

Figure 3.56: Distribution of maximum Chla concentrations 2000-01 recorded for the thirty HFM-MFM lakes, using an increment of 5 $\mu g\ l^{-1}$ Chla.

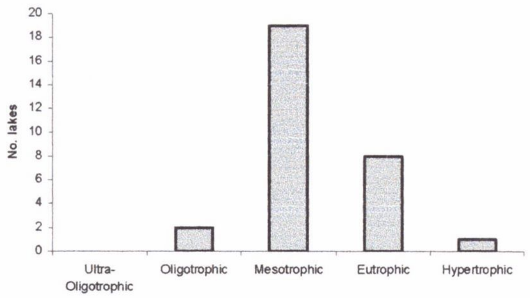

Figure 3.57: Frequency distribution of the thirty HFM-MFM lakes based on their trophic status, estimated using maximum Chla concentrations 2000-01.

Table 3.27: Trophic status classification based on mean and maximum chlorophyll-*a* and mean TP concentrations (μg l^{-1}), as described by OECD (1982), for the high and medium frequency lakes. Total numbers of samples (n) are also given.

Lakes	n	Mean Chla	Trophic Status	Max Chla	Trophic Status	Mean TP	Trophic Status
Acrow	4	8.1	Eutrophic	13.0	Mesotrophic	29.8	Mesotrophic
Atedaun	4	5.8	Mesotrophic	11.0	Mesotrophic	36.7	Eutrophic
Ballyallia	4	8.1	Eutrophic	12.1	Mesotrophic	21.0	Mesotrophic
Ballybeg	16	36.2	Hypertrophic	108.4	Hypertrophic	79.0	Eutrophic
Ballycar	4	9.4	Eutrophic	20.9	Mesotrophic	35.3	Mesotrophic
Ballycullinan	16	7.9	Mesotrophic	16.4	Mesotrophic	30.1	Mesotrophic
Ballyleann	4	13.2	Eutrophic	17.0	Mesotrophic	32.9	Mesotrophic
Burke	4	15.8	Eutrophic	35.1	Eutrophic	25.5	Mesotrophic
Castle	11	19.3	Eutrophic	33.9	Eutrophic	29.5	Mesotrophic
Clonlea	5	6.6	Mesotrophic	18.0	Mesotrophic	17.1	Mesotrophic
Cloonmackan	5	14.2	Eutrophic	17.9	Mesotrophic	27.2	Mesotrophic
Cloonsnaghta	4	9.0	Eutrophic	10.4	Mesotrophic	27.4	Mesotrophic
Cullaun	5	4.6	Mesotrophic	9.0	Mesotrophic	8.8	Oligotrophic
Cullaunyheeda	15	3.4	Mesotrophic	11.0	Mesotrophic	22.9	Mesotrophic
Doolough	16	7.3	Mesotrophic	17.5	Mesotrophic	22.3	Mesotrophic
Doon	4	9.2	Eutrophic	17.2	Mesotrophic	28.0	Mesotrophic
Dromore	15	9.1	Eutrophic	28.5	Eutrophic	19.9	Mesotrophic
Gortglass	16	13.5	Eutrophic	27.5	Eutrophic	23.9	Mesotrophic
Graney	16	7.7	Mesotrophic	21.0	Mesotrophic	19.0	Mesotrophic
Inchichronan	5	9.9	Eutrophic	17.2	Mesotrophic	22.1	Mesotrophic
Inchiquin	16	4.8	Mesotrophic	16.3	Mesotrophic	19.7	Mesotrophic
Keagh	13	5.7	Mesotrophic	13.3	Mesotrophic	40.2	Eutrophic
Killone	6	18.2	Eutrophic	48.9	Eutrophic	36.8	Eutrophic
Knockalough	5	7.7	Mesotrophic	13.4	Mesotrophic	22.4	Mesotrophic
Lickeen	16	12.4	Eutrophic	49.0	Eutrophic	21.5	Mesotrophic
Lisnahan	5	13.0	Eutrophic	42.5	Eutrophic	33.4	Mesotrophic
Moanmore	4	13.5	Eutrophic	27.8	Eutrophic	44.8	Eutrophic
Muckanagh	5	2.5	Oligotrophic	4.1	Oligotrophic	8.2	Oligotrophic
Naminna	5	4.4	Mesotrophic	6.2	Oligotrophic	11.5	Mesotrophic
Rosroe	4	5.9	Mesotrophic	8.5	Mesotrophic	14.1	Mesotrophic

For the thirty-nine lakes included in the low frequency monitoring, trophic status was estimated from maximum chlorophyll-*a* concentrations (Table 3.28). Four lakes were found to be ultra-oligotrophic, twelve oligotrophic, fifteen mesotrophic, seven eutrophic and one hypertrophic.

Table 3.28: Trophic status classification based on maximum chlorophyll-*a* and mean TP concentrations (μg l^{-1}), as described by OECD (1982), for the low frequency lakes. Total numbers of samples (n) are also given. Trophic status of lakes for which summer TP concentrations appeared too high for the associated chlorophyll-*a* concentrations are in bold and underlined if also associated with high turbidity values.

Lakes	n	Max Chla	Trophic Status	TP	Trophic Status
Achryane	2	23.7	Mesotrophic	21.9	Mesotrophic
Aillbrack	2	1.9	Ultra-Oligotrophic	18.0	Mesotrophic
Ballydoolavan	1	148.5	Hypertrophic	167.2	Hypertrophic
Ballyeighter	1	3.6	Oligotrophic	12.1	Mesotrophic
Ballyteige	2	9.1	Mesotrophic	39.5	Eutrophic
Black Dro	1	15.7	Mesotrophic	24.5	Mesotrophic
Black-Lis	1	66.7	**Eutrophic**	696.3	**Hypertrophic**
Bridget	1	8.3	Mesotrophic	24.9	Mesotrophic
Bunny	1	2.3	Ultra-Oligotrophic	5.5	Oligotrophic
Caum	2	25.0	Eutrophic	54.7	Eutrophic
Curtins	2	50.2	Eutrophic	45.6	Eutrophic
Dromoland	1	5.4	Oligotrophic	8.0	Oligotrophic
Drumcullaun	1	3.0	Oligotrophic	54.5	Eutrophic
Druminure	2	25.9	Eutrophic	51.8	Eutrophic
Eanagh	1	5.0	Oligotrophic	25.5	Mesotrophic
Effernan	2	5.5	Oligotrophic	28.4	Mesotrophic
Farrihy	1	46.7	**Eutrophic**	423.3	**Hypertrophic**
Finn	1	10.3	Mesotrophic	33.3	Mesotrophic
Garvillaun	2	17.5	**Mesotrophic**	76.4	**Eutrophic**
Gash	1	11.3	**Mesotrophic**	245.3	**Hypertrophic**
George	1	10.3	Mesotrophic	9.3	Oligotrophic
Girroga	2	4.9	Oligotrophic	9.5	Oligotrophic
Goller	1	40.8	Eutrophic	54.6	Eutrophic
Gortaganniv	2	23.9	Mesotrophic	55.5	Eutrophic
Gorteen	1	15.4	Mesotrophic	11.7	Mesotrophic
Kilgory	1	5.4	Oligotrophic	18.8	Mesotrophic
Knockerra	1	6.6	Oligotrophic	25.1	Mesotrophic
Luirk	1	2.1	Ultra-Oligotrophic	32.1	Mesotrophic
Luogh	2	7.3	Oligotrophic	47.9	Eutrophic
Mooghna	2	15.1	Mesotrophic	48.7	Eutrophic
More	1	7.8	Oligotrophic	22.3	Mesotrophic
Morgans	2	21.6	**Mesotrophic**	142.3	**Hypertrophic**
Muckinish	1	10.3	Mesotrophic	12.4	Mesotrophic
O'Briens	1	2.3	Ultra-Oligotrophic	12.1	Mesotrophic
O'Grady	1	17.4	Mesotrophic	47.7	Eutrophic
Rask	1	2.7	Oligotrophic	11.2	Mesotrophic
Rosconnell	1	62.7	Eutrophic	75.2	Eutrophic
Rushaun	1	18.5	Mesotrophic	31.3	Mesotrophic
Tullabrack	1	6.1	**Oligotrophic**	99.5	**Eutrophic**

As these lakes were only sampled once or twice over the summers, the classification into trophic classes has to be treated with extreme caution. Infrequent sampling is very likely to underestimate maximum seasonal chlorophyll-*a* concentrations. Among the twelve HFM lakes, maximum chlorophyll-*a* concentrations recorded in 2000-01 were compared with the chlorophyll-*a* concentrations recorded in August 2000 and August 2001, when most of the LFM sampling took place (Table 3.29). Except for Lough Keagh, where maximum chlorophyll-*a* concentration recorded over the monitoring period was measured in August, summer chlorophyll-*a* concentrations were lower than the observed maximum.

Table 3.29: Comparison between trophic status estimated based on maximum chlorophyll-*a* recorded during the summer sampling n=2 (August 2000 and 2001) and $n \geq 6$ sampling occasions for the HFM lakes. Chlorophyll-*a* concentrations ($\mu g\ l^{-1}$) recorded in August 2000 and 2001 and recorded maximum chlorophyll *a* concentrations are provided.

Lakes	Aug-00	Aug-01	Trophic Status n=2	Recorded Max. Chla	Trophic Status $n \geq 6$
Ballybeg	52.9	14.3	Eutrophic	108.4	Hypertrophic
Ballycullinan	6.8	16.4	Mesotrophic	16.4	Mesotrophic
Castle		15.9	Mesotrophic	33.9	Eutrophic
Cullaunyheeda	2.6	3	Oligotrophic	11.0	Mesotrophic
Doolough	6.2	9.6	Mesotrophic	17.5	Mesotrophic
Dromore	8.7	7.3	Mesotrophic	28.5	Eutrophic
Gortglass	10.6	5.5	Mesotrophic	27.5	Eutrophic
Graney	9.1	21	Mesotrophic	21.0	Mesotrophic
Inchiquin	1.5	12.5	Mesotrophic	16.3	Mesotrophic
Keagh	13.3	5.3	Mesotrophic	13.3	Mesotrophic
Killone		8.6	Mesotrophic	48.9	Eutrophic
Lickeen	6.6	6.6	Oligotrophic	49.0	Eutrophic

Variation in lake water chemistry among studied catchments

In order to detect general trends in the variation of the lake physico-chemical characteristics, principal component analyses were carried out using the results for the sixty-nine lakes, and also differentiating the sampling regime HFM, MFM and LFM. Similar trends as the one observed for all the lakes were obtained (Table 3.30). The first three principal components explained 72.3% of the variation. The first principal component (45.3% of the variance) was correlated with the lake nutrient status, phytoplankton biomass and colour. The second principal component (17.2% of the variance) reflected the acidity state of the lakes, while the third principal component (9.8% of the variance) showed an association between pH and phytoplankton biomass in the lakes.

Table 3.30: Principal component analysis of overall chemistry variables for the sixty-nine lakes monitored in 2000-01. First three principal components (I, II, III) are listed. Non-significant coefficients ($r<0.250$) have been omitted. (Turb: turbidity, Chla: chlorophyll-*a*, Cond: conductivity)

	I		II		III	
	Log(TN/TP)	0.3	Cond	-0.3	pH	0.5
	Log(TN)	-0.3	pH	-0.4	Log(Max Chla)	0.4
	Log(Turb)	-0.4	NO_3-N	-0.5	Log(Chla)	0.3
	Log(Max Chla)	-0.4	Alk.	-0.5	NO_3-N	-0.5
	Log(Chla)	-0.4				
	Log (TP)	-0.4				
	Colour	-0.4				
% Variance explained		45.3		17.2		9.8

III-3.3 Groundwater influence on lake water chemistry

Lakes that were likely to be influenced by groundwater (Figures 2.3 and 2.4), presented distinct patterns of seasonal variations in alkalinity, pH and conductivity. Alkalinity showed summer minimum and winter maximum and recorded greater ranges of variation. In addition, TDOC concentrations showed a clear pattern of increase from January to September. Lower averages of colour, turbidity and TDOC concentrations were recorded among these lakes, while higher NO_3-N and NO_3-N/TN ratios were found.

Alkalinity and conductivity averages over the monitoring period were significantly different ($p<0.05$) between lakes within the Fergus catchment or associated with underlying karstified aquifers and the other catchments. Finally, the ratio mean TP / chlorophyll-*a* concentrations was significantly greater ($p<0.05$) for the lakes likely to be influenced by groundwater than for those without groundwater influence.

III-4 Discussion

The monitoring of the sixty-nine lakes in Clare, between March 2000 and October 2001, was the most comprehensive sampling programme in the county. It covered 20% of the total number of lakes in the county, estimated at 358 (Kennelly, 1997). This study has provided an important development in the assessment of lakes in the county. Up until 2000, only thirty-eight of the county's lakes had been sampled and usually at infrequent intervals.

Sampling protocol and frequency

In this study, one sample was collected per lake on each sampling occasion and most samples were taken from the lakeshore near the outflow. Horizontal variations in the open water community, especially in small lakes, is likely to be much less than seasonal variations, so that provided regular seasonal sampling is possible, a reasonable measure of a lake state using a single station is attainable (Wetzel, 2001; Chapman, 1996). Sampling the centre of a lake would be preferable to avoid any localised littoral edge effects. However, this involves boat launching and is more time consuming than edge sampling. The water, as it enters the outflow, should be representative of the average surface water of the lake as a whole, or at least of its mixed layers. Comparison have been made for lakes in UK and suggest that near outflow or outflow samples, provided they are not taken some way down stream, are statistically indistinguishable from those taken in the centre of the lakes in most cases for most variables (Johnes *et al*, 1998b).

Lakes were monitored using a three-tier sampling frequency. Means were more representative of the overall annual seasonal variations in lake chemistry when more samples were taken evenly distributed over the monitoring period. The design of the monitoring programme provided lower frequency of sampling during the winter, with the assumption that a mid-winter sample (i.e. January 2001) would be representative of the winter period November-February.

Relatively high variability was found for conductivity among sampling months and between years. Conductivity in the lakes located in calcareous catchments is largely due to calcium and bicarbonate ions, both of which can be depleted during the summer, partly due to biological activity. Among the HFM lakes, the highest standard errors associated with the annual means of conductivity for 2000 and 2001 (see Table 21 – Appendix 2) were observed for the calcareous lakes (e.g. Loughs Ballybeg, Cullaunyheeda, Dromore and Inchiquin). This might suggest greater seasonal variations in conductivity levels in the hard-water lakes. In addition, variations in conductivity levels over the monitoing period for the HFM-MFM lakes (Table 3.9) were also found to be significantly greater (Mann-Whitney U test, $p=0.0001$, $\alpha=0.05$) for the calcareous lakes than for lakes lying on shales and similar rock types.

As the lakes were located on the west part of Ireland, inter-annual variation in conductivity levels could also be explained by the significant difference in rainfall amount between the two years, wind conditions around sampling time and influence of sea-salt deposition on the lake conductivity. However, no obvious relationship was found between variations in conductivity between years and the lake eastings. Previous work found only a poor relationship between Cl^- concentrations and distance from the Atlantic (Webb, 1947; Blew and Edmonds, 1995; Free, 2002). It is likely that higher concentrations were caused by episodic westerly storms, which increased aerosol deposition of sea-salts, as increased wind speed can lead to higher non-wet deposition (Ross and Lindberg, 1994; Gustafsson and Franzén, 2000; Allott *et al*, 1997). In addition, precipitation, with lower concentration of sea-salts, is likely to have a diluting effect on conductivity levels.

Seasonal variations

Seasonal variations in lake water chemistry were assessed in twelve lakes between March 2000 and October 2001. Lakes included in the HFM presented a broad variety of catchment characteristics representative of the catchment types found in the county.

Different patterns of variations in alkalinity and pH were observed between hard and soft-water lakes. Lakes lying on carboniferous limestone bedrock, such as Loughs Ballybeg, Ballycullinan, Dromore, Inchiquin and Cullaunyheeda, recorded greater levels of alkalinity with a summer increase in pH, probably owing to increased photosynthetic algal activity, associated with a decrease in alkalinity, due to precipitation of calcium carbonates. Precipitation of solid calcium carbonates occurs during period of high photosynthesis in marl lakes, which usually record very low to moderate algal productivity. This process can only occur in hard water areas with a good supply of calcium: $\underset{\textit{Soluble}}{Ca^{2+}} + 2\,\underset{\textit{Soluble}}{HCO_3^-} \leftrightarrow \underset{\textit{Insoluble}}{Ca(HCO_3)_2} \rightarrow CaCO_3, H_2O + \underset{\textit{taken up by plants}}{CO_2}$

The suspension of colloidal $CaCO_3$ can rapidly reduce light penetration (Otzuki and Wetzel, 1974). In addition, lakes influenced by groundwater, such as Loughs Ballybeg, Ballycullinan, Dromore and Inchiquin recorded greater range of variations in alkalinity. The difference between summer and winter levels could also be explained by reduced influence of groundwater inputs during the summer. A smaller range of variation in alkalinity and increase over the spring and the summer were observed for soft-water lakes, such as Loughs Lickeen, Keagh, Graney, Gortglass and Doolough.

Monthly variations in colour showed a general trend of decrease over the spring and summer in most lakes. However, lakes likely to be influenced by groundwater inputs did not show any clear seasonal patterns and usually displayed, overall, lower levels of colour. Several studies have shown that colour in lakes tends to show a seasonal pattern, decreasing during spring and summer and increasing in autumn and winter (Tipping and Woof, 1983; Naden and McDonald, 1989; Townsend *et al*, 1996). In Ireland, this seasonal variation has been documented for a limited number of lakes (Bowman *et al*, 1993; Bowman, 1986; Bowman, 1996; Free, 2002) and winter and summer sampling results have shown a similar trend in 53 lakes (Flanagan and Toner, 1975).

Seasonal patterns in nutrient concentrations were usually complex and variable between years and among lakes. A general trend of gradual decline of in-lake TN concentrations from winter to summer was observed for Loughs Castle, Cullaunyheeda, Dromore and Gortglass. Gradual decline of in-lake TN concentrations from winter to summer could be explained by sedimentation after incorporation into phytoplankton in lakes with low summer flushing, such as Loughs Keagh, Dromore, Killone and Gortglass, but also by replacement with water with lower nitrogen concentration for lakes with high summer flushing, such as Loughs Ballycullinan, Castle and Inchiquin. Similar patterns were observed for in-lake TP variations, with summer minimum and winter maximum in Loughs Cullaunyheeda, Doolough, Gortglass and Killone. It was clear from the data that the annual range of TP and TN concentrations increased as the annual maximum TP and TN increased. Enriched lakes showed a pronounced TP and TN minimum. The annual maximum values of in-lake TP and TN concentrations were correlated with the ranges and means, but less with annual minimum, especially in the case of TP concentrations. These findings verify the observations made on seasonal variation of in-lake TP concentrations for seventeen lakes in Scotland and Northern Ireland (Gibson *et al*, 1996). The settlement of particles is one of the main processes decreasing the TP concentration in a lake (Gibson *et al*, 1996) and it is possible that summer TP minima reflect a reduction of inflow and associated in-washed particulate phosphorus. Late summer and autumnal sediment release could explain the variations observed for Lough Ballybeg in 2000, which showed increasing concentrations in nutrients, more pronounced between July and September, and signs of long term stratification over the summer (Gibson *et al*, 1996; Moss *et al*, 1996). Lower nutrient concentrations recorded during the winter months could be explained by dilution owing to high groundwater flushing.

Signs of potential co-precipitation of phosphates with calcite during the summer were observed in Loughs Ballybeg and Cullaunyheeda between April/May and June 2000. Calcite precipitation is an effective and natural process to counteract the enrichment of phosphate in surface waters (Holzbecher and Nutzmann, 2000) and has been observed in many freshwater lakes (Koshel *et al*, 1983; Murphy *et al*, 1983; Kleiner, 1988; House, 1990). On the basis of the influx of phosphate, the process of eutrophication in hard-water lakes is slower than that in soft-water lakes where the carbonate saturation is reduced or absent (Otzuki & Wetzel, 1972). Substantial co-precipitation of PO_4^{3-} with calcite can occur when the pH is above 8.5 (Otsuki and Wetzel, 1972; Danen-Louwerse *et al*, 1995; Dittrich *et al*, 1997; Hartley *et al*, 1997).

