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

Volume II of II

By

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

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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

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V-1 INTRODUCTION

Lough Lickeen (Figure 5.1) is located in the northwest of County Clare (52°57'49'' north; 09°13'41'' west). The lake has high amenity value, particularly for angling, and is the main source of water supply for the northwest of the county. Located on lowlands, the catchment of the lake is on shales bedrock and is covered mainly by gley and peat soils.

The predominant land use classes are grasslands, peatlands and coniferous forests (CORINE database, 1989/90; NFS, 1998). Previous studies (Lucey *et al*, 1999; Irvine *et al*, 2001) showed a decline in the lake water quality, classifying Lough Lickeen as eutrophic. The lake was included in the monitoring programme carried out on the major lakes of the county from March 2000 until October 2001, recording a maximum chlorophyll-*a* concentration of 49.0 μg l^{-1} and mean TP concentration of 21.5 μg l^{-1} during that period (See Chapter 3).

Figure 5.1: Location of Lough Lickeen catchment (Co. Clare, Ireland)

Lough Lickeen catchment (Figure 5.2) was more intensively monitored between February 2002 and March 2003. This "localised risk" study provided estimates of nutrient loadings from different land use types. The validation of relationships between pressures from catchment activities with impacts on water ecological quality is important for the implementation of the Water Framework Directive (2000/60/EEC).

The use of nutrient export models can be of value in evaluating diffuse nutrient sources from catchments to lakes. It can also provide an insight into classifying the sources of nutrients in terms of risk of nutrient loadings to the lake. However, such an approach considers the catchment as a whole entity and does not account for catchment processes and impact of the spatial distribution of land use on nutrient losses.

Figure 5.2: Aerial photography of Lough Lickeen catchment (2000), also showing the catchment boundary (red line).

Studies (Irvine *et al*, 2001) aiming at applying nutrient export coefficients from the literature to Irish lakes showed a usefulness of simple models for identifying trends of in-lake phosphorus concentrations but of low predicative ability to quantify concentrations. In order to be of value for lake monitoring programmes in Ireland, such models will require intensive calibration.

Studies in catchments with impermeable bedrock type, where hydrological pathways are dominated with surface and shallow subsurface flow, have shown the importance of incorporating a distance-decay component in the export coefficient (Johnes and Heathwaite, 1997). Heathwaite *et al* (2000) found that areas most vulnerable to P losses were limited to small, well-defined areas of the sub-catchment near the stream channel, while larger areas contributed to nitrate leaching. Semi-natural areas and peatlands are usually associated with peat and peaty gley soils. These soils have a low capacity for storing P and usually generate overland flow because of poor infiltration. If located near a stream or river, their contribution to overland flow into water surface network can be significant (Daly *et al*, 2000). In Ireland, owing to high summer precipitation, P transport to streams occurs all year. Spreading of P fertilisers on saturated soils is highly susceptible to loss to streams (Morgan *et al*, 2000). Estimated P area export rates are, furthermore, strongly influenced by hydrology and management (Kurz, 2000).

The study of Lough Lickeen catchment aimed to:

- identify and assess impacts of potential nutrient sources to the drainage system and to the lake by dividing the catchment into spatially defined risk areas;
- link catchment management and nutrient loading dynamics for a specific type of catchment;
- test and calibrate mathematical models predicting nutrient export dynamics;
- produce a risk assessment map of risk areas within the catchment using GIS; and
- recommend sustainable catchment management options.

V-2 MATERIALS AND METHODS

V-2.1 Catchment descriptive variables

Physical (topography, slope, geology, soil types), hydrological (stream network, aquifers, rainfall) characteristics and land use of the catchment were extracted from the GIS databases collated for the whole of County Clare, as described in Chapter 2.

In Chapter 2, catchment boundaries were derived from the OSI 1:50,000 maps and manually digitised into the GIS database. A more accurate topographic coverage was obtained for Lough Lickeen catchment. Corrected digital elevation model (DEM) (Data courtesy, Paul Mills – Compass Informatics Ltd.) was used to compute more precisely the catchment boundary with the *Hydromodelling* extension of *ArcView 3.2* software. A DEM is a raster representation of a continuous surface, usually referring to the surface of the Earth. In order to compute sub-catchment delineation and stream network, the convergence of flow across a natural terrain surface is modelled by deriving flow direction and flow accumulation grids from the DEM. Assumptions are made that if the surface contains sufficient vertical relief, a flow path can be determined and that water can flow in from many cells but out through only one cell. Flow across a surface will always be in the steepest down slope direction. Once the direction of flow out of each cell is known, it is possible to determine which and how many cells flow into any given cell. This information can be used to define sub-catchment boundaries and stream networks (ESRI, 1997; Jenson and Domingue, 1988; Mark, 1988; Shreve, 1966; Strahler, 1957; Tarboton *et al*, 1991).

Farm surveys (Ryan and Bugler, 1999) were available for the Lough Lickeen catchment but did not provide accurate data on livestock numbers or spatial distribution of land usages. More detailed surveys (associated CD-Rom: Appendix 4/Farm survey) were carried out in the catchment in March 2003, in order to obtain more comprehensive information on farmland usages, cattle numbers, and farmyard practices. A total of twenty-nine farms and houses were surveyed. Land usages were identified for most of the field parcels in the catchment (85% of the total catchment field parcels area). A detailed coverage of the spatial distribution of the agricultural land use and related activities was built on the initial coverage of the field parcels (LPIS, 2000) from the Department of Agriculture. Potential overland run-off pathways from point sources of nutrients, such as septic tanks and farmyards were modelled with *Hydromodelling* extension of *ArcView 3.2*.

V-2.2 Monitoring Protocol 2002-03

Relationships between land use (agriculture land use, forestry and human population) and nutrient loadings were assessed for the different sub-catchments, categorised to represent zones of risk from point and diffuse nutrient sources. The catchment was divided into structural units based on physical features using GIS. Localised Risk Areas (LRAs) were identified based on the structural units, stream drainage basins and riparian zone around the lake (distance from the lake shore < 50 m). Application of nutrient export modelling estimated potential loads from each area. Identification of diffuse and point sources of nutrients was carried out with GIS, based on the CORINE coverage (1989/90) updated by the forestry data (NFS, 1998), Land Parcels Information System of the Department of Agriculture (2000) and detailed farm surveys. Validation of initial estimates of nutrient loading to surface waters involved soil and water monitoring between February 2002 and March 2003.