In-lake total phosphorus and total nitrogen concentrations were not always significantly correlated with chlorophyll-*a* levels, owing to the influence of other factors on phytoplankton growth, such as light penetration, wind exposure, other nutrient concentrations, trace metals and possible biotic effects, such as zooplankton grazing (Cole, 1975; Wetzel and Lickens, 1991). Catchments with high proportion of peats, such as Loughs Keagh, Lickeen and Doolough, had highly coloured water, which might limit phytoplankton growth owing to light limitation (Effler *et al*, 1985). The relationship between mean TP and chlorophyll-*a* concentrations was impacted by the lake colour, with no significant correlation found for high-colour lakes. Colour and turbidity of water determine the depth to which light is transmitted, controlling the rate of photosynhesis of the algae present (Chapman, 1996; Clesceri *et al*, 1998). In addition, County Clare is located in the West of Ireland and is likely to be subject to strong and variable wind conditions, which might also interfere with algal growth.

Most nitrogen found in the lakes could be associated with organic fractions. Recorded NH_4-N concentrations were generally low (< 0.05 mg l^{-1}). Greater concentrations were recorded for Loughs Ballycullinan, Ballybeg, Killone, Castle and Cullaunyheeda. Concentrations of NO_3-N were also low, especially during the summer months with the exception of Loughs Inchiquin and Castle. Limitation of algal growth by nitrogen is thought to take place if the ratio of NO_3-N and NH_4-N to PO_4-P is less than 10 by weight (Horne and Goldman, 1994; Irvine *et al*, 2001). The N/P ratio was estimated based on the TN/TP concentrations and would not truly account for the ratio of the dissolved available fractions. No indication of nitrogen limitation was found among the studied lakes. Only on one occasion, Lough Ballycullinan recorded a ratio lower than 10. However, this did not appear to be indicative of nitrogen limitation, as it was most likely associated with increased in-lake TP concentrations. However, low NH_4-N and NO_3-N concentrations and decreasing concentrations during the summer months could suppose that for some of the lakes seasonal nitrogen limitation does occur.

To give an indication of the occurrence of stratification in the lakes, temperature and oxygen-depth profiles were taken once during the summer. This only provided information of the stratification status at the time of the sampling, as stratification is known to be mainly dependant on wind speed, lake depth and area and temperature (Moss, 1992). Measurements of transparency (Secchi disc) and turbidity were negatively correlated and indicative of phytoplankton biomass at the time of sampling. Only four lakes: Loughs Ballybeg (classified as hypertrophic), Ballycullinan (mesotrophic), Inchiquin (mesotrophic) and Killone (eutrophic), showed sign of durable summer stratification. Hondzo and Stefan (1996) showed that oligotrophic lakes had larger thermocline depths than eutrophic lakes of the same depth and surface area, with higher transparency allowing radiation heat to penetrate deeper into the lake. However, lakes included in this study are likely to be subject to high wind speeds, which could interfere with temperature vertical profile by strongly influencing the mixing regime of the lakes. More regular measurements of temperature and oxygen depth profiles would therefore be necessary in order to assess seasonal patterns of summer stratification in the lakes.

Overview of the lake status

The sixty-nine lakes included in the study represented a wide range of water chemistry and catchment characteristics. Most variations in the overall water chemistry among the lakes were explained principally by their nutrient status, phytoplankton biomass and colour; and by their acidity status. Over the monitoring period, average pH ranged from 5.46 to 8.81, alkalinity from 0 to 291.6 mg $CaCO_3$ l^{-1} and conductivity from 72 to 14840 μS cm^{-1}. Twenty-nine lakes were highly coloured (colour >50 PtCo) and thirty-seven lakes had dissolved organic carbon less than 10 mg l^{-1}. Mean concentrations of nitrogen fractions were usually low, with NO_3-N ranging from 0.00 to 0.59 mg l^{-1} and TN from 0.30 to 2.73 mg l^{-1}. Mean TP and chlorophyll-*a* concentrations were very variable among lakes and ranged from 5.5 to 696.3 μg l^{-1} for TP and from 1.9 to 148.5 μg l^{-1} for chlorophyll-*a*. Compared with softer lakes, hard-water lakes were usually associated with lower colour, turbidity and TDOC averages, higher average NO_3-N concentrations, TN/TP and NO_3-N/TN ratios, while lower average of TN, TP and chlorophyll-*a* concentrations were observed.

Total nitrogen concentrations were usually low and in many of the lakes surveyed, mid-summer concentrations of nitrate-N were less than the detectable limit (<0.02 mg l^{-1}). This suggests the possibility that nitrogen may play an important role in nutrient limitation of phytoplankton growth. In addition, averages of NH_4-N concentrations were very low ($\leq$ 0.14 mg l^{-1}) among the twelve lakes that were sampled on a monthly basis. Among the HFM lakes, SiO_4-Si concentrations ranged from 0.34 to 2.50 mg l^{-1}, but not enough measurements were carried out to assess potential limitation owing to spring silicate depletion on the growth of diatom phytoplankton. Of the major plant nutrients, phosphorus is typically in shortest supply and so generally has the greatest potential to limit plant growth. Whether nitrogen or phosphorus availability actually limits plant growth depends on many factors, including light intensity, wind conditions and the availability of other major and trace plant nutrients (Mainstone and Parr, 2002). There is a strong temporal heterogeneity in controls upon phytoplankton biomass, with seasonal variations. In their long-term study of a shallow lake eutrophication processes, Lau and Lane (2002) found that phytoplankton was regulated by phosphorus, nitrogen and silicon in spring; phosphorus, nitrogen and zooplankton in summer and phosphorus, nitrogen, silicon and zooplankton in autumn. Among the thirty lakes that were included in the high and medium frequency monitoring, the average N/P ratios (based on TN / TP concentrations) were all over 10, suggesting that the lakes were all P-limited (Horne and Goldman, 1994). Among the thirty-nine lakes that were sampled during the summers 2000 and 2001, four lakes had a ratio lower or equal at eight, suggesting they might have been N-limited. No obvious seasonal trends were observed in the ratio TN:TP during the monitoring period. In the study of Lough Erne in northwest Ireland (2000), Zhou *et al* (2000) did not find any temporal trends in TN:TP ratio either. However, assessment of nitrogen limitations would require detailed seasonal concentrations of dissolved phosphorus fractions, allowing the identification of period of minimum molar ratio and hence of potential limitation and its temporal extent.

Lake classification

Based on maximum chlorophyll-*a* concentrations recorded during the monitoring period among the lakes included in the high and medium frequency monitoring, two lakes were found to be oligotrophic, nineteen mesotrophic, eight eutrophic and one hypertrophic, according to the modified OECD (1982) scheme described by Lucey *et al* (1999). For the thirty-nine lakes included in the low frequency monitoring, the classification into trophic classes gave only an indication of the lake nutrient status. Based on their chlorophyll-*a* concentrations (n=1) or maximum concentrations (n=2), four lakes were found to be ultra-oligotrophic, twelve oligotrophic, fifteen mesotrophic, seven eutrophic and one hypertrophic. In most lakes, TP and chlorophyll-*a* concentrations were very variable over the monitoring period and trophic status based on single summer concentrations underestimated the seasonal maximum chlorophyll-*a* concentrations. Such classification is therefore limited. The seasonal pattern of phytoplankton biomass in temperate lakes is dictated primarily by light availability, with highest rates occurring in the spring and the summer. Seasonal development of phytoplankton in some lakes presents a spring phytoplankton maximum and a second peak in mid to late summer (Sommer *et al*, 1986; Talling, 1993). This was clearly observed for Loughs Inchiquin, Keagh, Killone and Lickeen. In other lakes, such as Loughs Ballybeg (in 2000), Castle and Dromore, nutrient enrichment may however, reduce or eliminate the biomass minimum in early summer giving a unimodal pattern (Talling, 1993).

The use of fixed-boundary schemes, such as the OECD (1982) trophic classification, to assess lake water quality impairment owing to increased nutrient loadings, has been used widely to describe and classify lakes. However, it relies exclusively on suggestive boundary limit values and places too much emphasis on small differences for lakes where concentrations were recorded near boundary limit values. Moreover, it does not allow the actual degree of impairment in water quality in lakes of the same trophic level to be distinguished. The commonly used indicators of trophic status, annual mean TP and maximum chlorophyll-*a* concentrations, present different degrees and patterns of seasonality. The Phosphorus Regulations (DELG, 1998) permit the assessment of lake trophic status based on a single measurement of chlorophyll-*a* and establish baseline conditions based on the results of a study carried out in 1995/97 or monitoring done after 1995 if not included in the survey. It is increasingly accepted that catchment features have an influence on in-lake nutrient concentrations and water quality. The assessment of lakes with great variation in bedrock geology, soil types, aquifers and land use patterns, using the same boundary limits and quality target values, does not take into account the variability induced by the catchment features. Boundary limit values were established in the 1970s based on previous studies and are highly influenced by the limited number of lakes. They may not be representative of baseline reference conditions (undisturbed status), as set in the new European Water Framework Directive (2000/60/EC). For the lakes included in the high and medium frequency monitoring, there was concordance between state categories assessed by TP and maximum chlorophyll-*a*, although noticeable differences were observed near the boundary conditions. This led to different patterns of frequency distribution between lake trophic status and in-lake TP and chlorophyll-*a* concentrations.

Empirical relationships have been developed to predict water quality characteristics (chlorophyll-*a*, Secchi disc) as functions of phosphorus concentration (Dillon and Rigler, 1974; Riley and Prepas, 1985). The relationships have been extended to identify TP boundary values for trophic categories (Chapra and Dobson, 1981; OECD, 1982). Despite their statistical quality and widespread application, the basis for applying empirical models for trophic state determination remains subjective and thus leads to uncertainty. Relationships and log-linear regression models were assessed between mean and maximum chlorophyll-*a* concentrations and in-lake nutrient concentrations for the three sampling regimes. The log-linear models predicting variations of chlorophyll-*a* concentrations were based on in-lake TP concentrations, at the exception of the maximum chlorophyll-*a* for the HFM lakes, which were best predicted using TN concentrations. This could be explained by the fact that all lakes among the HFM presented signs of moderate to severe impairment of water quality. Associated R^2 values were usually low to moderate, owing to the probable influence of other variables (such as colour) on phytoplankton growth.

Based on the ECE acidity scheme (Premazzi and Chiaudani, 1992), the majority of the lakes (sixty-four) had an average pH greater than 6.5 and are unlikely to suffer any biological damage owing to acidity (H^+). Based on the alkalinity averages, five lakes indicated a very good buffering capacity (Alk. >200 mg $CaCO_3$ l^{-1}) against acidification; twenty-four a good buffering capacity (100-200 mg $CaCO_3$ l^{-1}), twenty-four a weak buffering capacity (20-100 mg $CaCO_3$ l^{-1}) and ten a low buffering capacity (10-20 mg $CaCO_3$ l^{-1}). In principle, limitations to the use of the OECD scheme in its validity to classify lakes should also apply to the ECE acidity scheme, which is a fixed-boundary scheme. However, the relationship observed between pH and alkalinity clearly identified three groups of lakes (alkalinity <10 mg $CaCO_3$ l^{-1}, 10-100mg $CaCO_3$ l^{-1} and >100mg $CaCO_3$ l^{-1}), for which a decrease in the lake pH will impact differently on the lake alkalinity level.

Six lakes, Loughs Acrow, Luogh, Keagh, Achryane, Naminna and Doolough, had a weak buffering capacity against acidification (Alk. <10 mg $CaCO_3$ l^{-1}) and associated pH levels were lower than 6.3 for Loughs Acrow, Luogh and Keagh. Their catchments had shales and similar rocks for bedrock and were principally covered by peat soils (≥60%). Such low buffering capacity is very important in terms of risk of acidification from atmospheric deposition or other anthropogenic activities (e.g. forestry). One of the main land cover types encountered among these catchments would be peatlands, but based on the 1998 FIPS data, conifer plantations covered up to 53.5% of the catchment area for Lough Naminna, 9% for Lough Achryane, 20% for Lough Acrow and 15% for Doolough catchments. Conifer plantations were not present or only very marginal activities for Loughs Keagh and Luogh catchments.

Relationships with catchment descriptive variables

Lakes with the highest conductivity values were located close to the sea. In small permanent lakes, close to and in some instance connected to the sea, such as Loughs Rask, Luirk and Muckinish, salinity and water level vary with the tide and the quantity of freshwater inputs. They are all fed by freshwater springs on their inland shore (Coxon and Drew, 1999). The solute chemistry of surface drainage system is dependant on many processes occurring within the catchment, with silica (SiO_2) and calcium (Ca^{2+}) principally products of weathering (Wite *et al*, 1971), while other ions, such as chloride (Cl^-) and sulphate (SO_4^{2-}) are generally deposited from the atmosphere.

Interrelationships found in Chapter 2 between catchment descriptive variables had identified two main types of landscape in Clare among the catchments:

- Lower elevation catchments covered with underlying carboniferous limestone, with well/moderately drained soils, such as brown earths, rendzinas, grey brown podzolics,
- Higher elevation catchments covered with underlying shales and sandstones, with poorly/imperfectly drained soils, such as gleys and peats.

Based on the water chemistry recorded during the monitoring period, each group was found to be associated with specific range of water chemistry. Seasonal variations in in-lake TP concentrations, alkalinity, conductivity and colour were influenced significantly by the nature of the underlying bedrock geology. As expected, higher alkalinity, pH and conductivity were associated with carboniferous limestone catchments. Such catchments present a natural capacity of buffering, making the risk of acidification negligible. The major risk to water quality from anthropogenic sources in the county to these lakes remains eutrophication. The low alkalinity lakes, associated with shales and similar rock type catchments, are likely to be vulnerable to acidification either through deposition from the atmosphere or as a consequence of intensification of coniferous forestry. Many previous studies have demonstrated the critical role for bedrock geology in catchment biogeochemistry (Webb, 1984; Lynch and Dise, 1985; Creasey *et al*, 1986; Adamson and Benefield, 1987; Thorne *et al*, 1988; Bricker and Rice, 1989; Mosello *et al*, 1991). Surface water in areas underlain by igneous rocks often exhibits low base cation concentrations and higher acidity than areas underlain by more reactive rocks (e.g. carbonates). These differences in chemical character are caused mainly by differences in weathering rates (Kram *et al*, 1997). Areas underlain by granitic bedrock are particularly vulnerable to acidic atmospheric deposition (Norton, 1980; Chadwick *et al*, 1991; Langan and Wilson, 1992). Thornton and Dise (1998) found that some ions such as sodium and magnesium showed fairly low variability across geology types and land uses, while others such as nitrates and alkalinity showed large difference. In addition, they found that catchments underlain by gleyed soils or thick soils showed the highest based cation and alkalinity concentrations, while alkalinity were low for catchments with thin and peaty soils. Evans *et al* (2000) found that water acidity was linked to catchment soil type and land use, with the most acidic conditions occurring in peat-dominated catchments where weathering is minimal and influence of atmospheric deposition most pronounced.

Calcareous catchments were associated with lower colour levels and TDOC concentrations, while acidic catchments recorded greater colour and TDOC concentrations. Hard-water lakes had clear water, while softer lakes were associated with more coloured and turbid water. Higher colour averages were recorded for catchments associated with peaty soils. Colour in Irish lakes is strongly influenced by the prevalence of peatlands. When high colour levels are recorded for catchment not lying on peatlands, it could be explained by the high prevalence of semi-natural areas (heath and moor). When no apparent relationship is found between colour and turbidity values, this may be related to the influence of particulate matter (mainly peat particles) and high colour from humic substances. The influence of other particulates (suspended sediments) in the water could lead to poor correlation found between turbidity and chlorophyll-*a*. The correlation between colour and total organic carbon levels could be explained by colour being highly influenced by humic matter in the water (Cole, 1975; Wetzel & Lickens, 1991; Flanagan, 1992).

Catchments included in the first group (carboniferous limestone) recorded higher average NO_3-N, TP concentrations and NO_3-N/TN ratios, and lower maximum chlorophyll-*a* concentrations and TN/TP ratios. Catchments included in the second group recorded lower average NO_3-N and TP concentrations and NO_3-N/TN ratios, and higher mean and maximum chlorophyll-*a* concentrations and TN/TP ratios. A significant correlation was observed between mean TP and chlorophyll-*a* concentrations for calcareous catchments, while no relationship was found for acidic lakes.

Sub-surface drainage and leaching may be important pathways of P losses from soil to water, under certain conditions, particularly if the soil is overloaded with phosphorus (Mainstone and Parr, 2002). Sandy soils and underlying sandstone geology are particularly vulnerable since they have a very low adsorption capacity for phosphorus. Other soils and geologies are less vulnerable, but may be more at risk than supposed owing to macropore and fissure flow within soil/rock structure (Heathwaite, 1997). Clay-based catchments may produce somewhat higher natural concentrations of total phosphorus than sand- and chalk-based catchments owing to the dominance of run-off as a hydrological pathway, but much of the natural load would be non-labile particulate form and would not be biologically available in the short term (Mainstone and Parr, 2002). As part of a study to quantify phosphorus losses from soil to water, it was found that phosphorus concentrations in overland flow are predominantly influenced by soil P levels, management factors and time of the year (Kurz, 2000). Mineral soils are characterised by high desorption values and at high P levels are losing more P to solution than the organic soils. In terms of P loss vulnerability, mineral soils of high P status risk losses to water, while organic soils with lower sorption capacities risk losses to water if amended with fertilisers and manures (Daly, 2000). As part of the development of a national P model, it was found also that semi-natural areas and peatlands are associated with peat and peaty gley soils. These soils have low capacity of storing and usually generate overland flow due to poor infiltration. If this land cover is located near watercourses, then its contribution to overland flow into a water body will be significant (Daly, 2000). Evans *et al* (2000) found that NO_3-N concentrations varied significantly with land use, with elevated concentrations observed in catchments containing forestry due to enhanced deposition inputs and catchments containing improved land linked to fertiliser use. Nitrates levels were also found to be higher in catchments underlain by thick soils (Thornton and Dise, 1998).

Groundwater influence

In the western limestone lowlands, surface and groundwaters are closely interlinked. Characteristics of these lakes are affected by their nature of their links to karst groundwater. Lake and turlough water chemistry are highly dependant on the surface-groundwater interactions. Coxon and Drew (1999) found that lakes with normal surface river inflows and outflows (fed by allogenic surface streams) had low alkalinity and total dissolved solids. Lake with surface inflow and outflow from shallow epikarst water had medium alkalinity and total dissolved solids, while lakes apparently largely isolated from surface waters had high alkalinity and total dissolved solids. Lakes that are part of the Fergus catchment recorded higher alkalinity and conductivity averages and greater seasonal variations in alkalinity, with a tendency for a summer minimum. This could be explained by groundwater inputs into the lake being reduced over the summer period. Also, lower colour, TDOC and turbidity averages were recorded for these lakes; while greater NO_3-N concentrations were recorded.

Drew (1988) described Loughs Bunny and Inchiquin as occupying shallow hollows in the limestone and as being in hydraulic connection with the main groundwater body of the lowlands and other lakes, fed by springs draining a part of the southern flank of the Burren. Coxon and Drew (1999) highlighted that Lough Inchiquin had periodic algal blooms owing to P increase. A natural geological source from phosphatic shales may be a contributory factor but it was also suggested that during the summer, silage effluent entering the karst limestone may discharge at springs a short distance upstream of the lake and so increase the nutrient loading. Allott (1990) found that Lough Ballycullinan (Southern basin) is receiving water from the shales and presented softer, more coloured and often turbid water. This was not verified in this study, as Lough Ballycullinan usually recorded lower colour and turbidity than other lakes included in the Fergus catchment although alkalinity was lower. Free (2002) found no distinct seasonal trend in colour but lower colour values among his study lakes, that were predominantly groundwater-fed, such as Loughs Lene, Owel and Rea.

A key distinction between acidic and calcareous catchments was that the ratios mean TP / chlorophyll-*a* and mean TP / maximum chlorophyll-*a* concentrations were significantly greater among calcareous lakes likely to be impacted by groundwater. High flushing from groundwater together with chemical precipitation of phosphorus with carbonate complexes may therefore provide an effective buffering against nutrient enrichment. Because phosphorus is often nutrient limiting the summer phytoplankton growth, any reaction that removes dissolved phosphorus from the lake water can be important for reduction in algal growth.

The impact of varying land use on lake water chemistry, in particularly phosphorus loadings to lakes, are assessed in Chapter 4, which evaluates catchment land use and lake water chemistry relationships with nutrient export modelling. In order to reduce any inherent variability in the lake water chemistry owing to bedrock geology, soil type distribution and hydrology, catchments were differentiated into groups based on bedrock and soil clusters that were identified in Chapter 2. A more detailed study of the impact of land use changes on inflowing streams and lake water quality in a small lowland catchment underlain by shales and similar rock types is described in Chapter 5.

CHAPTER 4: CATCHMENT LAND USES AND LAKE NUTRIENT STATUS: THE INFLUENCE OF CATCHMENT TYPES

IV-1 Introduction

Two main catchment types were identified among the sixty-nine catchments monitored in County Clare in 2000-01 (Chapters 2 & 3). Calcareous catchments (n=11) located in the north and southeastern side of the county were associated with clear and alkaline waters, while in the west and southwest, catchments lying on shales and similar rocks (n=13) were associated with more coloured and acidic waters. A small number of catchments (n=4) were underlain by Old Red Sandstone and Silurian quartzite. In this chapter, lake water chemistry is related to the spatial variation in land use types, which reflects the physical and hydrological environment, and through statistical and spatial analyses (GIS), annual average TP loading rates to surface waters were estimated.

Long-term increases in phosphorus concentrations have been reported in many rivers and lakes in recent decades (Sharpley *et al*, 1994; Gibson *et al*, 1995; Bowman and Clabby, 1998; Foy and Bailey-Watts, 1998). These increases have been attributed to population increase, the use of phosphorus detergents and the greater use of phosphorus fertilisers (Sharpley *et al*, 1994; Smith *et al*, 1999). Inputs of nutrients to surface waters can originate from localised sources (point sources) and also from diffuse sources (non-point sources). Although internal loading from lake sediments may be a factor in the maintenance of available pools of phosphorus in lake ecosystems (Søndergaard *et al*, 1993 & 1994), diffuse losses from agricultural sources are often considered to be the major cause of eutrophication (Sharpley *et al*, 1994; Foy *et al*, 1995; Gibson *et al*, 1995; Lucey *et al*, 1999). While P losses may arise from point sources within farmyards or incidental losses through fertilisation (Lee-STRIDE, 1995; Tunney *et al*, 1998; Morgan *et al*, 2000), they are mainly attributed to mobilisation and run-off of phosphorus accumulated in soils as a result of long-term inputs of chemical and organic fertilisers (Pote *et al*, 1996; Sharpley *et al*, 2000; Tunney *et al*, 2000). Many of the processes in the mobilisation of phosphorus from catchment to surface waters are affected by geographical factors such as soil types, underlying geology and catchment type. Land use and catchment management are also principal determining factors in the spatial variability observed in phosphorus export rates (Jennings *et al*, 2001). Although some studies report no clear land use/phosphorus loss relationship (Svendsen *et al*, 1995; Jordan *et al*, 1997), many have reported an increase in diffuse losses of phosphorus in catchments with greater agricultural intensity (Truman *et al*, 1993; Leinweber *et al*, 1999; Allott *et al*, 1998).

The Water Framework Directive (2000/60/EEC) requires that the different water bodies (coastal, surface and groundwater) be classified based on the assessment of ecological elements, including hydromorphology and water chemistry. The Directive (CEC, 2000) has also generated an increasing interest in water quality modelling in Europe. The use of mathematical models can assist in the understanding of hydrological and chemical dynamics in catchments and provide a useful way to predict trends in the ecological responses to changes in catchment management. Jennings *et al* (2001) carried out a wide literature review on seasonal discharge of phosphates to water bodies, including existing mathematical modelling. Water quality models can be distinguished between "process" models, based on fundamentals of physics and chemistry, and "empirical" models based on statistical analyses (Ball and Trudgill, 1995). In addition, they can be differentiated based on their "spatial" (units lumped or distributed) or "temporal" (single or continuous events) precision (Maidment, 1993).

Commonly referenced models, incorporating nutrient fate and transport elements, are listed in Appendix 3 (Tables 1 and 2). Two other important models, SHE (Systeme Hydrologique Europeen) (Abbott *et al*, 1986) and HSPF (Bicknell *et al*, 1986) should also be mentioned (Jennings *et al*, 2001). The SHE hydrological model has been the focus on considerable development, primarily in Europe, for many years. This includes SHETRAN (Bathurst and Purnama, 1991) and others. In addition to hydrological processes, the system provides detailed treatment of the sediment and contaminant components using the convection-dispersion equation in channel and overland flow, adsorption of contaminants onto sediment and soil and into immobile phases, plant uptake and recycling. A specific phosphorus module is currently under development (M. Bruen, UCD – ERTDI 2000-06 funded project). The HSPF system is a comprehensive system for the simulation of catchment and water quality for both conventional and toxic organic pollutants. It is actively supported by the US Environmental Protection Agency and is incorporated within their integrated GIS based water quality management system BASINS (Better Assessment Science Integrating Point and Nonpoint Sources).

Initial research and modelling efforts involving agricultural non-point-source pollution were concerned primarily with soil erosion. The Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) uses a simple lumped parameter approach, where input parameters are averaged on an area-weighed basis across the study area. The use of distributed parameter-models allows the influence of spatially variable controlling parameters to be incorporated. Recently, catchment modelling research has included the movement of pesticides and nutrients: AGNPS (Agricultural Non-Point Source Pollution Model, Young *et al*, 1989) and SWRRBWQ (Simulator for Water Resources in Rural Basins); both developed by the US Department of Agriculture, and ANSWERS (Areal Nonpoint Source Catchment Environmental Response Simulation, Beasley and Huggins, 1982) developed by the US EPA.

Phosphorus exports from a catchment can occur via surface run-off, sub-surface flow and leaching to groundwater (Truman *et al*, 1993; Sharpley *et al*, 1994; Heathwaite and Dils, 2000; Kurz, 2000;

Jennings *et al*, 2002). These pathways are spatially and temporally dynamic and depend on factors such as moisture, topography and the intensity and duration of rainfall (Heathwaite and Dils, 2000). Overland flow occurs when the infiltration capacity of the soil is exceeded. Loss of phosphorus via surface run-off is driven by the rainfall intensity and the relative importance of dissolved and particulate phosphorus transported depends on land use and management. Subsurface flow includes preferential flow (movement of water through the soil macropores and animal burrows) and artificial drainage systems. Its importance depends on soil and catchment characteristics. Phosphorus losses from soils via all hydrological pathways are mainly influenced by high rainfall events (Truman *et al*, 1993; Sharpley *et al*, 1994; Heathwaite and Dils, 2000; Kurz, 2000). The development of detailed models to predict P transfers are consequently dependent on the modelling of hydrology and soil hydraulic properties. The SmoRMod model developed by Zollweg *et al* (1997) uses a GIS based model to describe the extent and contributions of phosphorus exporting areas of a catchment but requires considerable volumes of data arising from field studies, which are generally not available at a catchment-scale in Ireland.

Export coefficient modelling developed by Vollenweider (1968, 1975, 1986) and applied by Johnes and O'Sullivan (1989) and Johnes *et al* (1996, 1998) allows the evaluation on an annual basis of the impact of changes in past land use and management on nutrient loadings delivered to both running and standing waters. This approach allows the prediction at the catchment scale of potential reductions in nutrient loading, which might be implemented through a catchment management strategy. It could also be used to forecast effects of changes in land use in the future and to hindcast past water quality to establish comparative or baseline conditions (Johnes *et al*, 1996; Johnes & Heathwaite, 1997). Although export coefficients can be modified to suit particular catchment characteristics, modelling requires these coefficients to be verified by some fieldwork and monitoring. This approach ignores the modelling-specific processes, including the complexities of soil-phosphorus interactions and does not require long-term and intensive chemical and hydraulic measurements, or a requirement to understand soil-phosphorus kinetics. However, it does require original calibration and validation procedures in order to determine suitable export coefficients. Nevertheless, although this process has been effectively applied within catchments, the extrapolation of a coefficient determined in one catchment for estimation of P load in other catchments is more controversial (Johnes *et al*, 1996; Irvine *et al*, 2002). Tests of these models (Irvine *et al*, 2001 & 2002; Free, 2002) have often found that while nutrient export across a range of water bodies are ranked successfully, the predictive power of the models can be modest.

Daly *et al* (2000) developed a model on quantification of phosphorus loss from soil to water, describing phosphorus levels in surface waters using available information on land use, land management, soil type and water quality. The model aimed at identifying areas at risk of diffuse P losses and variables controlling these losses. It provided an objective approach to modelling losses at a national scale and risk assessment maps for catchment management. Nevertheless, it did not provide accurate forecasts of phosphorus loss. Further work is currently being undertaken to improve the model (K. Daly, Teagasc – ERTDI 2000-06 funded project).

In the work presented in this thesis, annual mean concentrations of TP observed in the lakes monitored in 2000-01 allowed estimating annual averages of TP loading rates (kg P ha^{-1} yr^{-1}) (Foy, 1992; Free, 2002) for comparison with predicted loads from two simple mathematical models (Jordan *et al*, 2000; Johnes *et al*, 1994, 1996 & 1998). In addition, empirical relationships predicting annual average TP loading rates to surface waters were identified differentiating the catchment types in Co. Clare. Finally, a qualitative map of potential risks of TP loadings to surface waters was produced for Co. Clare.

The objectives of this chapter are to:

- Establish a method of monitoring lake water quality through risk assessment based on catchment characteristics (physical, hydrological, land uses and human activities),
- Identify empirical relationships between catchment characteristics and in-lake nutrient status, which could prove to be useful for reducing field monitoring,
- Identify and assess the land uses that constitute major threats to nutrient enrichment of lakes,
- Validate and assess the limitations of existing nutrient export models,
- Model the spatial distribution of areas representing the greatest potential pressure to lake water quality using Geographic Information Systems.

IV-2 Methods

IV-2.1 Annual average TP loading rates

In order to calculate annual average TP loading rates to lakes, it was necessary to estimate annual mean inflow TP concentration. Estimates of phosphorus inflow concentrations (P_{input}) were based on mean in-lake P concentrations (P_{lake}) and water retention time (t_w), using the reciprocal equations of the models developed by Foy (1992), OECD (1982) and Vollenweider (1968).

By rearranging Foy's equation (1992) (Equation 4.1), which was established for northern Irish lakes,

$$P_{lake}/P_{input} = 1.118 / (1 + t_w^{1/2})^{1.135} \qquad \textbf{Equation 4.1}$$

mean P inflow concentrations were estimated based on:

$$P_{input} = P_{lake} * (1 + t_w^{1/2})^{1.135} / 1.118 \qquad \textbf{Equation 4.2}$$

The OECD model (1982) (Equation 4.3), which was established for shallow lakes, and reservoirs:

$$P_{lake} = 1.02 \, [P_{input} / (1 + t_w^{1/2})]^{0.88} \qquad \textbf{Equation 4.3}$$

could also be rearranged to predict mean P inflow concentration, based on:

$$\mathbf{P_{input} = [P_{lake} / 1.02]^{1/0.88} * (1 + t_w^{1/2})} \qquad \textbf{Equation 4.4}$$

Finally, Vollenweider's equation (1968):

$$\mathbf{P_{lake}/P_{input} = 1 / (1 + t_w^{1/2})} \qquad \textbf{Equation 4.5}$$

was rearranged to estimate mean P inflow concentrations, based on:

$$\mathbf{P_{input} = P_{lake} * (1 + t_w^{1/2})} \qquad \textbf{Equation 4.6}$$

Relationships between annual average mean TP concentrations derived from Foy (1992), Vollenweider (1968) and OECD (1982) were assessed using Pearson's Product-Moment correlations with *DataDesk 6.0*.

The annual mean P input concentration (kg m^{-3}) was then used to calculate the annual P load from the catchment (kg yr^{-1}) (including lake area) (Equation 4.7), based on lake flushing rate (yr^{-1}) and volume (m^3). Lake area was included, as Foy's model included rainfall to the lake surface in P input estimates (Free, 2002).

$$\textbf{Load Catcht} = \textbf{Flushing Rate} * \textbf{Volume} * \mathbf{P_{input}} \qquad \textbf{Equation 4.7}$$

The P load (kg yr^{-1}) from atmospheric deposition onto the lake surface (Jordan, 1987) was estimated based on net rainfall (m), lake area (m^2) and TP rainfall concentration ($1.9\ 10^{-5}$ kg m^{-3}) (Gibson *et al*, 1995):

$$\textbf{Load Lake} = \textbf{Net Rainfall} * \textbf{Lake Area} * \mathbf{P_{rainfall}} \qquad \textbf{Equation 4.8}$$

The P load (kg yr^{-1}) from the drainage area was calculated based on the difference of the P load from catchment minus the P load from atmospheric deposition (Free, 2002). TP export rate from the drainage area was expressed as kg TP ha^{-1} yr^{-1}, by dividing subsequently by the drainage area (ha) (Equation 4.9):

$$\textbf{TP Export Rate} = (\textbf{Load Catcht} - \textbf{Load Lake}) / \textbf{Catchment Area} \qquad \textbf{Equation 4.9}$$

Reduction of TP loadings required to achieve a mesotrophic (mean annual TP in-lake concentration <35 μg l^{-1}) or oligotrophic (mean annual TP in-lake concentration <10 μg l^{-1}) state for the lakes, were also estimated based on limit TP concentrations, as described by the OECD (1982) scheme.

IV-2.2 Relationships between ecological variables and land use

For the thirty lakes included in the medium and high sampling frequency ($n \geq 4$ sampling occasions) relationships between catchment land use distribution and annual average TP loading rates and annual means of lake water quality variables obtained from the monitoring 2000-01 were estimated grouping catchment based on their predominant bedrock geology, as described in Chapter 2. Spearman's Rank correlations were used for the datasets that could not be normalised.

The thirty-nine lakes included into the low frequency monitoring ($n \leq 2$ sampling occasions) were not included in these analyses, as the one-off summer sample(s) taken in these lakes was (were) not representative of the overall annual mean water chemistry.

For prediction of annual average TP export rates, the influence of catchment characteristics (Table 4.1) was assessed by applying the following approaches:

1- Including all lakes from the high and medium frequency monitoring (n=30)

2- Dividing them according to their predominant bedrock characteristics (based on bedrock clusters described in Table 2.4 in Chapter 2), between

- Acidic catchments (1): n=13;
- Mixed geology (2): n=2;
- Calcareous catchments (3): n=11; and
- Catchments with ORS and Silurian quartzite (4): n=4.

3- Dividing them based on their coverage of peat soils, between:

- Peaty catchments (% peat soils ≥ 66% of catchment area) (Peaty): n=5; and
- Non-peaty catchments (% peat soils < 66% of catchment area) (Non-Peaty): n=25.

4- Dividing them based on their overall soil drainage properties between:

- Well-drained catchments (% well drained soils ≥ 66% catchment area) (Wd): n=5;
- Poorly-drained catchments (% poorly drained soils ≥ 66% catchment area) (Pd): n=12; and
- Moderately-drained catchments (Md): n=13.

Table 4.1: Catchments included in the high and medium frequency monitoring, grouped based on their overall soil drainage properties (Wd: well-drained, Pd: poorly-drained, Md: moderately-drained), coverage of peat soils and predominant bedrock geology (Table 2.4, Chapter 2).

Catchment	Drainage	Soils	Bedrock
Acrow	Pd	Peaty	1
Atedaun	Wd	Non-Peaty	3
Ballyallia	Wd	Non-Peaty	3
Ballybeg	Md	Non-Peaty	3
Ballycar	Md	Non-Peaty	3
Ballycullinan	Pd	Non-Peaty	2
Ballyleann	Pd	Non-Peaty	1
Burke	Pd	Non-Peaty	1
Castle	Md	Non-Peaty	4
Clonlea	Md	Non-Peaty	3
Cloonmackan	Pd	Non-Peaty	1
Cloonsnaghta	Md	Non-Peaty	1
Cullaun	Wd	Non-Peaty	3

Table 4.1 continued

Catchment	Drainage	Soils	Bedrock
Cullaunyheeda	Md	Non-Peaty	3
Doolough	Pd	Peaty	1
Doon	Md	Non-Peaty	4
Dromore	Md	Non-Peaty	3
Gortglass	Md	Non-Peaty	1
Graney	Md	Non-Peaty	4
Inchichronan	Md	Non-Peaty	4
Inchiquin	Wd	Non-Peaty	3
Keagh	Pd	Peaty	1
Killone	Md	Non-Peaty	2
Knockalough	Pd	Non-Peaty	1
Lickeen	Pd	Non-Peaty	1
Lisnahan	Pd	Non-Peaty	1
Moanmore	Pd	Peaty	1
Muckanagh	Wd	Non-Peaty	3
Naminna	Pd	Peaty	1
Rosroe	Md	Non-Peaty	3

IV-2.3 Use of mathematical modelling

Jordan *et al* (2000)

The model described by Jordan *et al* (2000) was used to predict annual average TP loadings into the thirty lakes included in the high and medium frequency monitoring in 2000-01. It is based on catchment land use distribution, attributing a specific export coefficient to each of the CORINE land use categories (Table 4.2). The model was developed based on datasets from Northern Ireland lakes. The coefficients were derived either from existing literature or based on regressions of land class areas against TP loadings to lakes (McGuckin *et al*, 1999). Coefficients ranged between –6.57 kg ha^{-1} (upstream water) and 4.90 kg ha^{-1} for non-irrigated arable land.

The model implies a net retention of P rather than export from freshwater (negative coefficient for "Water"). Annual average TP exports to the lakes were calculated with ("*Jordan-1*") or without ("*Jordan-2*") account of the coefficient assigned to upstream lakes (-6.57 kg ha^{-1} yr^{-1}) in order to identify the impact of upstream lakes on TP exports.

Table 4.2: TP export coefficients (kg ha^{-1} yr^{-1}) for each CORINE land class, as described by Jordan *et al* (2000).

CORINE Land Class	**TP Export coefficient (kg ha^{-1} yr^{-1})**
Arable	4.90
Artificial surface	0.18
Bare rocks	0.00
Beach, dunes and sand	0.00
Broadleaf forest	0.23
Complex cultivation	2.32
Coniferous forest	0.39
Inland marshes	0.23
Intertidal flats	0.00
Mixed forests	0.23
Moors and heathlands	0.10
Natural grasslands	0.64
High productivity grasslands	0.84
Low productivity grasslands	0.64
Mixed grasslands	0.75
Peat bogs exploited	0.23
Peat bogs unexploited	0.23
Peat bogs	0.23
Principally agriculture	0.49
Salt marsh	0.00
Sparsely vegetated areas	0.00
Transitional woodland / scrub	0.23
Urban green	1.02
Water	-6.57

Johnes *et al* (1994, 1996 & 1998)

The model developed initially by Johnes *et al* (1994) has been widely used (Johnes *et al*, 1996; 1998; Johnes and Heathwaite, 1997). Annual average TP exports from a catchment can be predicted by applying export coefficients to livestock, humans, and land classes:

$$L = \sum_{i=1}^{n} E_i [A_i (I_i)] + p \qquad \textbf{Equation 4.10}$$

where L: loss of nutrients
E: export coefficient for the nutrient source i
A: area of catchment occupied by land use, number of livestock or people type i
I: input of nutrient to source i
p: input of nutrients from precipitation

Export coefficients were derived from existing literature (Table 4.3, Johnes *et al* (1994)). Catchments included in the study were divided into regional types (Johnes *et al*, 1994, 1996, 1998) in order to apply this model (Table 4.4). Specific sets of coefficients were assigned to the different catchment types based on geology, soil type, topography, rainfall and agricultural practices (Table 4.5) for lakes in England (Johnes *et al*, 1994, 1996, 1998).