Catchment hydrology

The main lake represented less than 10% of the catchment area, while the two upstream lakes, Loughs Lickeen North-East and Ballard, accounted for <1%. Lough Lickeen had ten inflowing streams located mainly in the south and east of the catchment (Figure 5.3).

Daily and monthly rainfall data were obtained from the Met. Eireann weather station in Ennistymon. In addition, monthly potential evapotranspiration (PET) data, measured at the Shannon Airport weather station, were calculated. Monthly outflow discharge rate ($m^3\ s^{-1}$) were made available by the EPA (Data courtesy Michael McCartaigh and James Penny, EPA), and estimates of monthly outflow discharge (m^3) were estimated by:

$$\textbf{Monthly Outflow Discharge } (m^3) = \textbf{Discharge Rate } (m^3\ s^{-1}) * 86400 * n_{days}$$

Equation 5.1

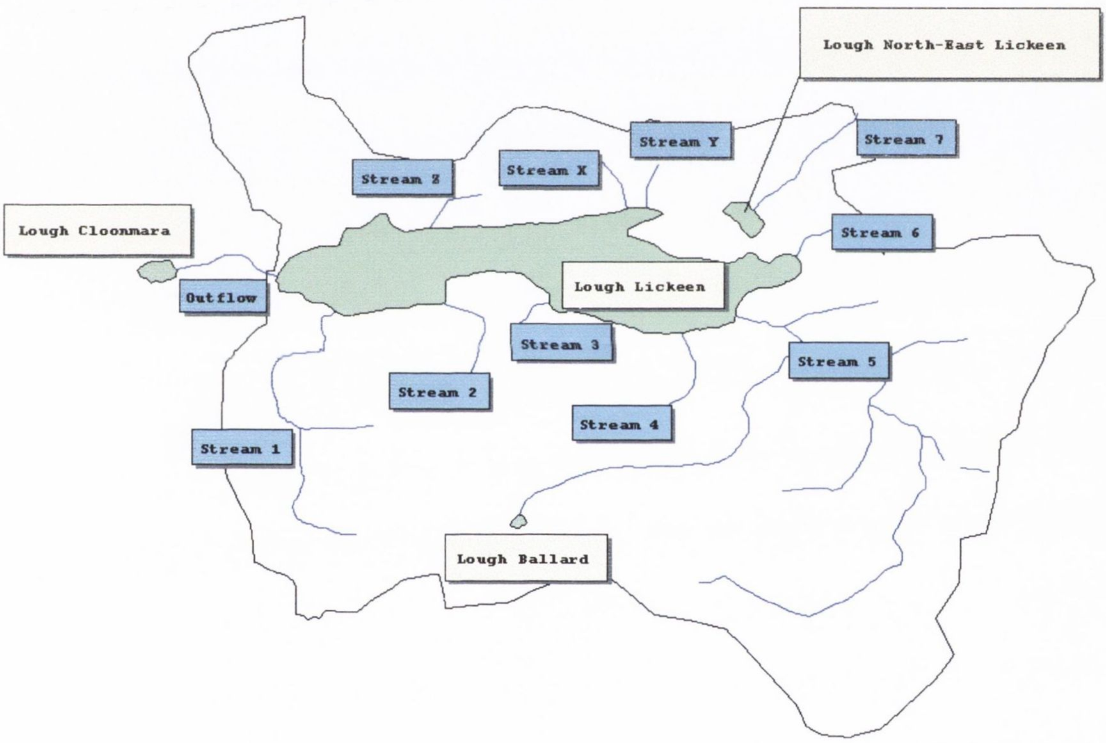

Figure 5.3: Identification of the stream network and lakes in the Lough Lickeen catchment

Estimates of annual and monthly run-offs (m^3) were made based on rainfall, PET and drainage area:

$$\textbf{Annual mean run-off } (m^3) = \textbf{(Annual mean rainfall-annual mean PET)(m)} * \textbf{Sub-catchment drainage area } (m^2)$$

Equation 5.2

Localised Risk Areas

Localised Risk Areas (LRA) were based on soil type (Gley soils (G) or Peat soils (P)) and topography (Topo 1: 0-100 m, Topo 2: 100-150 m; Topo 3: 150-175 m). A 50 m-buffer zone (corresponding to the riparian zone) around each lake was included as a separate zone. In total, fifty-two different risk areas were grouped into eight LRA categories (Table 5.1). This formed an initial categorisation of catchment attributes. The working hypothesis was that these areas represented separate categories of LRA.

Table 5-1: LRA type description

Soil Type	Elevation	Distance from Lakes	LRA Type
Gley	< 100 m	> 50 m	G-Topo1
Gley	100-150 m	> 50 m	G-Topo2
Gley	150-175 m	> 50 m	G-Topo3
Gley	< 100 m	< 50 m	G-Topo1-50m
Peat	< 100 m	> 50 m	P-Topo1
Peat	100-150 m	> 50 m	P-Topo2
Peat	150-175 m	> 50 m	P-Topo3
Peat	100-150 m	< 50 m	P-Topo2-50m

Using the CORINE land cover coverage, TP exports and export rates were estimated initially for each localised risk area, applying export coefficients used by Jordan *et al* (2000), as described in Table 2.4 (Figure 5.4). This indicated that greatest risks of TP export were within the 50m-buffer zone from the lakes, the northeastern part and west and south side of the catchment. The greater potential exports associated with the lake surroundings were explained by the land use distribution. In addition, as the catchment is lying on impermeable bedrock (shales and similar rock types), exports from the 50m-zone surrounding the lake are likely to have a greater effect on the overall nutrient loading into the lake than similar exports arising from areas outside the riparian zone.

Water Quality Monitoring

Initial identification of LRAs and their drainage network guided the choice of the monitoring. Overall, fifty-nine sites were monitored including thirty-nine sites on the inflowing streams; sixteen lake sites for Lough Lickeen and one site at each upstream lake. Lake samples were taken at each stream inlet and at five locations associated with LRA surrounding the lake where direct influence of a stream was unlikely. The outflow and downstream lake were also monitored (Figure 5.5). Samples were collected on a three-weekly basis from February 2002 until March 2003 (n=15 sampling occasions), following sampling and storage methods described in Chapter 3, with the exception that lake samples (shore and middle lake samples) were taken from a boat.