Table 4.3: Variations in export coefficients expressed as % of inputs to the system or rates (kg ha^{-1} or kg $head^{-1}$) (Johnes *et al*, 1994)

Land Uses	**Location**	**N (kg ha^{-1})**	**N (%)**	**P (kg ha^{-1})**	**P (%)**
Arable	UK	25-70			
	UK	13			
	UK	30-120			
	UK		5-50	0.5-5.0	
Cereals	UK		12	0.06-0.7	
Grassland	Europe	4.0	4	0.22	
	UK		1-5		
	UK	3-6			
	UK	8			
	UK	12-30			
	UK		5	0.2	
	UK		10-40		
Forest	Europe	0-6		0.01-0.06	
	UK	13			
Rough Grazing	UK	6.4			
	UK	<10			
	UK	4			
	UK	3-6			
Livestock					
Manure applied to land					
	Europe		17		3
	Cattle		7.2-16.2		1.3-2.85
	Pigs		7.2-14.5		1.3-2.55
	Sheep		8.5-17.0		1.5-3.0
	Poultry		7.7-15.3		1.35-2.7
Manure voided					
	Cattle	44.4-74.8		7.65-17.6	
	Pigs	6.6-18.8		1.4-5.63	
	Sheep	7.0-10.1		1.47-1.8	
	Poultry	0.2-0.9		0.1-0.3	
People		1.86-8.6		0.3-3.9	
Mean Rainfall input					
	UK	24			
	UK	20			
	UK	8.7-19		0.2-1.0	
	UK	17			
	UK	10			

Table 4.4: Description of the different catchment regional types as described by Johnes *et al* (1994, 1996, 1998).

Regional Type		
1	**Description**	Extensive livestock & Upland regions - Small human population
	Weather	wet & cold
	Annual Mean Runoff	> 1000mm
	Soils	Thin, acid and often peaty podzolic soils
	Geology	Impermeable, igneous or metamorphic rock
	Topography	Uplands with steep slopes
2	**Description**	Lowland dairy regions
	Weather	moderately wet
	Annual Mean Runoff	> 500mm
	Soils	Mixed, deep and fertile, often poorly drained soils
	Geology	Usually impermeable metamorphic rocks with flat topography
	Topography	Flat lowlands
3	**Description**	Mixed arable and dairying regions - Large human population
	Weather	Variable
	Annual Mean Runoff	200-600mm
	Soils	Mixed, varying depths, fertile, often calcareous
	Geology	Permeable, sedimentary with moderate slope
	Topography	Lowland with moderate to steep slopes
4	**Description**	Mixed arable & dairying regions
	Weather	Variable
	Annual Mean Runoff	300-800mm
	Soils	Mixed, varying depths, fertile, often acidic
	Geology	Impermeable, metamorphic rock with steep slopes
	Topography	Lowlands with steep slopes
5	**Description**	Intensive arable regions - Large human population
	Weather	warm & dry
	Annual Mean Runoff	< 200mm
	Soils	Deep, fertile, well-drained soils (easily eroded)
	Geology	Permeable, sedimentary rocks often on glacial drift - very flat
	Topography	Flat lowlands

Table 4.5: Nitrogen and Total phosphorus export coefficients expressed as % of input to the system or rates (kg ha^{-1} or kg head^{-1}) (Johnes *et al*, 1994, 1996, 1998)

Regional Types	1	2	3	4	5
Nitrogen:					
Permanent grass (%)	1.00	15.00	5.00	7.50	1.70
Temporary grass (%)	2.00	15.00	5.00	7.50	1.70
Cereals (%)	10.00	25.00	12.00	12.00	4.00
Woodland (kg ha^{-1})	1.00	1.00	1.00	1.00	0.30
Rough grazing (kg ha^{-1})	1.00	1.00	1.00	1.00	0.30
People (kg head^{-1})	2.14	2.14	2.14	2.14	2.14
Cattle (%)	7.20	16.20	16.20	16.20	5.40
Pigs (%)	7.20	14.50	14.50	14.50	4.80
Sheep (%)	8.50	17.00	17.00	17.00	5.70
Poultry (%)	7.70	15.30	15.30	15.30	5.10
Rainfall	25.00	25.00	25.00	25.00	8.30

Table 4.5 (continued)

Regional Types	**1**	**2**	**3**	**4**	**5**
Phosphorus:					
Permanent grass (kg ha^{-1})	0.30	0.80	0.10	0.40	0.03
Temporary grass (kg ha^{-1})	0.30	0.12	0.40	0.40	0.10
Cereals (kg ha^{-1})	0.60	0.90	0.65	0.60	0.22
Woodland (kg ha^{-1})	0.02	2.00	0.02	0.02	0.07
Rough grazing (kg ha^{-1})	0.02	0.02	0.02	0.02	0.07
People (kg head^{-1})	0.38	1.00	0.38	0.38	0.38
Cattle (%)	1.30	5.70	2.90	2.90	0.95
Pigs (%)	1.30	5.10	2.60	2.60	0.85
Sheep (%)	1.50	6.00	3.00	3.00	1.00
Poultry (%)	1.40	5.40	2.70	2.70	0.90
Rainfall (%)	25.00	25.00	25.00	25.00	8.30

Export coefficient of livestock was based on a 3% export to runoff. Sheep were assumed to input 1.5 kg P head^{-1} yr^{-1}. Mass of P excreted by humans was estimated at 0.24 kg P yr^{-1} head^{-1} for un-sewered population and 0.38 kg P yr^{-1} head^{-1} for sewered population (Johnes *et al*, 1994; 1996; 1998). Cattle were assumed to input 7.65 kg P head^{-1} yr^{-1} (Johnes *et al*, 1994, 1996; Irvine *et al*, 1998, 2001). Exports from peatlands were estimated from gross precipitation containing an estimated mean concentration of 15 µg l^{-1} (Gibson *et al*, 1995) and assuming a net annual through put of 100% (Gibson *et al*, 1995). As poultry and horses were not included in the agricultural census, they were not accounted for in the modelling, as no accurate and reliable data could be obtained. They are, however, likely to represent small inputs in the study catchments. No large pig units were recorded in Co. Clare in 2000 (EPA – IPC licensing, 2000).

Comparison with calculated datasets

Predicted annual average TP export rates were compared to calculated annual average TP export rates (kg P ha^{-1} yr^{-1}) from the monitoring 2000-01 for the thirty lakes included in the high and medium frequency monitoring. Comparisons between predicted and calculated values were carried out on export rates (kg P ha^{-1} yr^{-1}) rather than exports (kg P yr^{-1}), as relationships may be influenced by the catchment area. Very large catchments ought to export more TP than small catchments owing to their larger catchment area (Free, 2002).

IV-2.4 Empirical modelling

Empirical relationships were identified by carrying out stepwise multiple regressions to predict variations in annual average TP loading rates (kg P ha^{-1} yr^{-1}) into lakes based on catchment descriptive variables. Regressions were carried out for all thirty lakes included into the high and medium frequency monitoring and differentiating them among the different catchment types.

Regression models used either land use data from the CORINE coverage updated by FIPS (1998) or agricultural land uses from the CSO Agricultural Census. Linear regression models were derived for all lakes and grouping them (level 1), as described below. No multiple regressions were carried out for small sample size (*), i.e. n<11, in this case. The influence of other physical variables (level 2) on the predictive power of the derived linear models was assessed by differentiating catchments when looking at relationships between predicted and calculated export rates.

All lakes (n=30) **Level 1** *Level 2*

- **Acidic catchments (n=13)**
  - *Acidic peaty catchments (n=5)*
  - *Acidic non-peaty catchments (n=8)*
  - *Acidic poorly drained catchments (n=11)*
  - *Acidic moderately drained catchments (n=2)*
- **Calcareous catchments (n=11)**
  - *Calcareous well-drained catchments (n=5)*
  - *Calcareous moderately drained catchments (n=6)*
- **Peaty catchments (n=5*)**
- **Non-peaty catchments (n=25)**
  - *Non-peaty acidic catchments (n=8)*
  - *Non-peaty calcareous catchments (n=11)*
  - *Non-peaty moderately drained catchments (n=13)*
  - *Non-peaty poorly drained catchments (n=7)*
  - *Non-peaty well-drained catchments (n=5)*
- **Well-drained catchments (n=5*)**
- **Moderately drained catchments (n=13)**
  - *Moderately drained acidic catchments (n=2)*
  - *Moderately drained calcareous catchments (n=6)*
- **Poorly drained catchments (n=12)**
  - *Poorly drained non-peaty catchments (n=7)*
  - *Poorly drained peaty catchments (n=5)*

The Nash-Sutcliffe measure (R^2_{NS}) (ASCE, 1993; Evans *et al*, 2001) was used to assess the "goodness-of-fit" between calculated and predicted values. A R^2_{NS} value of 1 would be indicative of a perfect fit.

$$R^2_{NS} = 1 - [\,\sum(\text{Calculated data} - \text{Predicted data})^2\,] \,/\, [\,\sum(\text{Calculated data} - \text{Mean data})^2\,]$$

Equation 4.11

IV-2.5 Application of GIS to modelling

Examples of the potential use of GIS as a component of the modelling process were given by producing maps of spatial variation in annual average TP loading rates to surface water in County Clare by applying the different derived regression models.

IV-3 Results

IV-3.1 Calculated annual average TP export rates from catchments

Annual mean TP input concentrations into the thirty lakes included in the high and medium frequency monitoring were estimated following Foy (1992), Vollenweider (1968) and OECD (1982), based on lake retention time and observed mean annual TP concentrations (Table 4.6).

Table 4.6: Estimated annual mean TP input concentrations (μg l^{-1}) 2000-01, following Foy (1992), Vollenweider (1968) and OECD (1982) for the thirty lakes included in the high and medium frequency monitoring 2000-01.

Lakes	TP Input - Foy (μg l^{-1})	TP Input - Vollenweider (μg l^{-1})	TP Input - OECD (μg l^{-1})
Acrow	62.7	63.3	98.4
Atedaun	34.6	38.5	61.5
Ballyallia	26.4	28.3	41.9
Ballybeg	106.8	113.7	201.7
Ballycar	51.5	54.4	86.4
Ballycullinan	32.8	35.9	55.8
Ballyleann	48.0	50.6	79.7
Burke	37.3	39.3	59.8
Castle	30.5	33.5	52.0
Clonlea	34.3	34.9	50.2
Cloonmackan	40.3	42.4	65.1
Cloonsnaghta	42.1	44.1	67.7
Cullaun	10.3	11.1	14.6
Cullaunyheeda	40.4	41.7	62.5
Doolough	32.6	34.3	51.3
Doon	31.8	34.5	53.1
Dromore	49.8	49.2	72.4
Gortglass	49.6	50.2	75.7
Graney	26.0	27.7	40.4
Inchichronan	33.6	35.3	52.6
Inchiquin	23.9	25.8	37.9
Keagh	125.6	121.0	195.8
Killone	91.0	90.1	144.0
Knockalough	36.5	38.0	56.8
Lickeen	37.4	38.6	57.3
Lisnahan	75.6	75.7	119.3
Moanmore	69.1	72.4	118.9
Muckanagh	10.0	10.8	14.0
Naminna	18.5	19.3	26.3
Rosroe	35.1	34.7	48.7

Estimates of annual mean TP input concentrations based on Foy (1992) and Vollenweider (1968) were very close, while estimates following OECD (1982) gave greater values. As the Foy (1992) model was developed for Northern Irish lakes, it was decided to use this equation to estimate annual mean TP input concentrations (Table 4.7).

Table 4.7: Calculated annual average TP export rates (kg P ha^{-1} yr^{-1}) and TP exports (kg P yr^{-1}) among the thirty catchments in Co. Clare, included in the high and medium frequency monitoring 2000-01.

Lakes	TP export rates (kg P ha^{-1} yr^{-1})	TP exports (kg P yr^{-1})
Acrow	0.11	6.5
Atedaun	0.30	8578.2
Ballyallia	0.20	482.4
Ballybeg	0.76	314.1
Ballycar	0.04	13.3
Ballycullinan	0.28	159.7
Ballyleann	0.08	23.0
Burke	0.35	81.5
Castle	0.11	1480.6
Clonlea	0.21	114.3
Cloonmackan	0.40	114.5
Cloonsnaghta	0.32	40.0
Cullaun	0.08	666.6
Cullaunyheeda	0.24	704.9
Doolough	0.22	501.6
Doon	0.21	2054.1
Dromore	0.35	73.9
Gortglass	0.29	60.5
Graney	0.17	1927.3
Inchichronan	0.23	761.7
Inchiquin	0.22	3220.4
Keagh	0.07	2.2
Killone	0.64	81.8
Knockalough	0.28	72.9
Lickeen	0.24	208.0
Lisnahan	0.10	7.3
Moanmore	0.20	68.2
Muckanagh	0.07	289.0
Naminna	0.16	33.5
Rosroe	0.20	77.1

Annual average TP export rates ranged between 0.04 kg P ha^{-1} yr^{-1} for Lough Ballycar catchment and 0.76 kg P ha^{-1} yr^{-1} for Lough Ballybeg catchment (Table 4.7), while annual average TP exports ranged between 2.2 kg P yr^{-1} for Lough Keagh catchment to 8578.2 kg P yr^{-1} for Lough Atedaun catchment. Summary statistics of annual average TP export rates calculated among the different catchment types are summarised in Table 4.8.

No significant differences were observed between annual average TP export rates calculated among calcareous and acidic catchments (Two-sample t-test, $\alpha=0.05$, $p=0.7$, ns) and also among annual average TP export rates calculated for well, moderately and poorly-drained catchments (Two-sample t-test, $\alpha=0.05$, $p>0.1$, ns). However, a significant difference was observed between annual average TP export rates calculated for peaty and non-peaty catchments (Two-sample t-test, $\alpha=0.05$, $p<0.05$) (Figure 4.1).

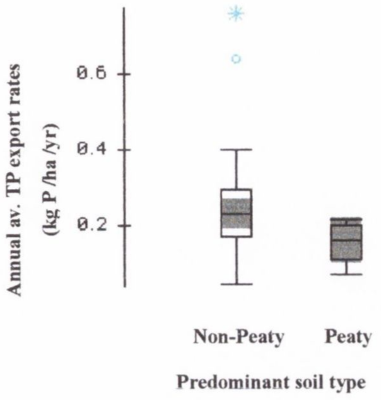

Figure 4.1: Distribution of calculated annual average TP export rates (kg P ha^{-1} yr^{-1}) between peaty and non-peaty catchments observed for 30 lakes monitored seasonally in County Clare in 2000-01.

Table 4.8: Summary statistics of calculated annual average TP export rates in 30 catchments monitored seasonally in County Clare in 2000-01. The different catchment types are differentiated. Number of lakes (n) is provided and means, standard errors (SE), medians and ranges are expressed in kg P ha^{-1} yr^{-1}.

Type	n	Mean	SE	Median	Range
All lakes	30	0.24	0.03	0.22	0.04-0.76
Acidic	13	0.22	0.03	0.22	0.07-0.40
Calcareous	11	0.24	0.06	0.21	0.04-0.76
Well-drained	5	0.17	0.04	0.20	0.07-0.30
Moderately drained	13	0.29	0.06	0.23	0.04-0.76
Poorly drained	12	0.21	0.03	0.21	0.07-0.40
Peaty	5	0.15	0.03	0.16	0.07-0.22
Non-Peaty	25	0.25	0.03	0.23	0.04-0.76

The reduction in TP exports from catchments with impaired water quality (i.e. eutrophic and mesotrophic – Table 3.28) required to achieve a mesotrophic (for the lakes classified as eutrophic) or oligotrophic status (for the lakes classified as mesotrophic) was assessed. Based on the upper limits of the range of mean in-lake TP concentrations defining a mesotrophic (e.g. 35 µg l^{-1}) and oligotrophic (e.g. 10 µg l^{-1}) trophic classes, reduced TP export rates were calculated and compared with calculated annual average TP export rates. Nineteen of the catchments monitored would require a reduction of at least 50% of their current TP export rates in order to improve their trophic status.

Table 4.9: Calculated TP export rates and reduced TP export rates that would be associated with an improved water quality status, i.e. a mesotrophic and oligotrophic status, for the lakes classified, respectively, as eutrophic and mesotrophic in 2000-01. Reduction in calculated TP export rates (expressed as % of calculated TP export rates) required to achieve reduced rates are also given

Lakes	Reduced TP export rates (kg P ha^{-1} yr^{-1})	Calculated TP export rates (kg P ha^{-1} yr^{-1})	Required Reduction of TP loading rate (%)
Acrow	0.03	0.11	75
Atedaun	0.29	0.30	5
Ballyallia	0.09	0.20	53
Ballybeg	0.33	0.76	56
Ballycar	0.04	0.04	1
Ballycullinan	0.09	0.28	69
Ballyleann	0.02	0.08	72
Burke	0.13	0.35	62
Castle	0.04	0.11	66
Clonlea	0.12	0.21	43
Cloonmackan	0.14	0.40	66
Cloonsnaghta	0.11	0.32	65
Cullaun	0.08	0.08	0
Cullaunyheeda	0.10	0.24	58
Doolough	0.09	0.22	57
Doon	0.07	0.21	64
Dromore	0.16	0.35	54
Gortglass	0.11	0.29	62
Graney	0.09	0.17	48
Inchichronan	0.10	0.23	56
Inchiquin	0.11	0.22	50
Keagh	0.06	0.07	19
Killone	0.61	0.64	5
Knockalough	0.12	0.28	59
Lickeen	0.10	0.24	56
Lisnahan	0.02	0.10	77
Moanmore	0.16	0.20	22
Muckanagh	0.07	0.07	0
Naminna	0.14	0.16	14
Rosroe	0.13	0.20	33

IV-3.2 Relationships between lake chemistry and catchment land use

pH, Alkalinity and Conductivity

Means 2000-01 of in-lake pH, alkalinity and conductivity were significantly correlated ($n=30$, $p\leq0.05$) with measures of catchment land use (Table 4.10). No significant correlations were found when grouping catchments into calcareous ($n= 11$) and acidic ($n=13$) (Table 4.10).

Table 4.10: Spearman's Rank correlation coefficients between mean 2000-01 pH, alkalinity and conductivity and catchment land use for the HFM-MFM lakes (n=30, p≤0.05). Coefficients significant at p≤0.01 are in bold.

	% Total Peatlands	% Total Pasture - CSO	% Total Pasture - CORINE	% Conifers
pH	-0.53	**0.51**	0.39	-0.43
Alkalinity	-0.49	**0.56**		
Conductivity	-0.54	**0.59**		-0.46

Colour, TDOC and Turbidity

Mean colour 2000-01 was significantly correlated (p≤0.05) with catchment land use for all HFM-MFM catchments (n=30) and when differentiating acidic catchments (n=13) (Table 4.11). No significant correlations were found between TDOC and turbidity and catchment land use.

Table 4.11: Spearman's Rank correlation coefficients between mean 2000-01 colour and catchment land use for all HFM-MFM lakes (n=30, p≤0.05) and when differentiating acidic catchments (n=13, p≤0.05). Coefficients significant at p≤0.01 are in bold.

	HFM-MFM catchments (n=30)	Acidic Catchments (n=13)
% Total Peatlands	**0.58**	0.65
% Conifers	0.46	
% Improved Grasslands	-0.41	
% Broadleaf Forests	-0.58	
% Total Pasture - CSO	-0.42	

NO_3-N and TN

No significant correlations were found between mean 2000-01 NO_3-N and TN concentrations and catchment land use types when considering all lakes (n=30) or grouping lakes into acidic (n=13) and calcareous (n=11) catchments.

Chlorophyll-*a* (Chl-a)

For all lakes (n=30), maximum chlorophyll-*a* concentrations were significantly positively correlated with %Total silage – CSO (r=0.41, p≤0.05), while mean chlorophyll-*a* concentrations were negatively correlated with % Total Peatlands (r=-0.91, p≤0.01, n=13) for the calcareous lakes.

TP and TP export rates

Among the thirty lakes, no significant correlations were found between annual mean TP concentrations 2000-01 or annual average TP export rates and catchment land use. For the acidic catchments, annual average TP export rates were significantly positively correlated with %

unimproved grasslands, while significantly positively correlated with % mixed grasslands and % Broadleaf forests for the calcareous catchments (Table 4.12).

Table 4.12: Spearman's Rank correlation coefficients ($p \leq 0.05$) between calculated annual average TP export rates 2000-01 and catchment land use when differentiating catchments into acidic (n=13) and calcareous (n=11). Coefficients significant at $p \leq 0.01$ are in bold.

	Calculated annual average TP export rates
Acidic Catchments (n=13)	
% Unimproved Grasslands	**0.88**
Calcareous Catchments (n=11)	
% Mixed Grasslands	0.77
% Broadleaf Forests	0.73

IV-3.3 Mathematical modelling

Predicted annual average TP export rates were calculated using the models described by Jordan *et al* (2000) and Johnes *et al* (1994, 1996, 1998) (Table 4.13). They ranged from –0.74 kg P ha^{-1} yr^{-1} (Lough Ballyallia) to 0.83 kg P ha^{-1} yr^{-1} (Lough Lisnahan) with *Jordan-1* model; from 0.23 kg P ha^{-1} yr^{-1} (Lough Acrow) to 0.83 kg P ha^{-1} yr^{-1} (Lough Lisnahan) with *Jordan-2* model, and finally from 0.02 kg P ha^{-1} yr^{-1} (Lough Dromore) to 0.67 kg P ha^{-1} yr^{-1} (Lough Lisnahan) when using *Johnes* model.

Usually, TP export rates predicted using *Jordan-1* model were closer to the calculated values than when using *Jordan-2* model, except for Loughs Ballyallia, Ballybeg and Dromore. In these three catchments, known underground connections between the lake and upstream lakes could explain the discrepancies (i.e. dilution effect). Both Jordan's model usually overestimated the TP export rates, except for Loughs Acrow and Ballyallia (*Jordan-1*) and Loughs Ballybeg, Dromore, Gortglass and Killone (*Jordan-1 & 2*). For twenty of the lakes, the *Johnes* model overestimated the export rates.

Overall, none of the different models gave accurate estimates of the calculated annual average TP export rates for the 30 catchments monitored in 2000-01. No significant correlations (Pearson's Product-Moment correlations, n=30) were found between predicted and calculated annual average TP export rates when using *Jordan-1* (r_p=0.01, ns), *Jordan-2* (r_p=0.01, ns) and *Johnes* (r_p=0.23, ns), for all lakes or when dividing the lakes between calcareous and acidic catchments. However, significant linear regression models were found when carrying multiple linear regressions between predicted (*Jordan-1 & 2*) and calculated annual average TP export rates (Tables 4.14 & 4.15). Both models (Figures 4.2 and 4.3) were based on mean elevation (m), mean slope (°) and annual mean rainfall 00-01 (mm) (Appendix 4 – Table 3). No significant regression model was obtained using TP export rates predicted by the *Johnes* model.

Table 4.13: Predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) based on the models described by Jordan *et al* (2000) and Johnes *et al* (1994, 1996, 1998). For the Jordan's model, export rates were estimated with (*Jordan-1*) or without accounting for upstream water (*Jordan-2*). Calculated annual average export rates (kg P ha^{-1} yr^{-1}) in the 30 catchments monitored seasonally in 2000-01 are also provided (Table 4.7).

Catchment	**Calculated TP Export Rates**	***Jordan-1* TP Export Rate**	***Jordan-2* TP Export Rates**	***Johnes* TP Export Rates**
Acrow	0.11	0.09	0.23	0.13
Atedaun	0.30	0.41	0.51	0.24
Ballyallia	0.20	-0.74	0.59	0.51
Ballybeg	0.76	0.22	0.52	0.32
Ballycar	0.04	0.56	0.69	0.38
Ballycullinan	0.28	0.51	0.51	0.55
Ballyleann	0.08	0.62	0.62	0.31
Burke	0.35	0.58	0.63	0.43
Castle	0.11	0.45	0.59	0.14
Clonlea	0.21	0.37	0.63	0.36
Cloonmackan	0.40	0.47	0.47	0.15
Cloonsnaghta	0.32	0.68	0.68	0.34
Cullaun	0.08	0.32	0.51	0.26
Cullaunyheeda	0.24	0.38	0.55	0.34
Doolough	0.22	0.33	0.33	0.09
Doon	0.21	0.46	0.56	0.14
Dromore	0.35	-0.06	0.24	0.02
Gortglass	0.29	0.28	0.54	0.46
Graney	0.17	0.36	0.41	0.07
Inchichronan	0.23	0.40	0.46	0.22
Inchiquin	0.22	0.49	0.49	0.21
Keagh	0.07	0.23	0.23	0.18
Killone	0.64	0.58	0.58	0.66
Knockalough	0.28	0.61	0.61	0.46
Lickeen	0.24	0.43	0.45	0.45
Lisnahan	0.10	0.83	0.83	0.67
Moanmore	0.20	0.33	0.33	0.20
Muckanagh	0.07	0.63	0.64	0.27
Naminna	0.16	0.27	0.29	0.07
Rosroe	0.20	0.25	0.41	0.38

Table 4.14: Multiple linear regression models predicting Log (Calculated annual av. TP export rates) based on Log (Jordan-Predicted annual av. TP export rates). Coefficient of determination R^2, degree of freedom (df) and F-Ratio are given

Model	Equation	Multiple Linear Regression Models			
		Log (Calculated TP Export Rates) (kg P ha^{-1} yr^{-1}) =	**R^2**	**df**	**F-Ratio**
Jordan-1	4.12a	-0.785 * Log(*Jordan-1* Predicted TP Export rates) -0.005 * Elevation (m) + 0.196 * Slope (degree) + 0.001 * Rainfall (mm) - 2.689	0.39	4, 23	5.34
Jordan-2	4.12b	-1.045 * Log(*Jordan-2* Predicted TP Export rates) -0.005 * Elevation (m) + 0.189 * Slope (degree) + 0.001 * Rainfall (mm) - 2.282	0.35	4, 25	4.88

Table 4.15: Pearson's Product-Moment correlation coefficients between Predicted and Calculated Log (TP export rates) using equations 4.12a and 4.12b. Correlation coefficients (r_p), degree of freedom (df), probability (p) and associated figures are given.

Equation	r_s	df	p	Figures
4.12a	0.69	26	<0.01	4.16
4.12b	0.66	28	<0.01	4.17

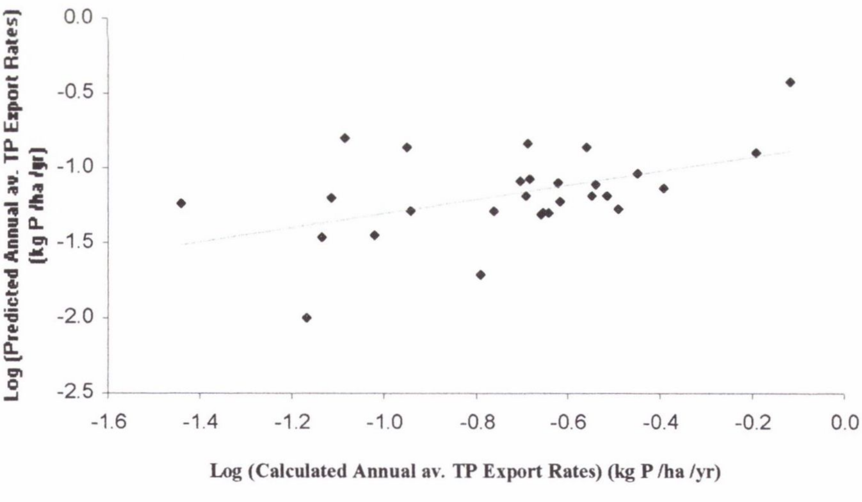

Figure 4.2: Comparison between Predicted and Calculated Log (annual av. TP export rates) (kg P ha^{-1} yr^{-1}) using the linear multiple regression model described by equation 4.12a (r_p=0.69, n=28, p<0.01).

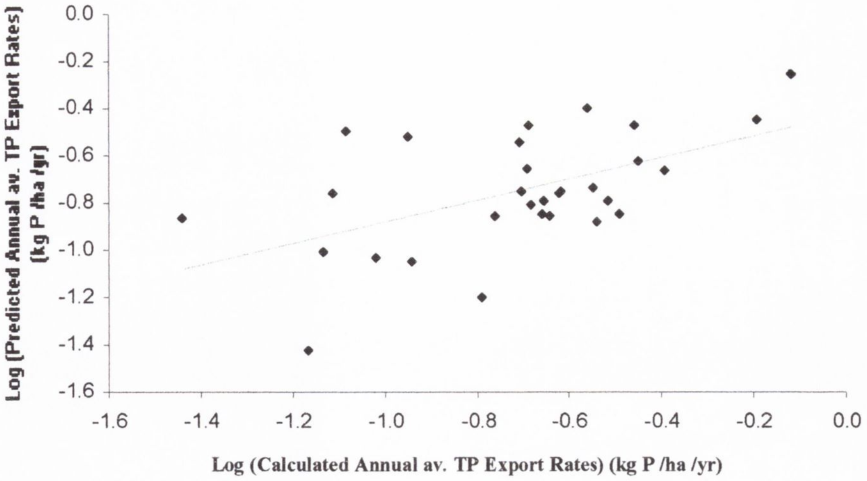

Figure 4.3: Comparison between Predicted and Calculated Log (annual av. TP export rates) (kg P ha^{-1} yr^{-1}) using the linear multiple regression model described by equation 4.12b (r_p=0.66, n=30, p<0.01).

IV-3.4 Empirical relationships

Several multiple regression models predicting annual average TP export rates were derived from the calculated annual TP export rates and catchment descriptive variables for all lakes and for lake groups based on bedrock geology, soil drainage properties and peat soil coverage (Appendix 4 – Tables 4 to 9). The best models identified in each case are listed in Table 4.16. The main factors in the models were elevation (-), rainfall (+), slope (+), soil Morgan P levels (+), soil P desorption index (-), % peat soils (-), peatlands (+/-) and mixed grasslands (+). Based on their coefficients, the most important factors influencing annual average TP export rates were slope, soil P desorption index and soil P status (soil Morgan P). The different regression models were applied to all lakes and for each group of lakes based on their bedrock, soil drainage and peat coverage (Table 4.17) to predict annual average TP loading rates.

Table 4.16: Multiple linear regression models predicting annual av. TP export rates. Coefficient of determination R^2, degree of freedom (df) and F-Ratio are given. Land use classes are expressed as % of catchment area. Factors the most significant are in bold. MixAg: Mixed agriculture; MixGrass: Mixed grassland; HPG: high productivity grassland; PdesInd: soil P desorption index; SoilMorgP: Soil Morgan P levels; %Peats: % peat soils.

Type	**Model**	**Multiple Linear Regression Models**			
		Predicted TP Export Rates (kg P ha^{-1} yr^{-1}) =	**R^2**	**df**	**F-Ratio**
All types	**Model 1**	-0.002 * Elevation (m) + 0.085 * **Slope** (degree) + 0.055 * **SoilMorgP**(mg P l^{-1}) – 0.292 * **PDesInd** + 0.001 * Rainfall (mm) + 0.004 * MixGrass – 0.914	0.59	5, 23	7.87
Acidic Bedrock	**Model 2**	-0.002 * Elevation (m) + 0.001 * Rainfall (mm) – 0.260 * **PDesInd** – 0.003 * Peatlands – 0.316	0.81	4, 8	13.6
Calcareous Bedrock	**Model 3**	0.255 * **Slope** (degree) + 0.256 * **SoilMorP** + 0.007 * MixGrass – 0.012 * MixAgri + 0.006 * % Peats – 2.077	0.92	5, 5	24.8
Non-Peaty Catchments	**Model 4**	-0.005 * Elevation (m) + 0.173 * **Slope** (degree) + 0.062 * **SoilMorgP** (mg P l^{-1}) – 0.424 * **PDesInd** + 0.001 * Rainfall (mm) – 0.807	0.60	5, 19	8.26
Moderately-drained Soils	**Model 5**	-0.009 * Elevation (m) + 0.151 * **Slope** (degree) + 0.002 * Rainfall (mm) + 0.013 * Peatlands – 1.833	0.82	4, 8	14.2
Poorly-drained Soils	**Model 6**	-0.006 * Peatlands – 0.004 * Conifers + 0.084 * **SoilMorgP** - 0.456 * **PDesInd** + 0.001 * Rainfall (mm) – 0.002 * HPG – 1.091	0.85	6, 5	11.8

Table 4.17: Predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) applying the linear regression models 1 to 6 described in Table 4.16. Drainage, soil and bedrock groups as described in Table 4.1 are also listed. Calculated annual average export rates (kg P ha^{-1} yr^{-1}) observed in the 30 catchments monitored seasonally in 2000-01 are also provided (Table 4.7).

Catchment	Drainage	Soils	Bedrock	Calc. TP export rates	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Acrow	P	Peaty	1	0.11	0.05	0.06				0.08
Atedaun	W	Non-Peaty	3	0.30	0.28		0.30	0.25		
Ballyallia	W	Non-Peaty	3	0.20	0.21		0.18	0.28		
Ballybeg	M	Non-Peaty	3	0.76	0.45		0.73	0.52	0.62	
Ballycar	M	Non-Peaty	3	0.04	-0.01		0.10	-0.01	0.12	
Ballycullinan	P	Non-Peaty	2	0.28	0.33			0.33		0.27
Ballyleann	P	Non-Peaty	1	0.08	0.17	0.14		0.06		0.10
Burke	P	Non-Peaty	1	0.35	0.24	0.33		0.29		0.36
Castle	M	Non-Peaty	4	0.11	0.18			0.22	0.18	
Clonlea	M	Non-Peaty	3	0.21	0.11		0.19	0.15	0.17	
Cloonmackan	P	Non-Peaty	1	0.40	0.36	0.39		0.43		0.40
Cloonsnaghta	M	Non-Peaty	1	0.32	0.38	0.26		0.30	0.31	
Cullaun	W	Non-Peaty	3	0.08	0.25		0.05	0.29		
Cullaunyheeda	M	Non-Peaty	3	0.24	0.14		0.27	0.11	0.18	
Doolough	P	Peaty	1	0.22	0.26	0.22				0.16
Doon	M	Non-Peaty	4	0.21	0.22			0.26	0.18	
Dromore	M	Non-Peaty	3	0.35	0.41		0.39	0.44	0.43	
Gortglass	M	Non-Peaty	1	0.29	0.30	0.29		0.25	0.27	
Graney	M	Non-Peaty	4	0.17	0.18			0.12	0.13	
Inchichronan	M	Non-Peaty	4	0.23	0.22			0.21	0.31	
Inchiquin	W	Non-Peaty	3	0.22	0.24		0.26	0.19		
Keagh	P	Peaty	1	0.07	0.09	0.07				0.12
Killone	M	Non-Peaty	2	0.64	0.63			0.58	0.71	
Knockalough	P	Non-Peaty	1	0.28	0.19	0.28		0.22		0.28
Lickeen	P	Non-Peaty	1	0.24	0.21	0.21		0.23		0.25
Lisnahan	P	Non-Peaty	1	0.10	0.16	0.10		0.18		0.10
Moanmore	P	Peaty	1	0.20	0.36	0.22				0.18

Table 4.17 (continued)

Catchment	Drainage	Soils	Bedrock	Calc. TP export rates	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Muckanagh	W	Non-Peaty	3	0.07	0.13		0.08	0.13		
Naminna	P	Peaty	1	0.16	0.14	0.25				0.19
Rosroe	M	Non-Peaty	3	0.20	0.24		0.13	0.34	0.16	

Model 1 – All catchments

Model 1 (Table 4.16) derived for all lakes (n=30) had a good accuracy and predictive power with R^2_{NS} =0.7 and R^2=0.59 (df=28) when predicting annual average TP export rates. When differentiating catchments based on their predominant bedrock geology (Figure 4.4), the model had a strong predictive power when applied to catchments characterised by "Other bedrock" (mixed geology & catchment with ORS and Silurian quartzite, n=6, R^2=0.98). The model predictive power was good for calcareous catchments (n=11, R^2=0.55) and acidic catchments (n=13, R^2=0.62).

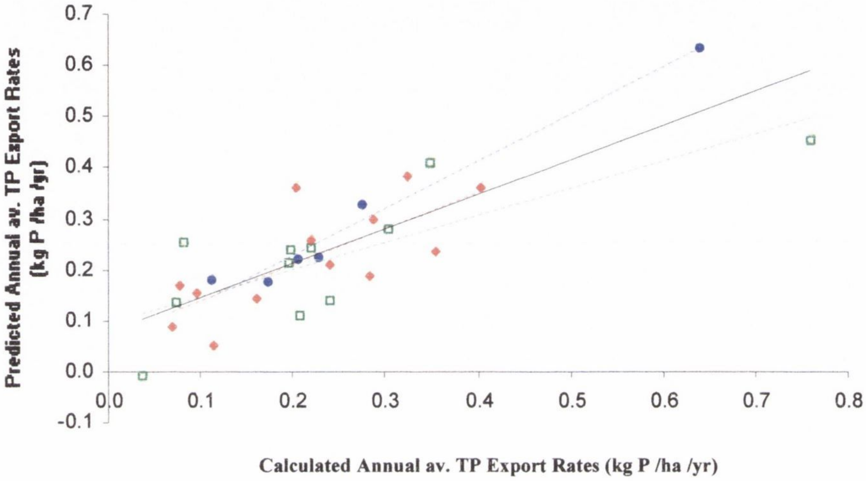

Figure 4.4: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 1 (r_p=0.82, n=30, $p \leq 0.01$). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.59, df=28, $p \leq 0.05$). The catchments are differentiated among acidic (♦ - regression line: dotted red line, R^2=0.55, df=11), calcareous (□ – regression line: dotted green line, R^2=0.62, df=9) and other bedrock geology (● – regression line: dotted blue line, R^2=0.98, df=4).

The model had a strong predictive power for catchments with moderately drained soils (n=13, R^2=0.75), while its predictive power decreased when considering catchments with poorly drained (n=12, R^2=0.50) and well-drained soils (n=5, R^2=0.43) (Figure 4.5). Finally, the model predictive power increased when differentiating the catchments between non-peaty (n=25, R^2=0.69) and peaty (n=5, R^2=0.70) (Figure 4.6).

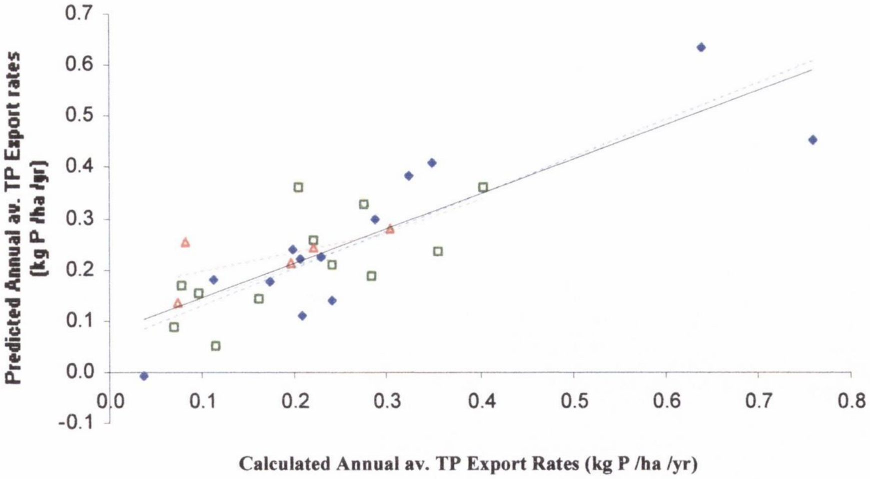

Figure 4.5: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 1 (r_p=0.82, n=30, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.59, df=28, p≤0.05). The catchments are differentiated among moderately drained (♦ - regression line: dotted blue line, R^2=0.75, df=11), poorly drained (□ – regression line: dotted green line, R^2=0.50, df=10) and well drained soils (△ – regression line: dotted red line, R^2=0.43, df=3).

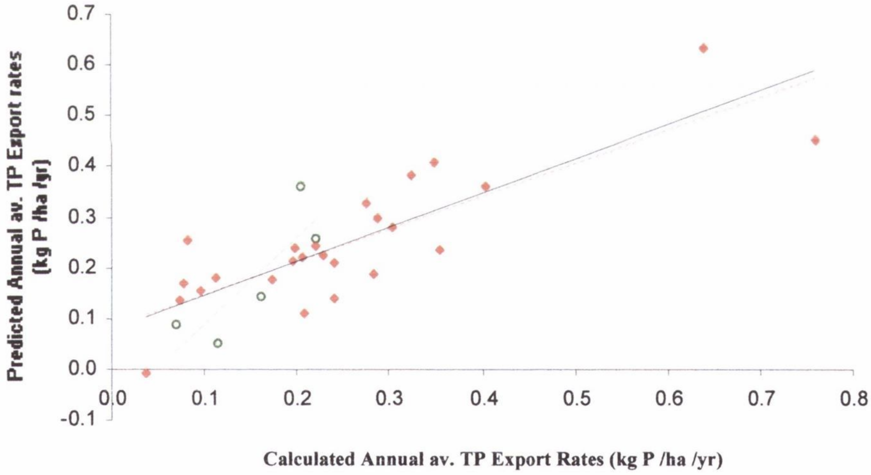

Figure 4.6: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 1 (r_p=0.82, n=30, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.59, df=28, p≤0.05). The catchments are differentiated among non-peaty (♦ - regression line: dotted red line, R^2=0.69, df=23) and peaty catchments (○ – regression line: dotted green line, R^2=0.70, df=3).