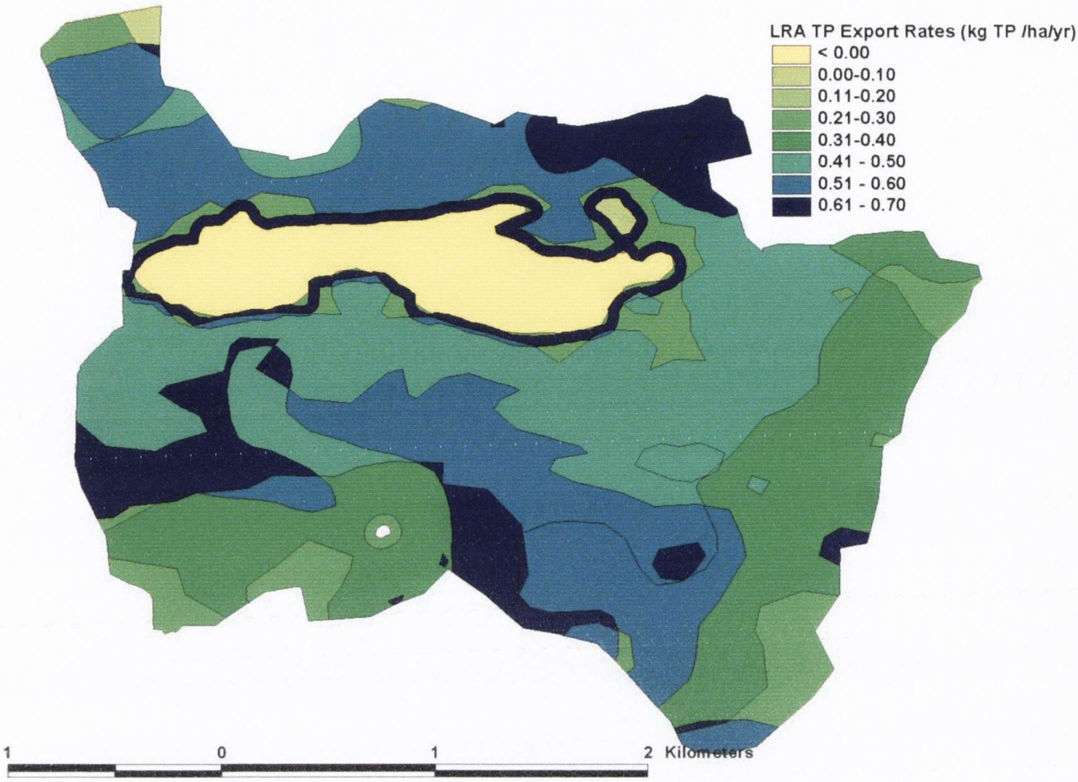

Figure 5.4: Preliminary assessment of TP export rates (kg P ha^{-1} yr^{-1}) in the Lough Lickeen catchment, applying the model described by Jordan *et al*, 2000.

Over the monitoring period February 2002-March 2003, the sampling protocol comprised three phases (Table 5.2). The initial phase (February 2002-May 2002, n= 4 sampling occasions) included 53 sites (14 lake sites, 38 stream sites and the outflow). Based on the results of this, the number of sites monitored was reduced using criteria of similar drainage basin characteristics and stream/lake water chemistry, estimated with PCA, cluster analysis using *Primer 5* and two samples t-test using *Data Desk.* The number of sites monitored was reduced to 42, including 31 stream sites, 10 lake sites and the outflow from Lough Lickeen. The revised monitoring was carried out on a three-weekly basis from June 2002 until March 2003. The monitoring protocol was further modified in September 2002, by including one stream that did not figure on the OSI map and was found on site (Stream Z), the lake located downstream (Lough Cloonmara) in order to evaluate its trophic status, and four middle lake samples (Lake Middle A, B, C and D) in order to assess variations observed in the chemistry of the lakeshore sites, bringing the number of sites monitored in the revised phase to 48 sites. GPS-location and map of sampling sites are provided in the associated CD-Rom (Appendix 4/LRA Monitoring protocol). The drainage basins of sampling stations were delineated based on the DEM of the catchment and using *Hydromodelling* extension of the *ArcView* software.

Table 5.2: Description of the discrete monitoring carried out in the Lough Lickeen catchment between February 2002 and March 2003. The type of monitoring carried out is listed for each sampling location (Full: February 02 – March 03; Reduced: February 02-May 02, showing associated sites with similar characteristics in brackets; Revised: September 02-March 03). Description of site surroundings (bedrock type, land cover and associated preliminary localised risk area class (LRA class), as described in Table 5.1), are also given.

Site Code	Monitoring Type	Bedrock Type	LRA Class	Surface Cover
Catchment Lake sites				
L1	Full	Water	Lake	Water
L2	Full	Water	Lake	Water
L3	Full	Water	Lake	Water
L4	Full	Water	Lake	Water
L5	Full	Water	Lake	Water
L6	Full	Water	Lake	Water
L7	Full	Water	Lake	Water
L8	Full	Water	Lake	Water
L9	Full	Water	Lake	Water
L10	Reduced (L14)	Water	Lake	Water
L11	Reduced (L14)	Water	Lake	Water
L12	Reduced (L14)	Water	Lake	Water
L13	Reduced (L14)	Water	Lake	Water
L14	Full	Water	Lake	Water
L. Middle A	Revised	Water	Lake	Water
L. Middle B	Revised	Water	Lake	Water
L. Middle C	Revised	Water	Lake	Water
L. Middle D	Revised	Water	Lake	Water
Stream sites				
1a	Full	GI	G-Topo1-50m	Low Productivity Grassland
1b	Reduced (1a)	GI	G-Topo1	Low Productivity Grassland
1c	Full	GI	G-Topo1	Mixed Grassland
1d	Full	GI	G-Topo2	Low Productivity Grassland
1e	Full	GI	G-Topo1	Low Productivity Grassland
1f*	Reduced	CCG	P-Topo2	Coniferous Forest
2a	Full	GI	G-Topo1-50m	Low Productivity Grassland
2b	Full	GI	G-Topo1	Low Productivity Grassland
3a	Full	GI	G-Topo1-50m	Low Productivity Grassland
3b	Full	GI	G-Topo1	Principally Agriculture
4a	Full	GI	G-Topo1-50m	Principally Agriculture
4b	Full	GI	G-Topo1	Broadleaf Forest
5a	Full	GI	G-Topo1-50m	Principally Agriculture
5b	Reduced (5a)	GI	G-Topo1	Principally Agriculture
5c	Reduced (5a)	GI	G-Topo1	Principally Agriculture
5d	Full	GI	G-Topo1	Principally Agriculture
5e	Full	CCG	G-Topo2	Low Productivity Grassland
5f	Full	CCG	P-Topo2	Coniferous Forest
5g	Full	GI	G-Topo1	Principally Agriculture
5h	Full	GI	G-Topo1	Coniferous Forest
5j	Full	GI	G-Topo1	Peat Bogs
5k	Reduced (5j)	GI	G-Topo1	Principally Agriculture
5l	Reduced (5j)	GI	P-Topo1	Principally Agriculture
5m	Full	GI	P-Topo1	Low Productivity Grassland
5n	Reduced (5m)	GI	P-Topo1	Low Productivity Grassland

Table 5.2 (continued)

Site Code	Monitoring Type	Bedrock Type	LRA Class	Surface Cover
5o	Full	GI	P-Topo1	Low Productivity Grassland
5p	Full	GI	P-Topo1	Coniferous Forest
5q	Full	CCG	P-Topo2	Low Productivity Grassland
5r	Full	GI	G-Topo1	Principally Agriculture
5s	Full	GI	P-Topo1	Principally Agriculture
5t	Full	GI	P-Topo1	Low Productivity Grassland
5u	Full	GI	G-Topo1	Low Productivity Grassland
6a	Full	GI	G-Topo1-50m	Low Productivity Grassland
6b	Full	GI	G-Topo1	Low Productivity Grassland
7a	Full	GI	G-Topo1	Low Productivity Grassland
7b	Full	GI	P-Topo1	Low Productivity Grassland
X**	Full	GI	G-Topo1	Low Productivity Grassland
Y**	Full	GI	G-Topo1	Low Productivity Grassland
Z**	Revised	GI	G-Topo1-50m	Low Productivity Grassland
Downstream sites				
Outflow	Full			
L. Cloonmora	Revised			

*: no access to stream, **: streams that were not featured on the OSI maps 1:50,000*

Based on the sampling sites and stream network, the catchment was divided into forty-seven sub-catchments, grouped into ten stream basins and six drainage basins of lake sampling sites. Descriptive variables were estimated for each sub-catchment.

Samples were processed as described in Chapter III, although ammonia and silicates concentrations were not determined. As well as determination of TP concentrations, P fractions in the samples were measured. Total dissolved phosphorus (TDP) and soluble reactive phosphorus (SRP) concentrations were determined on filtered samples (after acid persulphate digestion for the TDP determination) followed by reaction with molybdate and measured spectrophotometrically at 882 nm after colourimetric reaction with ascorbic acid (Eisenreich *et al*, 1975; Murphy and Riley, 1962). From September 2002, determinations of N fractions (NO_3-N and TN) were carried out by Flow Injection Analysis using an Auto-analyser AA3 Braun-Luebbe (Braun and Luebbe GmbH, 2001). The analytical methods remained the same, than the ones used previously with the Tecator FIA.