Model 2 – Acidic catchments

Model 2 (Table 4.16) derived for acidic catchments gave more accurate estimates (R^2_{NS}=0.9) and had a strong predictive power with R^2=0.81 (df=11). When differentiating the catchments between non-peaty and peaty, the predictive power of the model increased with, respectively, R^2=0.92 (df=6) and R^2=0.73 (df=3) (Figure 4.7).

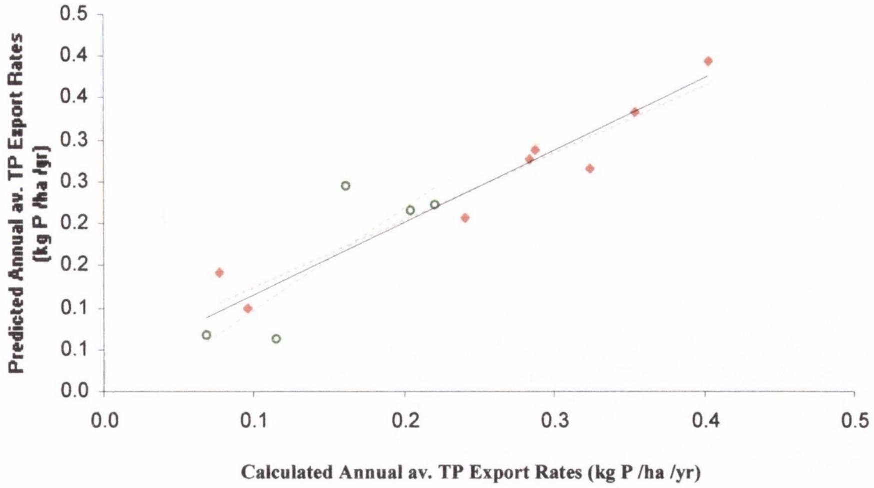

Figure 4.7: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 2 (r_p=0.93, n=13, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.81, df=11, p≤0.05). The catchments are differentiated among non-peaty (♦ - regression line: dotted red line, R^2=0.92, df=6) and peaty catchments (○ – regression line: dotted green line, R^2=0.73, df=3).

Model 3 – Calcareous catchments

Model 3 (Table 4.16) gave very accurate estimates R^2_{NS} =0.9. It also had a very strong predictive power with R^2=0.92 (df=9). The model predictive power was stronger for moderately drained soils (R^2=0.96, df=4) and for well-drained soils (R^2=0.95, df=3) (Figure 4.8).

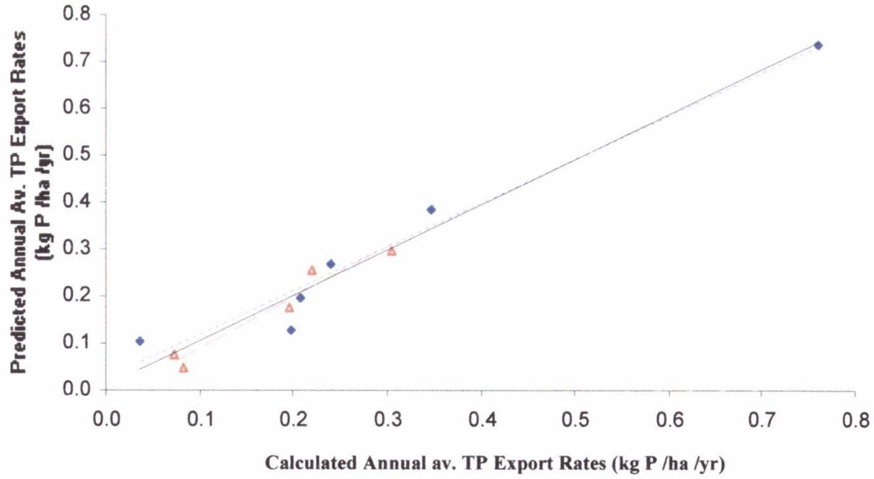

Figure 4.8: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 3 (r_p=0.98, n=11, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.92, df=28, p≤0.05). The catchments are differentiated among moderately drained (♦ - regression line: bule dotted line, R^2=0.96, df=4) and well drained soils (△ – regression line: red dotted line, R^2=0.95, df=3).

Model 4: Non-peaty catchments

Model 4 (Table 4.16) gave accurate estimates with R^2_{NS} =0.7 and had a moderate predictive power (R^2=0.60, df=23). Differentiating catchments based on their bedrock geology increased the predictive power of the model for acidic and other bedrock types (resp. R^2=0.81, df=6; R^2=0.88, df=4), while lower predictive power was obtained for calcareous catchments (R^2=0.57, df=9) (Figure 4.9). When differentiating the catchments based on their soil drainage properties, stronger predictive power was obtained for moderately and poorly drained soils (resp. R^2=0.74, df=11; R^2=0.78, df=5); while the model could not be applied to well drained soils alone (R^2=0.07, df=3) (Figure 4.10).

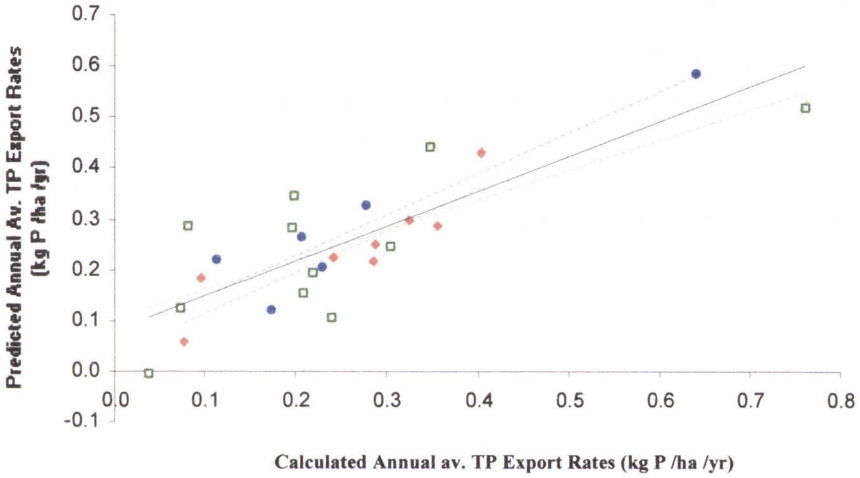

Figure 4.9: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 4 (r_p=0.83, n=25, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.60, df=23, p≤0.05). The catchments are differentiated among acidic (♦ - regression line: dotted red line, R^2=0.81, df=6), calcareous (□ – regression line: dotted green line, R^2=0.57, df=9) and other bedrock geology (● – regression line: dotted blue line, R^2=0.88, df=4).

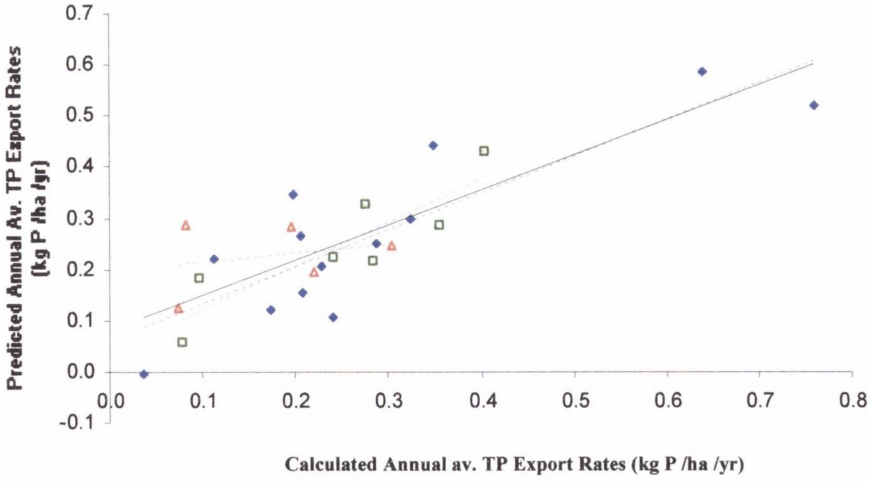

Figure 4.10: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 4 (r_p=0.83, n=25, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.60, df=23, p≤0.05). The catchments are differentiated among moderately drained (♦ - regression line: dotted blue line, R^2=0.74, df=11), poorly drained (□ – regression line: dotted green line, R^2=0.78, df=5) and well drained soils (△ – regression line: dotted red line, R^2=0.01, df=3).

Model 5: Moderately drained catchments

Model 5 (Table 4.16) gave very accurate estimates of annual average TP export rates among moderately drained catchments (R^2_{NS} =0.9). It also had a strong predictive power with R^2=0.82 (df=11). The model predictive power was also strong when differentiating the catchments between calcareous and other bedrock with, respectively, R^2=0.89 (df=4) and R^2=0.94 (df=3) (Figure 4.11).

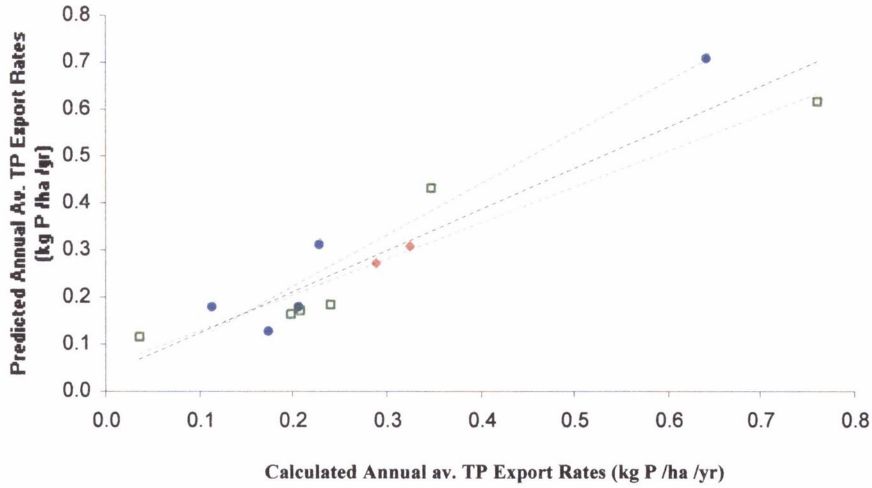

Figure 4.11: Comparison between observed and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 5 (r_p=0.97, n=13, p≤0.01). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.82, df=4, p≤0.05). The catchments are differentiated among acidic (♦), calcareous (□ – regression line: dotted green line, R^2=0.89, df=4) and other bedrock geology (● – regression line: dotted blue line, R^2=0.94, df=3).

Model 6: Poorly drained catchments

Model 6 (Table 4.16) gave very accurate estimates of annual average TP export rates among poorly drained catchments (R^2_{NS} =0.9). It also had a strong predictive power with R^2=0.85 (df=10). The model applied well to non-peaty catchments (R^2=0.99, df=5), but only had a moderate predictive power for peaty catchments (R^2=0.50, df=3) (Figure 4.12).

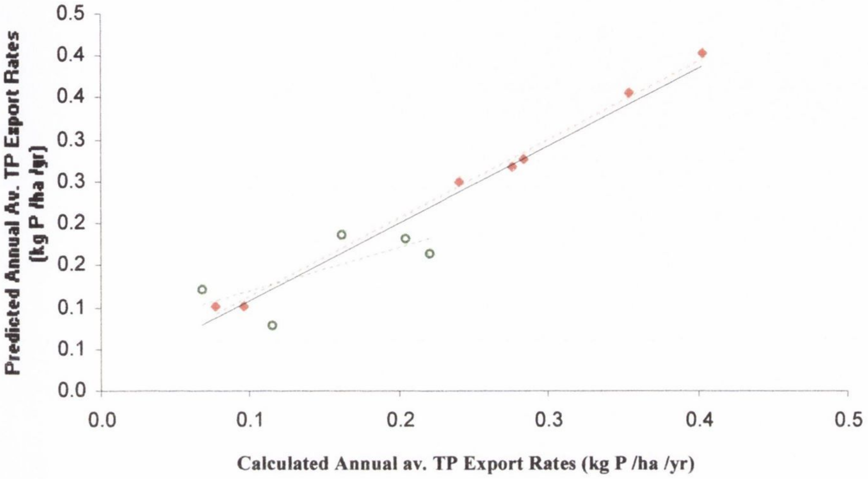

Figure 4.12: Comparison between calculated and predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) when applying the regression model 6 (r_p=0.94, n=12, $p \leq 0.01$). The regression line between predicted and calculated export rates is shown (black line) (R^2=0.85, df=10, $p \leq 0.05$). The catchments are differentiated among non-peaty (♦ - regression line: dotted red line, R^2=0.99, df=5) and peaty catchments (○ – regression line: green dotted line, R^2=0.50, df=3).

Predicted annual average TP export rates for the LFM catchments

Annual average TP export rates were predicted for the 30 catchments included in the low frequency monitoring 2000-01 using the models described in Table 4.16. Based on the correlation coefficients (r_p), model predictive power (R^2) and accuracy (R^2_{NS}), Model 6 was applied for poorly drained catchments and Model 5 for moderately drained catchments. Well-drained catchments were all associated with calcareous bedrock types and Model 3 was used (Table 4.18). Some lakes had negative predicted TP export rates. However, negative values were still obtained when using the other models.

Table 4.18: Predicted annual average TP export rates (kg ha^{-1} yr^{-1}) using the regression models described in Table 4.16 for the 30 catchments included in the low frequency monitoring 2000-01. Drainage, soil and bedrock groups are listed, as well as the model applied.

Catchment	Drainage	Soils	Bedrock	Predicted Annual TP Export Rates (kg ha^{-1} yr^{-1})	Model applied
Achryane	P	P	1	0.30	Model 6
Aillbrak	P	NP	1	0.37	Model 6
Ballydoolavan	P	NP	1	0.17	Model 6
Ballyeighter	W	NP	3	-0.28	Model 3
Ballyteige	W	NP	3	0.27	Model 3
Black	P	NP	1	0.37	Model 6
Black-dro	M	NP	3	0.74	Model 5
Bridget	M	NP	1	0.13	Model 5
Bunny	W	NP	3	0.47	Model 3
Caum	P	NP	1	0.27	Model 6
Curtins	P	NP	1	0.58	Model 6
Dromoland	W	NP	3	0.56	Model 3
Drumcullaun	P	NP	1	0.24	Model 6
Druminure	P	NP	1	-0.08	Model 6
Eanagh	P	NP	1	0.15	Model 6
Effernan	M	NP	1	0.25	Model 5
Farrihy	P	NP	1	0.14	Model 6
Finn	M	NP	3	0.17	Model 5
Garvillaun	P	NP	1	0.32	Model 6
Gash	W	NP	3	0.14	Model 3
George	W	NP	3	0.51	Model 3
Girroga	W	NP	3	0.36	Model 3
Goller	P	NP	1	0.04	Model 6
Gortaganniv	P	NP	1	0.20	Model 6
Gorteen	M	NP	4	-0.44	Model 5
Kilgory	M	NP	3	0.13	Model 5
Knockerra	M	NP	1	0.29	Model 5
Luirk	W	NP	3	1.62	Model 3
Luogh	P	P	1	-0.15	Model 6
Mooghna	P	NP	1	0.17	Model 6
More	P	NP	1	0.09	Model 6
Morgans	P	NP	1	0.28	Model 6
Muckinish	W	NP	3	1.76	Model 3
O'Briens Big Lough	W	NP	3	0.54	Model 3
O'Grady	M	NP	4	-0.19	Model 5
Rask	W	NP	3	1.48	Model 3
Rosconnell	P	NP	1	0.24	Model 6
Rushaun	P	NP	1	0.21	Model 6
Tullabrack	P	NP	1	0.26	Model 6

IV-3.5 GIS application

A map of annual average TP export rates into surface waters was derived for the whole county based on Model 1 (Table 4.16), using the *Spatial Analyst* extension of *ArcView 3.2* (Figure 4.13). This illustrated the potential use of GIS as part of the modelling process and catchment management decision-making process.

The new coverage was produced based on grid coverages of elevation (Elevation-Grid), slope (Slope-Grid) and soil P levels (SoilP-Grid) and on a grid coverage of soil P desorption index (PDesInd-Grid) derived from the soil coverage. A grid coverage of annual mean rainfall 2000-01 (Annual Mean Rainfall00-01-Grid) was derived from the interpolated surfaces of monthly rainfall for 2000 and 2001 (Chapter 2). A grid coverage of Mixed Grasslands (MixGrassland-Grid) was produced by converting the CORINE vector coverage into a grid, subsequently reclassified by indexing every land use classes by the value "0", except for Mixed grasslands, indexed by the value "1". The following map calculation based on Model 1 was applied to each cell of the grid coverages:

(Predicted annual TP export rates (kg P ha^{-1} yr^{-1}))-Grid=

-0.002 * *Elevation-Grid* + 0.085 * *Slope-Grid* + 0.055 * *SoilP-Grid* – 0.292 * *PDesInd-Grid* + 0.001 * *AnnualMeanRainfall00-01-Grid* + 0.004 * *MixGrass*-Grid - 0.914

Equation 4.13

Maps of annual average TP export rates into surface waters were also derived for areas in Clare underlain respectively by acidic or calcareous bedrock (Figures 4.14 and 4.15) applying respectively Models 2 and 3 (Table 4.16). The coverages Peatlands-Grid and MixAgri-Grid were derived from the CORINE coverage, following the same method than for mixed grasslands. Peats-Grid was derived form the soil coverage by indexing cells with the value "1" if associated with peat soils and "0" if associated with other soil types. The following map calculations were used:

(Predicted annual TP export rates (kg P ha^{-1} yr^{-1}))-Grid=

-0.002 * *Elevation-Grid* + 0.001 * *AnnualMeanRainfall00-01-Grid* – 0.260 * *PDesInd-Grid* – 0.003 * *Peatlands-Grid* – 0.316

Equation 4.14

(Predicted annual TP export rates (kg P ha^{-1} yr^{-1}))-Grid=

0.255 * *Slope-Grid* + 0.256 * *SoilMorP-Grid* + 0.007 * *MixGrass-Grid* – 0.012 * *MixAgri-Grid* + 0.006 * *Peats-Grid* – 2.077

Equation 4.15

Maps produced using Models 1, 2 and 3 are also available in the associated CD-Rom (Appendix 3/Models).