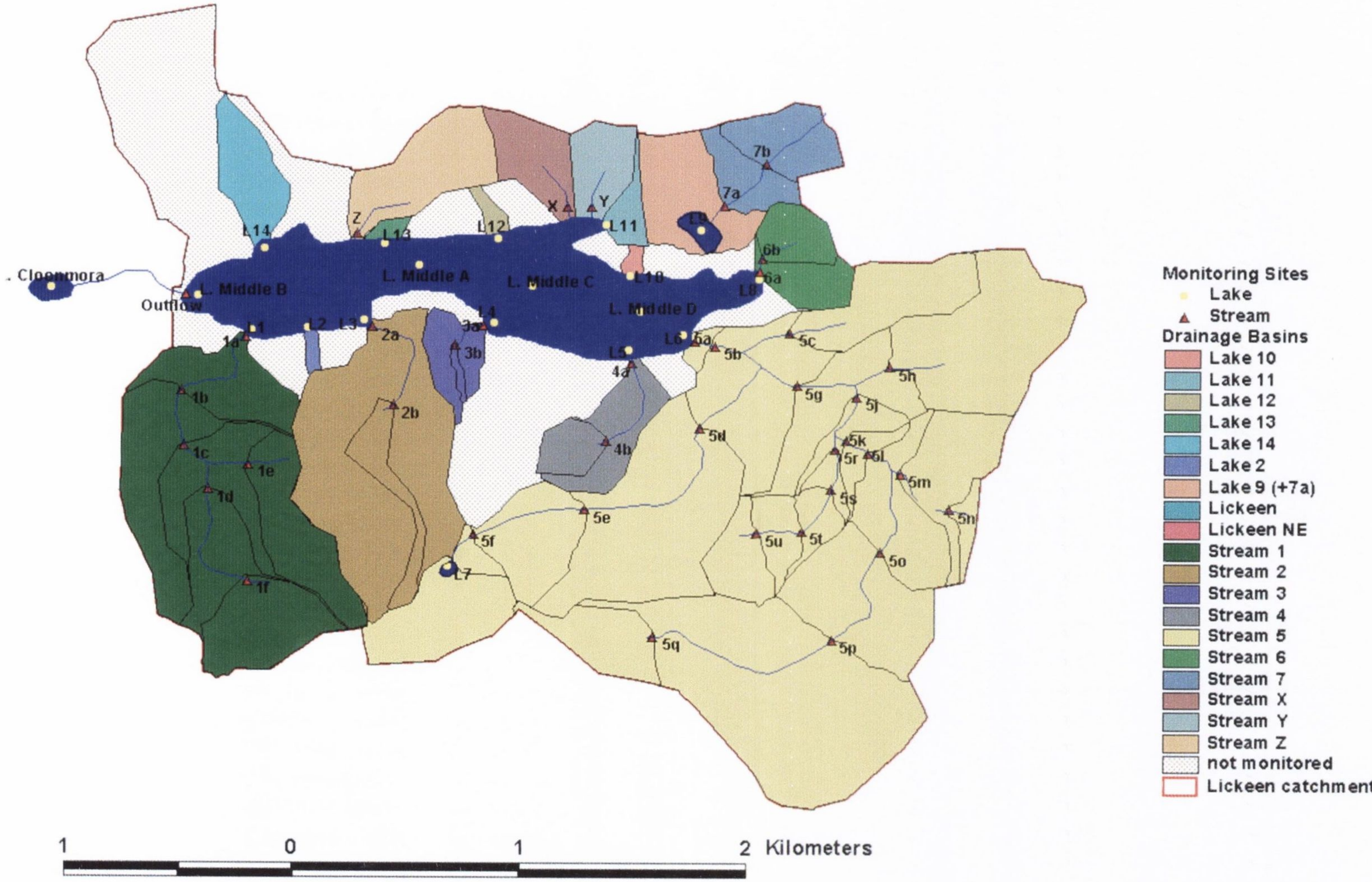

Figure 5.5: Location of the different sampling sites (●: lake site; ▲: stream site) monitored in the Lough Lickeen catchment between February 2002 and March 2003. Sub-catchments of inflowing streams are shown in different colours and sampling site sub-drainage basins are delineated with a black line.

Soil sampling

Soil samples were collected in late February (prior to spreading of manures and fertilisers), July and October 2002, in order to validate measures of soil Morgan P levels of each area; as this factor could be important when assessing the P exports and risk of soil P losses to water due to P desorption (Daly *et al*, 2002; Daly *et al*, 2000; Kurz, 2000). Soil samples were collected within 50 m of each sampling station (n=45 sites), as it was assumed that P losses from soils by run-off that were most likely to affect in-stream P levels, would arise from soils located in the proximity of the streams. To obtain a representative sample of the immediate site surroundings, 15 core samples were taken applying a "W" sampling pattern and combined in a composite sample. Soils were sampled to 10 cm (2.5 cm-diameter cores) (Teagasc, 1998; Daly, 2000). Samples were stored in closed plastic bags before being air-dried, sieved through a 2mm-mesh stainless sieve and stored in boxes at room temperature prior to analysis (Allen, 1989; Daly, 2000).

Phosphorus concentrations extracted from soil to solution were measured using a modified Murphy and Riley (1962) molybdate method, referred to as "ascorbic acid method". Readily desorbable P was determined using measurements of water extractable P, expressed as total and soluble P. After extraction with distilled water, the solutions were centrifuged and filtered, and P concentrations were determined using the ascorbic acid method and measured spectrophotometrically at 880 nm, with a Shimadzu UV-1601 spectrophotometer (Van der Paauw, 1971; Daly, 2000). Plant available P was estimated using the agronomic test for P (Morgan's P) according to standard Teagasc procedure, as described by Daly (2000). Soil Morgan's P levels were determined by colourimetry after extraction with glacial acetic acid.

The non-phosphorus soil parameters (pH, % organic matter, % carbonates content and exchangeable iron (Fe)) were measured once on the samples collected in October 2002. Soil pH was measured on a mixture of soil/distilled water, with a ratio of 1:2.5, using a Jenway 3030 pH-meter, with a Reagecon combination pH electrode (GCF11) (Daly, 2000). An approximate measure of the organic content of the soil samples was obtained by 'loss-on-ignition' (Allen, 1989). A further ignition of the samples at a temperature of 1000 °C was then used to approximate carbonate content of the soil. Using ammonium oxalate extractant, soil extractable Fe was determined by atomic absorption spectrophotometry using a Perkin-Elmer AA3-3100 Atomic Absorption Spectrophotometer (Perkin-Elmer, 1982; Freeze *et al*, 1992; Daly, 2000).

V-2.3 Data analysis

Monitoring data

Variations in stream water chemistry variables over the monitoring period were assessed statistically using correlations, principal component and cluster analyses and M-ANOVA. For analysis, some variables were transformed in order to stabilise the dataset variance. However, it was not possible to normalise all datasets, owing to their skewed distribution, and relationships were therefore assessed using Spearman's Rank correlations. Comparisons were made between sites and stream basins, and water chemistry seasonal variations were assessed among the monitored lakes. Cluster and principal component analyses, carried out using *Primer 5.2,* grouped the different sites. Impacts of variations in the water chemistry at the stream inlets (sites: 1a, 2a, 3a, 4a, 5a and 6a) on the lakeshore samples (sites: L1, L3, L4, L5, L6 and L8) were assessed using Pearson's Product-Moment correlation tables.

Spatial distribution of the water quality within Lough Lickeen was assessed and modelled using GIS, based on water chemistry recorded at the sixteen lake sampling stations. Spatial visualisation of trophic status was produced by using surface interpolations and overlaying different indexed coverages. Limitation of algal growth by nitrogen is thought to be occurring if the ratio (NH_4 + NO_3)/MRP is lower than 10 (Horne and Goldman, 1994; Irvine *et al*, 2001). A likely case of nitrogen limitations would be during the period of high algal biomass with high SRP and low NO_3-N concentrations. Ratios of NO_3-N/SRP concentrations were calculated during the monitoring period for the four lakes. Soil chemistry was compared with water chemistry of associated streams and with the soil type definition and land use. These results assessed the risk of P loss from the soils to water.

Nutrient export modelling on sub-catchment-basis

TP loadings to the lake (kg P yr^{-1}) and area-weighted loading rates (kg P ha^{-1} yr^{-1}), referred as annual average TP loading rates, were calculated following Foy (1992), as described in Chapter 4, and also for each stream sampling location, based on annual mean TP concentrations, annual mean run-offs (Equation 5.2) and drainage area:

Annual TP Loading (kg P yr^{-1}) =

$$\textbf{Annual mean TP concentrations (kg m}^{-3}\textbf{) * Annual mean run-off (m}^{3}\textbf{ yr}^{-1}\textbf{)}$$

Equation 5.3

Annual TP Loading Rates (kg P ha^{-1} yr^{-1}) =

$$\textbf{Annual TP Loading (kg P yr}^{-1}\textbf{) / Sub-catchment drainage area (m}^{2}\textbf{) * 10000}$$

Equation 5.4

Nutrient export coefficient models (Johnes *et al*, 1996, 1998; Jordan *et al*, 2000), as described in Chapter 4, were applied on a sub-catchment basis. The model described by Daly *et al* (2000) for wet soils, was also applied to predict annual stream MRP (Equation 5.5):

$$\textbf{Annual MRP (mg l}^{-1}\textbf{)} = -0.039 * (-1.2056 * \text{Higrass} - 1.861 * \text{Desorption} - 0.1511 * \text{Soil P} + 2.81 * \text{Semi-Peat} + 4.083) + 0.097 \quad \textbf{Equation 5.5}$$

Where: Higrass is % improved grassland in the catchment
Desorption is soil P desorption index
Soil P: soil Morgan P levels (mg l^{-1})
Semi-Peat is the sum of % semi-natural and peatlands areas in the catchment

Modelled exports were compared with calculated loadings from the monitoring data using Pearson's Product-Moment correlations and linear regression models (*DataDesk 6.0)*. 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 (See Chapter 4).

Empirical relationships and modelling of nutrient status of streams

Through correlations and stepwise multiple regressions, empirical relationships were extrapolated in order to predict variations in annual average nutrient loading rates to surface waters in the catchment. A progressive investigation of the different empirical relationships was carried out looking at correlations between predicted and calculated values, the accuracy of the predicted values at the sub-catchment scale and the accuracy of the model when applied at the entire catchment-scale. Specific export coefficients were derived for the Lickeen catchment based on calculated annual average TP loading rates and sub-catchment descriptive characteristics. The use of GIS allowed illustration of the spatial variation in annual average TP loading rates predicted by the empirical relationships, and the derivation of estimates of overall annual average exports for the entire catchment. A distance – decay concept was also introduced in the modelling approach by differentiating the riparian zone from the rest of the catchment.

It was hoped to apply the linear regression models derived in Chapter 4 for all lakes (Model 1), acidic catchments (Model 2) and poorly drained soils (Model 5) (Table 4.13) at the sub-catchment-scale in the Lickeen catchment. They, however, required detailed data of rainfall distribution within the Lickeen catchment, which were not available.

Spatial analysis – Risk Assessment Map

Spatial analyses were carried out with GIS, using *ArcView 3.2* and *Spatial Analyst* extension, to produce a map of relative risk to water quality. This approach was validated by modelling annual TP exports from twelve acidic catchments in Clare included in the 2000-01 monitoring.

V-3 RESULTS

V-3.1 Catchment and sub-catchment characteristics

Overview of the Lickeen catchment characteristics

- Physical and hydrological characteristics

Lough Lickeen catchment is less than 9 km^2. It has an undulating topography with an elevation ranging from 67 to 162 m (Figure 5.6) and a slope of up to 22.7° (Figure 5.7). The catchment drains in a south-southeast to west direction. It is underlain by impermeable bedrock of shales and similar rock types, composed of Clare Central Group (CCG) and Gull Island (GI) bedrock. It is covered by wet and poorly drained soils, with 53% of gley soils and 37% of peats (Figure 5.8; Table 5.3). Lough Lickeen is a small shallow lake with an area of 0.8 km^2, a volume and estimated mean depth of, respectively, 3.3 10^6 m^3 and 3.9 m (Irvine *et al*, 1998) (Figure 5.9).

The annual mean rainfall over the monitoring period was estimated at 1019 mm and the annual mean PET at 532 mm (Table 5.4). Highest rainfall levels were recorded in February, March and November 2002. Estimates of catchment run-offs were derived from the datasets (Table 5.4, Figure 5.10). In June, July, September and October 2002, the catchment received less water through rainfall than loss by PET (Figure 5.10). No significant difference (Mann-Whitney U test, α=0.05) was found between median rainfall levels recorded during the winter (October-March) and summer months (April-September). Lough Lickeen water level and outflow discharge rate were variable with a mean discharge rate ± 95% CI of 0.52 ± 0.23 m^3 s^{-1} during the monitoring period. Very high discharge rates occurred in February 2002 (Table 5.4, Figure 5.10).

Over the monitoring period, the annual abstraction volume for water supply was 1.61 10^6 m^3 yr^{-1}, with 1.53 10^6 m^3 yr^{-1} abstracted by the water treatment plant and 50,000 gallons day^{-1} (equivalent to 0.08 10^6 m^3 yr^{-1}) by a group water scheme. Estimates of lake flushing rates (F_r) and lake retention time (R_t) were corrected for the volume of abstracted water for water supply. Over the monitoring period, the lake flushing rate was estimated at 1.20 times yr^{-1} with a mean retention time of 305 days. Highest flushing rates occurred during the winter.

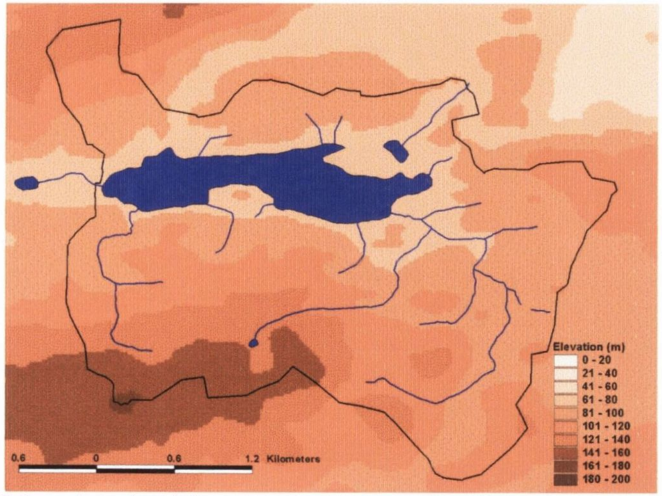

Figure 5.6: Lough Lickeen catchment Elevation (m), also showing the catchment boundary (black), lakes (blue shade) and stream network (blue line).

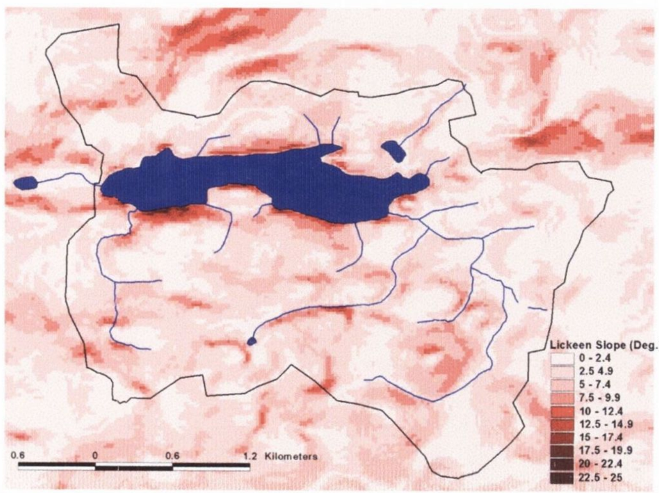

Figure 5.7: Lough Lickeen catchment Slope analysis (degree), also showing the catchment boundary (black), lakes (blue shade) and stream network (blue line).