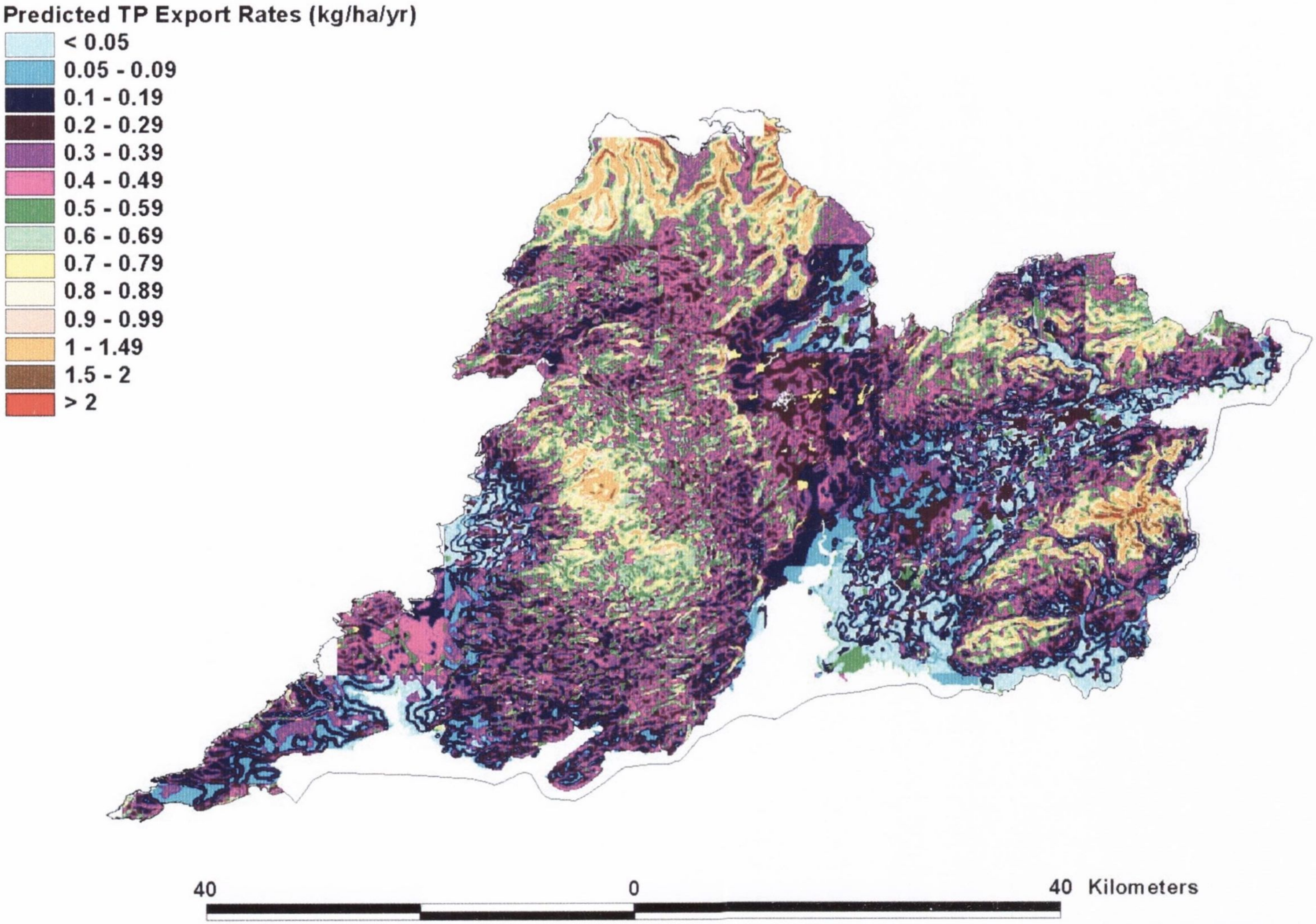

Figure 4.13: Spatial variation in predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) to surface waters in County Clare, based on the regression model 1. The grid-coverage was produced by applying the following map calculation: *(Predicted annual TP export rates (kg P* ha^{-1} yr^{-1}*))-Grid*= -0.002 * *Elevation-Grid* + 0.085 * *Slope-Grid* + 0.055 * *SoilP-Grid* – 0.292 * *PDesInd-Grid* + 0.001 * *AnnualMeanRainfall00-01-Grid* + 0.004 * *MixGrass*-Grid - 0.914.

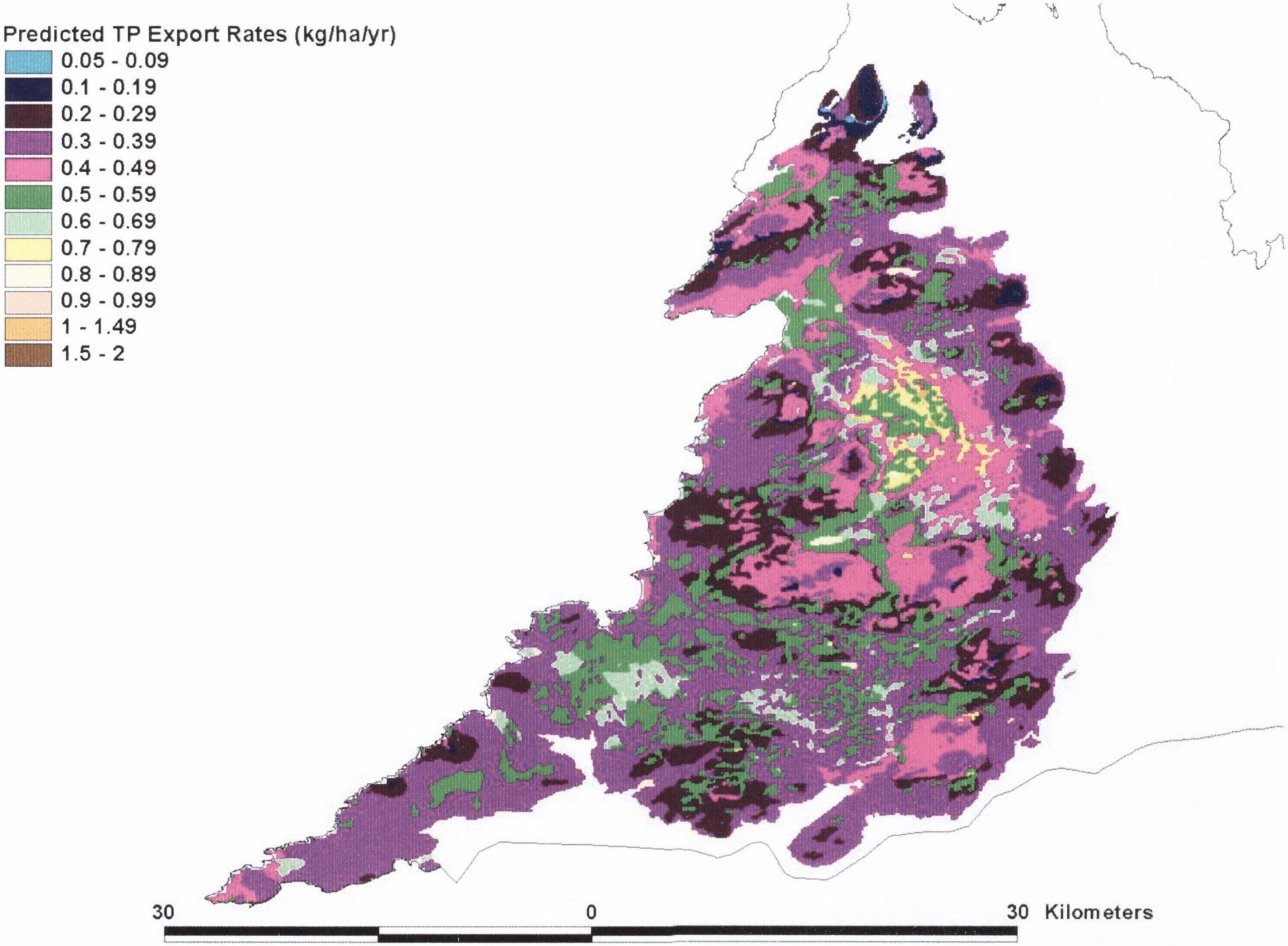

Figure 4.14: Spatial variation in predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) to surface waters in County Clare for areas of acidic-bedrock type, based on the regression model 2. The grid-coverage was produced by applying the following map calculation: *(Predicted annual TP export rates (kg P ha^{-1} yr^{-1}))-Grid*= -0.002 * *Elevation-Grid* + 0.001 * *AnnualMeanRainfall00-01-Grid* – 0.260 * *PDesInd-Grid* – 0.003 * *Peatlands-Grid* – 0.316.

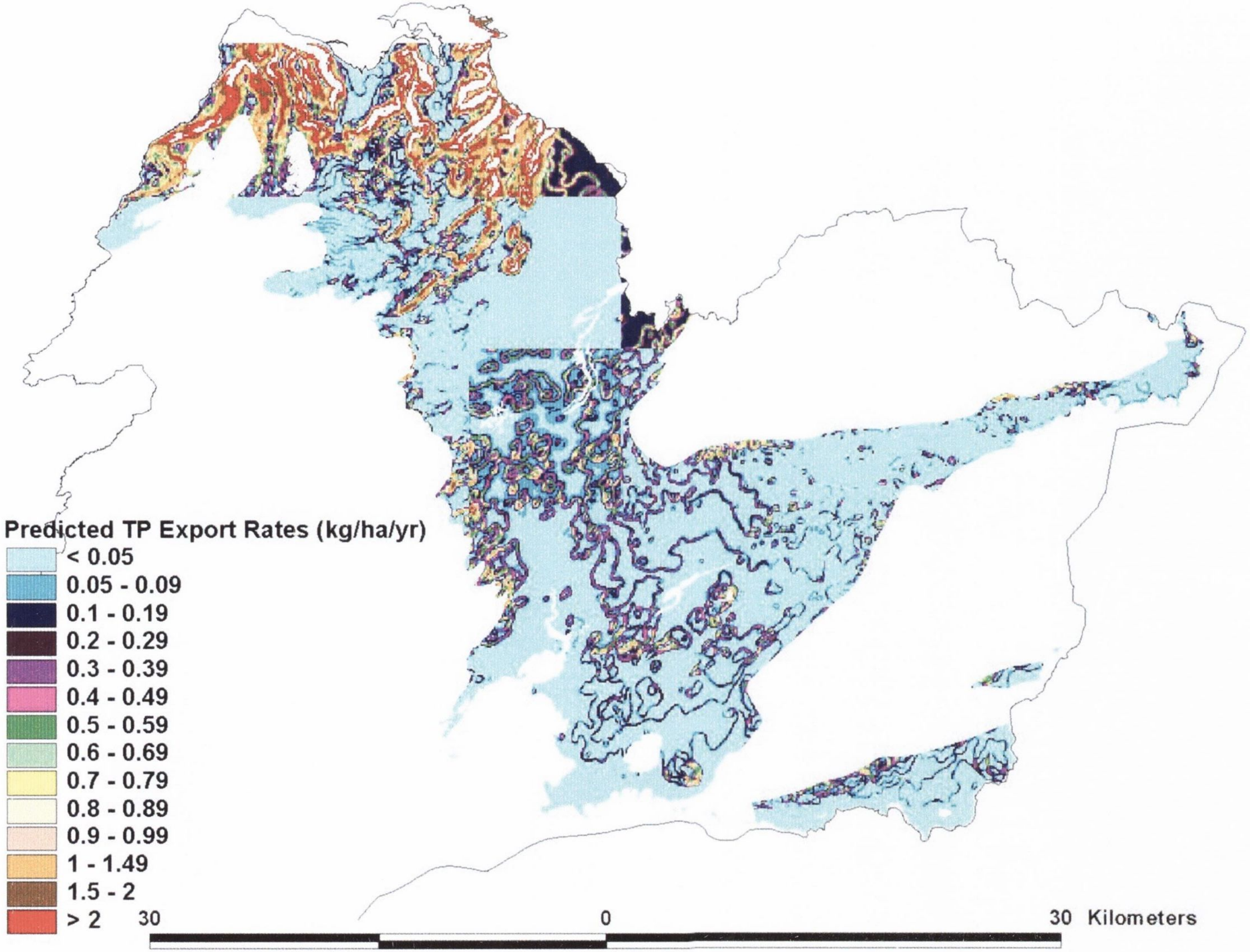

Figure 4.15: Spatial variation in predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) to surface waters in County Clare for areas of calcareous-bedrock type, based on the regression model 3. The grid-coverage was produced by applying the following map calculation: *(Predicted annual TP export rates (kg P* ha^{-1} yr^{-1}*))-Grid*= 0.255 * *Slope-Grid* + 0.256 * *SoilMorP-Grid* + 0.007 * *MixGrass-Grid* – 0.012 * *MixAgri-Grid* + 0.006 * *Peats-Grid* – 2.077..

When deriving the surfaces of predicted annual average TP export rates based on the empirical models, it appears that the predicted export rates could be influenced by the distribution of slope and soil Morgan P in the county, with maximum predicted export rates associated with steepest slopes and/or highest soil Morgan P levels. This could be explained by the fact that the models were derived from catchments with limited ranges of physical and climatic characteristics compared with the rest of the county (Table 4.19). Therefore the validity of the GIS-models may be limited and would require further validation for areas of the county with different ranges of parameters, especially for elevation, slope and soil Morgan P levels (Figures 4.16). Based on the model coefficients, slope and mean soil Morgan P are likely to be the predominant factors influencing the predicted export rates, especially for Model 1 (Figure 4.17) and Model 3 (Figure 4.18). However, for Model 2, any possible limitations (Figure 4.19) would be expected to be minor due to the low coefficients associated with elevation and mean annual rainfall.

The models may therefore require further validation for areas with steep slopes and high soil Morgan P levels, which are principally located in the North and East of the county.

Table 4.19: Comparison between the ranges of elevation, slope, soil Morgan P levels, soil P index and annual average rainfall 2000-01 calculated for County Clare and among the HFM-MFM catchments used to derive the empirical models. Ranges provided for County Clare were calculated from the values associated with each cell of the different grid-coverages. Ranges provided for the HFM-MFM catchments relate to the mean values of each variable in the catchments used to derive the models.

	Elevation (m)	Slope (degree)	Mean soil P (mg P l^{-1}),	Soil P Index	Annual Rainfall 2000-01 (mm)
HFM-MFM Catchments	14 - 203	0 - 5	4.7 - 8.8	1.0 - 1.9	1064 - 1481
County Clare	0 - 526	0 - 31	4 - 16	1.0 - 1.9	1024 - 1583

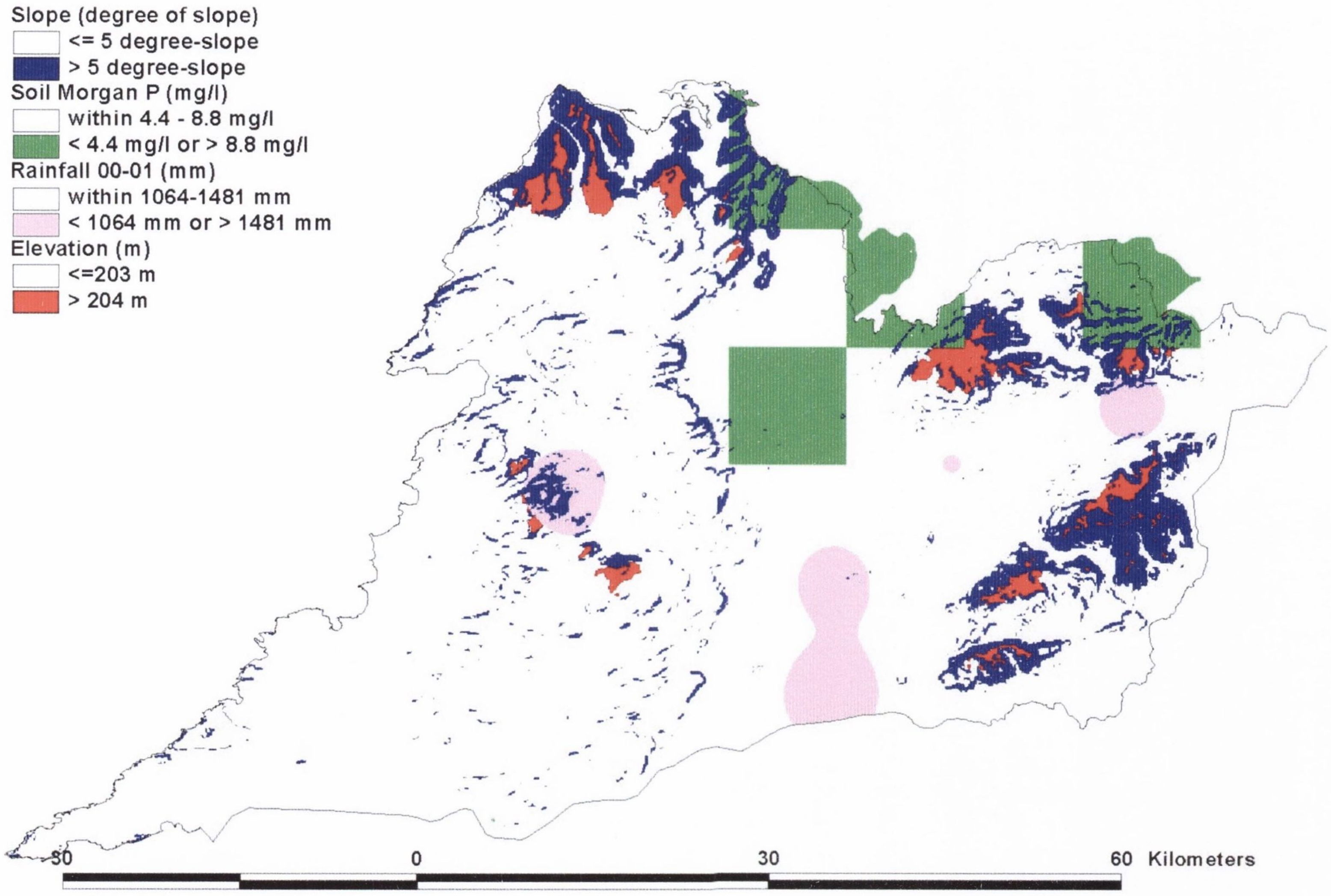

Figure 4.16: Areas of County Clare with physical and climatic variables (e.g. elevation, slope, soil Morgan P levels and annual mean rainfall 2000-01) outside the ranges of means observed for the thirty HFM-MFM catchments used to derive the empirical models predicting annual average TP export rates.

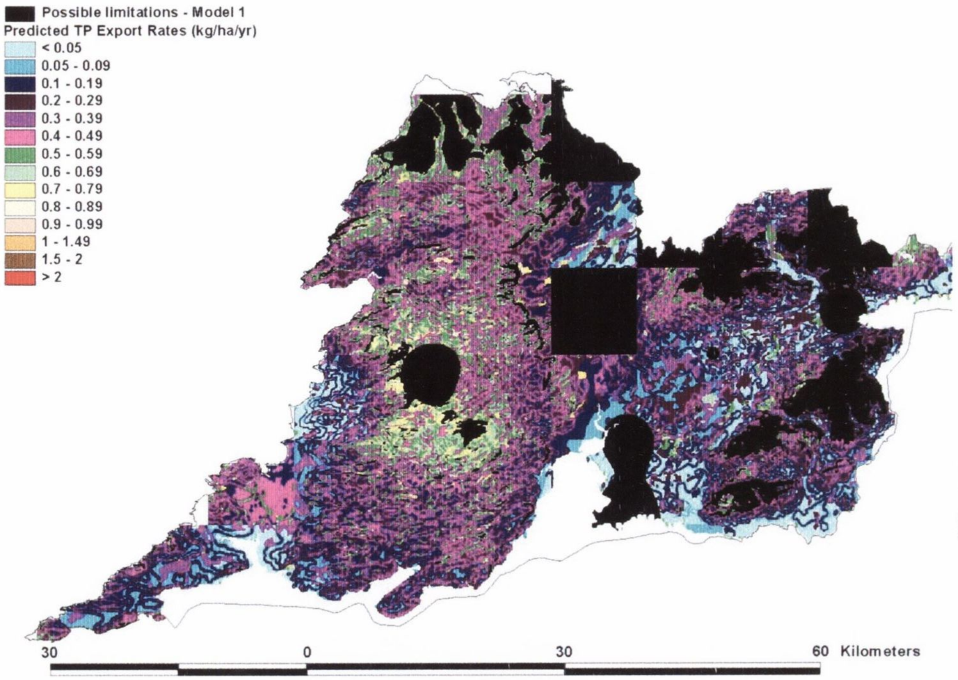

Figure 4.17: Predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) for the whole of Co. Clare derived using Model 1. Areas where the model could be of limited use and requires further validation are highlighted in black.