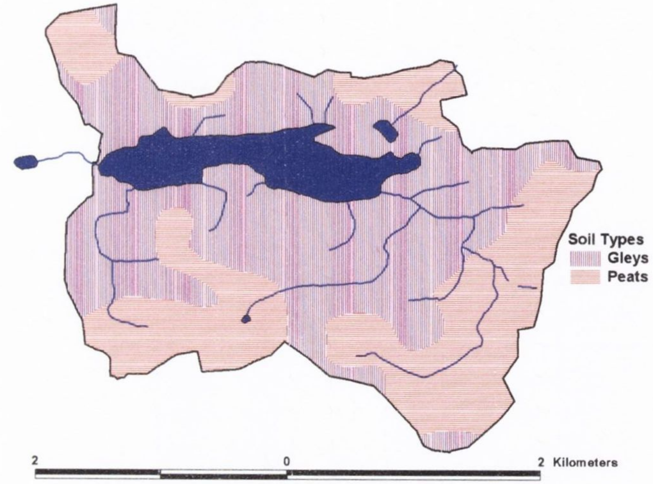

Figure 5.8: Lough Lickeen catchment soil type distribution, also showing the catchment boundary (black), lakes (blue shade) and stream network (blue line).

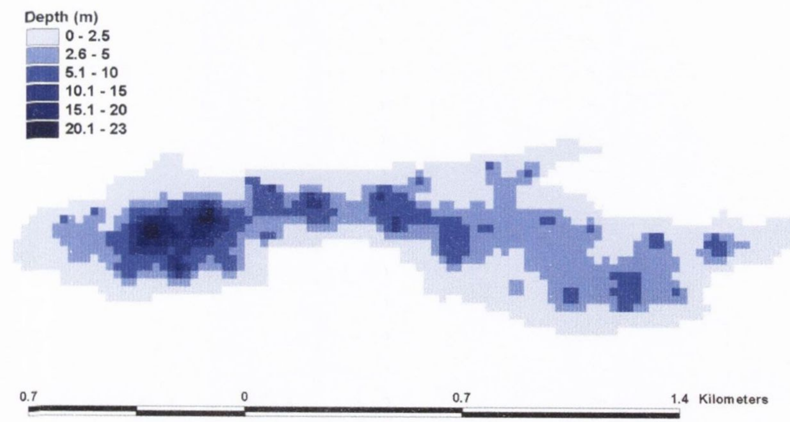

Figure 5.9: Lough Lickeen bathymetric map (Irvine *et al*, 1998)

Table 5.3: Description of Lough Lickeen catchment physical (topography, slope, soil types, bedrock geology) and limnological characteristics

Physical Variables		**Limnological Variables**	
Catchment area (km^2)	8.96	Lough Lickeen	
Catchment perimeter (km)	15.50	Lake area (km^2)	0.84
Drainage area (km^2)	8.12	% Catchment area covered by lake	9
Minimum elevation (m)	67	Lake shoreline (km)	6.29
Maximum elevation (m)	162	Minimum depth (m)	0
Range elevation (m)	95	D_{max}: Maximum depth (m)	23
Mean elevation (m)	98	Range depth (m)	23
Gley soils (Kilrush Serie) (km^2)	4.79	D_m: Mean depth (m)	3.5
% Catchment area covered by Gley soils	53	Estimated Lake Volume (10^6 m^3)	3.30
Peats (Aughty Serie) (km^2)	3.35	Volume development $V_d = 3*D_m/D_{max}$	0.45
% catchment area covered by Peats	37	Upstream lakes	
GI (Gull Island Formation) bedrock (km^2)	7.35	Lough Lickeen NE area (km^2)	0.02
% Catchment area underlain by GI bedrock	82	Lough Lickeen NE shoreline (km)	0.56
CCG (Central Clare Group) bedrock (km^2)	1.61	Lough Ballard area (km^2)	< 0.01
% Catchment area underlain by CCG bedrock	18	Lough Ballard shoreline (km)	0.21
		Total upstream lake area (km^2)	0.02
		% Catchment area covered by upstream lakes	< 1
		Downstream lake	
		Lough Cloonmora area (km^2)	0.02
		Lough Cloonmora shoreline (km)	0.48

A significant ($p<0.01$, $n=11$) correlation was found between Log(monthly outlet discharge) (m^3) and Log(Monthly catchment run-off-Abstraction) (m^3) ($r_p=0.75$; Figure 5.11), while no significant correlation ($r_p=0.55$, ns) was found with Log(Monthly catchment run-off) (m^3) without the correction for the abstraction.

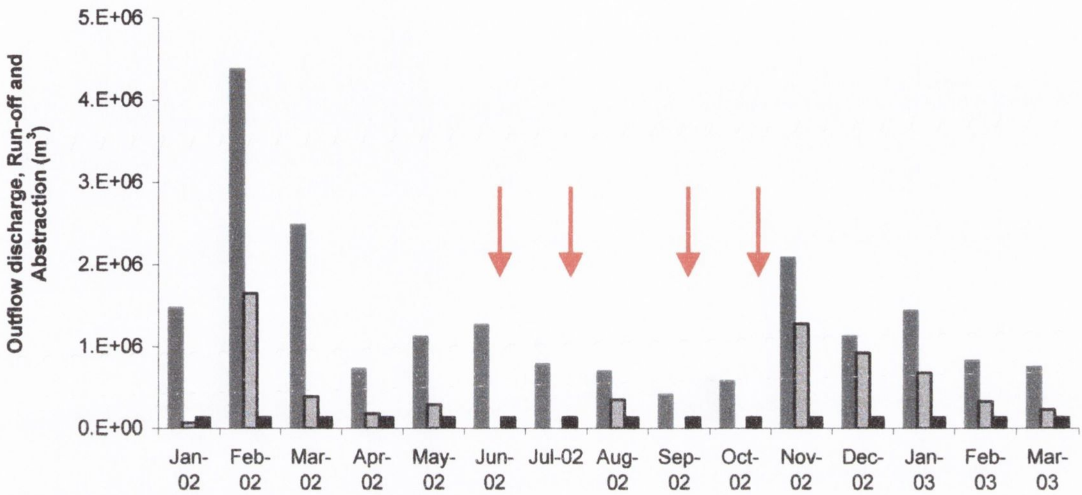

Figure 5.10: Monthly outflow discharge (m^3) (grey shade), estimates of run-offs (m^3) (grey stripes) and monthly abstraction for water supply (m^3) (black shade) in the Lough Lickeen catchment between January 2002 and March 2003. Months for which PET exceeded amount of rainfall perceived are highlighted with a red arrow.