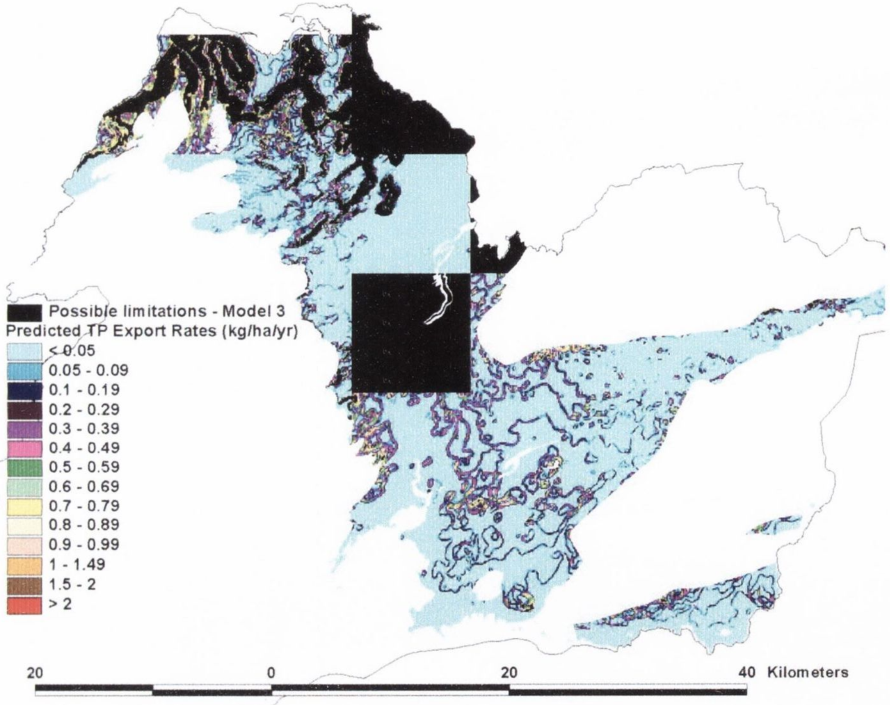

Figure 4.18: Predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) for areas of Co. Clare lying on calcareous bedrock derived using Model 3. Areas where the model could be of limited use and requires further validation are highlighted in black.

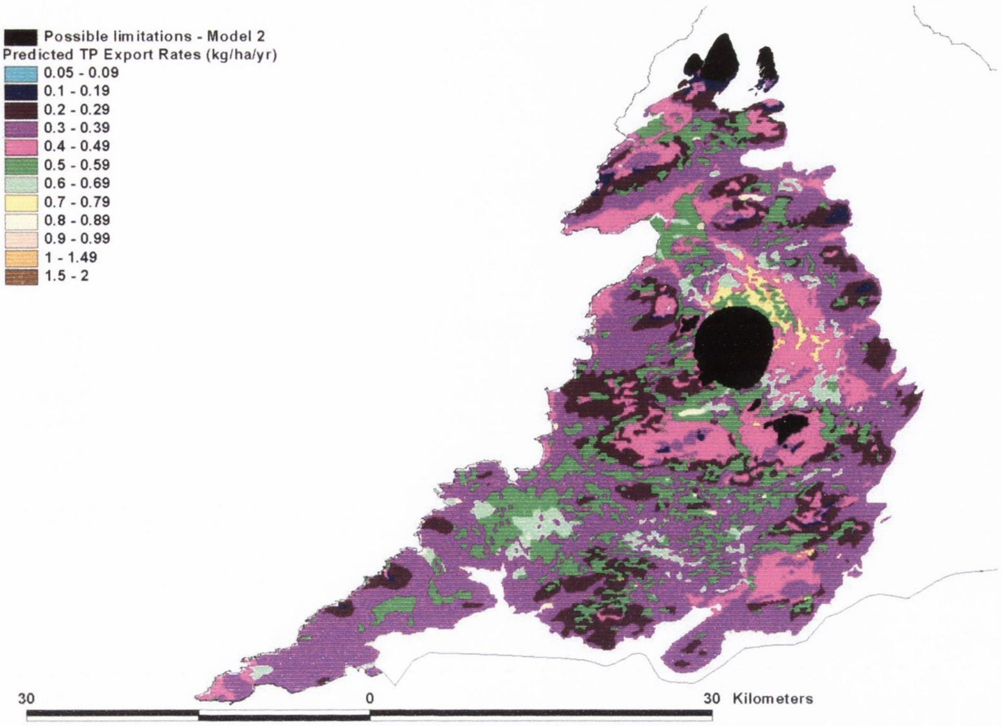

Figure 4.19: Predicted annual average TP export rates (kg P ha^{-1} yr^{-1}) for areas of Co. Clare lying on acidic bedrock derived using Model 2. Areas where the model could be of limited use and requires further validation are highlighted in black.

IV-4 Discussion

In this chapter, relationships between catchment descriptive variables (Chapter 2), with an emphasis on land use (CORINE land covers and agricultural land use from CSO), and lake water chemistry from the monitoring carried out seasonally on thirty lakes in County Clare in 2000-01 (Chapter 3) were assessed. Existing mathematical models predicting annual average TP export rates were applied and empirical relationships were derived from the various datasets. The influence of catchment bedrock, soil and drainage characteristics was also assessed.

Relationships between catchment land use and lake water chemistry

Relationships observed between lake water chemistry and catchment land use supported those observed in Chapters 2 and 3 between catchment hydro-physical variables and lake water chemistry outlining interrelationships among the different catchment descriptive variables. The hydro-physical environment is likely to influence catchment management practices and, thus, lake water quality.

Measures of lake acid state, such as pH and alkalinity, were correlated with the occurrence of peatlands and conifers in the catchments. In Chapter 3, it was found that alkaline lakes were usually associated with calcareous bedrock, while more acidic waters were found on acidic bedrock.

Peatlands and conifers were also usually associated with acidic bedrock. In the 1990s, there were a number of studies related to the influence of forestry on water quality. Allott *et al* (1990) examined the influence of closed canopy plantation forests on surface water chemistry in Connemara and South Mayo. The study concluded that afforestation increased acidity, aluminium and dissolved organic matter in these poorly buffered catchments. Bowman (1991) observed increased acidity in run-off from extensive coniferous forests on soils of poor buffering capacity. Acid-sensitive areas were identified, characterised by rain-fed peat soils with high concentrations of organic acids. However, Ryan and Farrell (1998) outlined that the exact role of organic acids in surface water acidification had yet to be resolved. Increased acid deposition and greater rates of evapotranspiration associated with coniferous forests (Blackie and Newson, 1986; Johnson, 1998) decrease total runoff and, hence, pH in areas with base-poor soils and bedrock (Bird *et al*, 1990; Allott *et al*, 1997; Kelly-Quinn *et al*, 1997; Tervet, 2001). Bowman (1991) found that naturally occurring acid-sensitive waters were located mainly in areas with granite, shale, gneiss and sandstone bedrock, because of poor buffering capacity of the acid soils (including peats) in the catchment.

Lake colour was also positively associated with peatlands in the catchments. In Chapter 3, it was observed that lakes lying on acidic bedrock were usually associated with more acidic and coloured waters, than those lying on calcareous bedrock. Colour results from the presence of humic and fulvic acids, derived from incomplete microbial degradation of organic material. Several studies have shown that peatlands release more colour than other land classes (Urban *et al*, 1989; Free, 2002; Kortelainen, 1993; Rasmussen *et al*, 1989).

In this study, areas covered with broadleaf forests and mixed grasslands for calcareous catchments and with unimproved grasslands for acidic catchments were associated with greater annual average TP export rates. It would be expected to observe lower TP exports associated with broadleaf forests as forested ecosystems conserve phosphorus and P exports from non-fertilised forested catchments are usually lower than those observed for other land uses (Dillon and Kirchner, 1975; Wendt and Corey, 1980; Leinweber *et al*, 1999). In the models developed by Johnes (Johnes *et al*, 1994, 1996 & 1998) and Jordan (Jordan *et al*, 2000), export coefficients associated with broadleaf forests are among the lowest. Riparian forests can intercept a significant proportion of nutrients moving towards streams (Cooper *et al*, 1987; Griffiths *et al*, 1997). However, Norton and Fisher (2000) found that while forests located away from streams in the Delmarva Peninsula (USA) could act as sink for nutrients, those located closest to streams could act as a TP source. In addition, export from forests depends greatly on management practices and forestation stages. Greater exports are to be expected during establishment and deforestation and also following fertiliser applications (Hobbie and Lickens, 1973; Allott *et al*, 1998; Nisbet, 2001). In this study, the positive correlation between broadleaf forests and TP export rates among the thirty catchments could be partly explained by greater soil Morgan P levels associated with the areas covered by broadleaf forests and likely to be influencing the relationship with TP export rates.

Many studies have reported increased diffuse phosphorus loss with increased percentage of agricultural land (Truman *et al*, 1993; Sharpley and Rekolainen, 1997; Allott *et al*, 1998). In Ireland, the major diffuse phosphorus loss to surface waters is from grasslands (Tunney, 1997). Foy *et al* (1994) showed that silage making could increase nutrient losses to surface waters. In general increased use of fertilisers, organic manures or animal wastes increases phosphorus losses (Lennox *et al*, 1997; Haygarth and Jarvis, 1999; Leinweber *et al*, 1999; Heathwaite and Dils, 2000). Daly *et al* (2000) showed that for wet soils, low MRP concentrations in streams were associated with semi-natural areas and peatlands. Soils with high % OM are usually associated with lower P desorption levels which could be explained by low P levels and biological immobilisation and stabilisation by humic substances. If not fertilised (chemical or organic), they are less likely to lose P to waters than dry soils (Daly, 2000).

In this study, no relationships were observed with average cattle density. However, previous work associated the decline in surface water quality in Ireland and Northern Ireland with areas of intensive cattle farming (Allott *et al*, 1998; Foy and Withers, 1995). The lack of relationship between TP export rates and cattle density could partly be explained by the small range of cattle densities among the catchments included in this study, with only 8 catchments recording cattle densities greater than 1.1 cattle ha^{-1}, but also by the influence of soil type and characteristics on the dynamics of P losses to surface waters. It also could result from the lack of accuracy of agricultural land use data from the CSO. As previously stated in Chapter 2, agricultural data were provided on a DED-basis. Catchment land use datasets were estimated, assuming the equal spatial distribution in land use and livestock density within DED but also within catchments.

Calculated annual average export rates in County Clare

Most catchments included in this study would require an important reduction in the current annual TP loadings in order to improve lake water quality. Annual average TP export rates estimated for the thirty catchments monitored seasonally in County Clare in 2000-01 ranged between 0.04 kg P ha^{-1} yr^{-1} for Lough Ballycar and 0.76 kg P ha^{-1} yr^{-1} for Lough Ballybeg. These values are comparable with TP export rates found by Free (2002) in 31 catchments across Ireland, ranging between 0.00 kg P TP ha^{-1} yr^{-1} for Loughs Maumwee (Co. Galway) and Talt (Co. Sligo) and 0.76 kg P ha^{-1} yr^{-1} for Lough Mullagh (Co. Cavan), except for Lough Egish (Co. Monaghan), which was almost certainly affected by point sources and had an estimated TP export rate of 3.33 kg P ha^{-1} yr^{-1}. No significant differences were found between export rates calculated in calcareous and acidic catchments, or between catchments with well, moderately or poorly drained soils. TP export rates from non-peaty catchments were found to be significantly greater than those from peaty catchments.

Based on their predominant type of land covers and agricultural land uses, TP exports would be expected to be much higher in catchments, such as Loughs Muckanagh, Cullaun and Ballycar. With pasture comprising, respectively, 65%, 54% and 69% of their catchment area and cattle densities estimated at 1.0, 0.9 and 1.5 cattle ha^{-1}, Loughs Muckanagh, Cullaun and Ballycar had very low calculated annual average TP export rates, with 0.07, 0.08 and 0.04 kg P ha^{-1} yr^{-1}. High flushing from groundwater together with chemical precipitation of phosphorus with carbonate complexes may therefore provide an effective buffering against nutrient enrichment. Because phosphorus often limits summer phytoplankton growth, any reaction that removes dissolved phosphorus from the lake water can be important for reduction in algal growth. Similar processes are likely to be occurring in Loughs Bunny, Ballyeighter, Dromoland and Girroga, which recorded very low chlorophyll-*a* ($\leq$ 5.4 μg l^{-1}) and TP ($\leq$ 12.1 μg l^{-1}) summer concentrations.

Mathematical modelling

Numerous mathematical models have been developed to predict TP export rates. Increasingly they have an integrated GIS-approach, but usually require the input of extensive datasets on catchment descriptive variables in order to work accurately. A simpler approach, in terms of data requirement and calculations, is to apply nutrient export coefficient modelling.

Two models, described by Jordan *et al* (2000) and Johnes *et al* (1994, 1996, 1998) were applied to the thirty catchments monitored seasonally between 2000-01. Predicted annual TP export rates were then compared with calculated values from the monitoring. Both models tended to overestimate the export rates. Free (2002) observed the same pattern when applying both models in his study on lake water chemistry in thirty-one lakes in Ireland between 1996 and 1997. One possible explanation for the differences between calculated and predicted export rates could be that calculated export rates rely on estimates of annual average TP exports from the monitoring 2000-01, based on the Foy's (1992) equation and estimates of run-off and flushing rates. Another explanation may be that the proximity of land use to surface waters should have been accounted for, particularly for catchments with impermeable bedrock, with the inclusion of a riparian zone associated with greater TP export rates, as described by Johnes and Heathwaite (1997). In addition, catchments included in this study had low to moderate agricultural intensity and, overall, low to moderate soil P levels ranging between 4 and 9 mg P l^{-1}. This may not be representative of the intensity of agriculture and soil P of the catchments used to develop the models in Northern Ireland (Jordan *et al*, 2000) and in England and Wales (Johnes *et al*, 1994). Finally, model development may have been based on lakes with greater in-lake TP concentrations than those used in this study (2000-01 range mean TP concentrations: 8-79 μg l^{-1}).

The influence of upstream water on the annual average P export rate was assessed by using Jordan's model with or without including the negative coefficient for upstream lakes (-6.57 kg P ha^{-1} yr^{-1}) (previously referred as *Jordan-1* and *Jordan-2*). Usually the difference between predicted and observed were less when using the *Jordan-1* model, implying that upstream lakes were sinks for nutrients. However, for three lakes: Loughs Ballyallia, Dromore and Ballybeg, predicted values using *Jordan-2* model were closer to the calculated values. These lakes are underlain by calcareous permeable bedrock and underground groundwater connection, with, almost certainly, groundwater and upstream lakes affecting lake water quality.

No significant correlations were found between predicted and calculated export rates, even when differentiating catchment types. A significant multiple linear regression model between calculated and predicted export rates using the Jordan model was based on mean elevation (-), mean slope (+) and rainfall (+). Significant correlations were found between the "new predicted" export rates (i.e. applying the multiple linear regression model) and the calculated values. This suggests that export coefficient approach should take into account catchment hydromorphology. More studies would be required to develop suitable coefficients for all land classes, differentiating catchment types.

If nutrient export coefficient modelling is to be of value in widespread lake monitoring programmes, it will require more development and calibration studies. Both models (Johnes and Jordan) were applied at the sub-catchment scale in an attempt to predict annual average TP export rates to surface waters within Lough Lickeen catchment, which could be described as a lowland acidic catchment, covered by poorly-drained soils. Specific coefficients were also derived for the different land uses based on catchment land uses and intensive monitoring in 2002-03. These are explained fully in Chapter 5.

It is likely that significant correlations between predicted and calculated TP export rate values would have been obtained if the statistical analyses had been carried out on TP loadings (kg P yr^{-1}) instead of loading rates (kg P ha^{-1} yr^{-1}). However, it was decided to standardise for catchment size using area-weighted measures of TP exports. There are a number of other factors that might impinge upon the strength of the models. Reduced accuracy and correlation with calculated export rates of the mathematical models could also result from agricultural land use data from the CSO and because datasets from CORINE were derived from satellite imagery taken in 1989/90. Even if updated by the forestry data from 1998 (FIPS, 1998), derived datasets might not truly represent the land cover distribution in 2000/01. Catchment boundaries were derived from the topography and might not account for groundwater influence for the calcareous catchments. This would not affect land cover distribution but would impact on hydrological variables such as flushing rate and retention time. Finally, calculated export rates were obtained based on estimates of lake flushing rate and retention time, which depend on drainage area and rainfall.

Deriving empirical modelling

Empirical relationships predicting annual average TP export rates to surface waters were derived at different levels, looking at all thirty catchments seasonally monitored in 2000-01 and then differentiating them among main catchment groups, based on predominant bedrock types (acidic/calcareous), soil properties (peaty/non-peaty) and drainage characteristics (well/moderately/poorly-drained soils). Overall, the accuracy and predictive power of the six derived models were good, with $R^2 \geq 0.67$ and increased when differentiating the catchments into different types. For all six models, the predominant factors influencing annual average TP export rates were the catchment slope (+), soil P levels (+) and desorption index (-).

Soil P desorption index was the predominant factor in four of the models and was associated with a negative coefficient. Another recurring factor was soil Morgan P levels, associated with a positive coefficient in four of the models. Among the study catchments, soils with lower soil P desorption index (e.g. peat soils) were more likely to lose P than soils with higher desorption index (i.e. brown earths, podzolics, grey brown podzolics). Daly (2000) identified soils vulnerable to P loss by desorption as soils having elevated soil P levels and low P sorption capacities. In the different models in this study, TP export rates increased with slope. Steep topography is usually more prone to erosive losses of P to surface waters through runoff. Slope length and angle increase phosphorus in runoff (Johnes, 1994). Ahuja *et al* (1982) associated increased P concentration with slope length with an increase of P sorbed per unit area.

Peatlands were associated with negative coefficients in the models derived for acidic and poorly drained catchments, while associated with a positive coefficient for moderately drained catchments. % Peat soils had also a positive coefficient for calcareous catchments. As peatlands are usually associated with soils having low capacity for storing P (e.g. Peats) and usually prone to overland flow, owing to poor infiltration, it is not easily explained how peatlands could act as sink for P among acidic and poorly drained catchments. In wet soils, P can be immobilised with iron and manganese colloidal complexes, rendering it unavailable to plants and hence less mobile (Khalid *et al*, 1977). Peat soils have a high organic matter content, which can immobilise inorganic P, while humic substances stabilise organic P (Harrison, 1987; Daly, 2000), but also low sorption capacity (less Al and Fe binding sites). One possible explanation of the difference observed for peatlands between acidic and calcareous catchments could reside in the difference observed in soil P levels among these two catchment groups, with significantly greater soil Morgan P levels (two- sample t-test, $\alpha=0.05$, $p<0.01$) observed for calcareous catchments. Other factors contributing to annual average TP export rates were identified as rainfall input, mixed and unimproved grasslands, while elevation had a negative effect.

Overall conclusion

An important aim of modelling is to derive empirical or mathematical relationships which could be applied widely in different catchments. This would reduce the need for intensive monitoring of water quality. In this chapter, relationships between catchment agricultural land uses and annual TP export rates were identified. Soil hydrology, P content and desorption properties and impact of varying physical environments were shown to be important in controlling P losses to surface waters. This study has shown that general modelling should account for difference in catchment types. Empirical relationships were derived for the different groups of catchment types. Strong correlations were obtained between predicted and calculated values for the regression models. However, the validity and usefulness of these models would have to be verified by applying them to other catchments, presenting similar lake types, but with different agricultural management practices. Based on the empirical models developed in this chapter, maps of predicted annual average TP export rates were produced using GIS for the whole of the county, and for separately areas of the county lying on calcareous and acidic bedrock. As these models were derived for a limited range of catchment physical and climatic characteristics, their extrapolation to areas with different characteristics may be of limited applicability and would require further validation. When extrapolating the models to the whole of the County (Model 1) and also to areas of the county lying on calcareous bedrock (Model 3), it appeared likely that predicted values of annual average TP export rates associated with areas of steepest slopes and highest soil Morgan P levels were influenced by the terms relating to the slope and soil Morgan P levels. However, it would be worthwhile further testing the model predictions in such areas.

In order for a modelling approach to be successful and of value for the Water Framework Directive (2000/60/EEC), it would require a better data management system in Ireland (e.g. more effective and accurate co-ordination and data management systems). Modelling should also account for catchment types and allow for spatial variation within catchment (e.g. concepts of variable source areas and riparian zones). There is currently a need to assess, and maybe further develop, existing modelling approaches, rather than deriving new models. GIS is important for the modelling process, in particular for data management, spatial analysis, extrapolating models to other and wider geographical areas to produce maps showing risk of P loss to surface waters. It could also constitute a decisive tool in catchment management and decision making process.

In this section, the modelling approach was carried out at the catchment level. In the following chapter, relationships between catchment land uses and lake nutrient status will be assessed for a particular type of catchment in Lough Lickeen, accounting for spatial variation within the catchment.