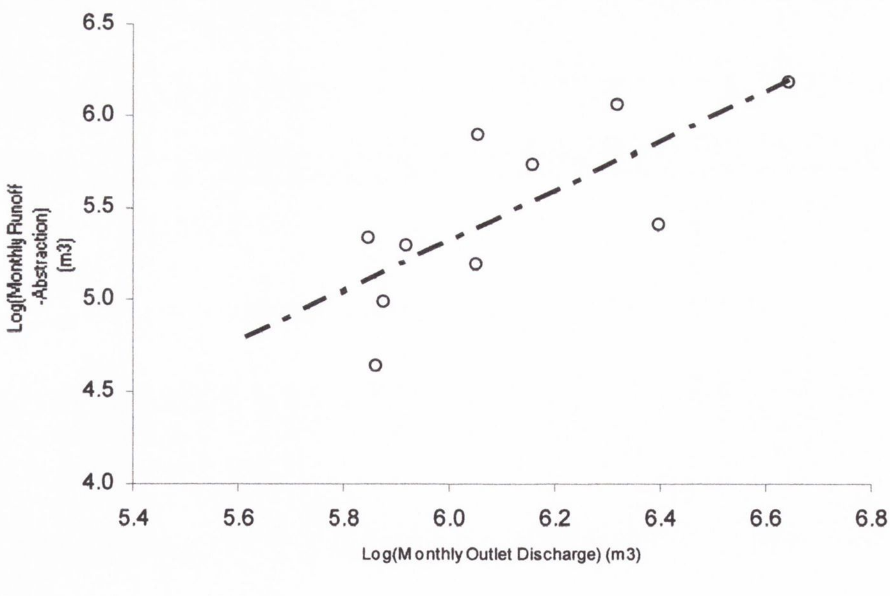

Figure 5.11: Comparison of Log(Monthly outlet discharge) against Log(Monthly run-off-Abstraction) – Pearson's Product-Moment correlation coefficient $r_p=0.75$, $n=11$, $p< 0.01$. Also showing linear regression line (- - -) ($R^2=0.55$, $p \leq 0.0001$)

Table 5.4: Hydrological data recorded for Lough Lickeen catchment in 2002-03. Outflow discharge rate (m^3/s) and monthly discharge (10^6 m^3) (Data courtesy, Michael MacCarthaigh and James Penny, EPA), monthly rainfall (mm) (Met Eireann, Ennistymon weather station), monthly potential evapotranspiration (PET) (mm) (Met Eireann, Shannon Airport weather station) and estimates of monthly catchment run-offs (10^6 m^3) are given. Annual and seasonal cumulative data are also summarized, expressed as total winter 2001-02 (Oct 01-March 02), total summer 2002 (April 02-Sepember 02), total winter 2002-3 (October 02- March 03) and total annual 2002 (January-December 2002). Average data are provided over the monitoring period. Annual and seasonal mean of outflow discharge rates are also given, expressed as mean ± 95% confidence interval.

Month	Outflow Discharge Rate (m^3/s)	Discharge (10^6 m^3)	Rainfall (mm)	PET (mm)	Catchment Run-off (10^6 m^3)
Jan-02	0.55	1.47	17.4	8.8	0.07
Feb-02	1.81	4.38	228.2	24.9	1.65
Mar-02	0.93	2.48	85.8	37.7	0.39
Apr-02	0.28	0.72	94.0	72.0	0.18
May-02	0.42	1.12	117.8	82.0	0.29
Jun-02	0.49	1.26	12.7	83.3	
Jul-02	0.29	0.78	71.5	74.0	
Aug-02	0.26	0.70	107.4	64.1	0.35
Sep-02	0.16	0.41	39.6	52.9	
Oct-02	0.22	0.58	16.5	21.2	
Nov-02	0.81	2.09	167.2	9.5	1.28
Dec-02	0.42	1.13	114.4	1.0	0.92
Jan-03	0.54	1.44	88.1	4.6	0.68
Feb-03	0.34	0.83	61.4	20.5	0.33
Mar-03	0.28	0.75	75.6	47.0	0.23
Total Winter 2001/02	0.83 ± 0.58	12.80	669.1	101.2	4.61
Total Summer 2002	0.32 ± 0.12	5.01	443.0	428.3	0.82
Total Winter 2002/03	0.43 ± 0.22	6.82	523.2	103.8	3.44
Total Annual 2002	0.55 ± 0.29	20.15	1297.6	603.5	6.37
Average total annual 2002-03	0.52 ± 0.23	14.48	1019.4	531.8	4.70

- Catchment land use

Lickeen catchment is a low intensity-farming catchment with low to moderate intensity livestock-rearing activities. Based on the CORINE coverage updated by the forestry data, the main catchment land covers were low productivity grasslands (42% of the catchment area); principally agricultural (16%); peat bogs (16%) and coniferous forests (13%).

Based on the Agricultural Censuses of 1991 and 2000 (CSO, 1991, 2000), 75% of the catchment area was used for agricultural purposes, with total pasture, as main farmland usage. Cattle and sheep densities were estimated at, respectively, 1.07 and 0.29 per hectare in 1991. The major changes between the 1991 and 2000 Census data were the increasing use of farmland for silage and rough grazing. Pasture still represented the major farmland usages (45%). A decline in livestock rearing activity over the period 1991-2000 appeared with a decrease in average cattle density to 0.99 per hectare in 2000 and in average sheep density to 0.02 per hectare. No major changes appeared in the total human population living in the catchment between 1996 and 2002, with a total of 114 in 1991 and 109 in 2002 (CSO, 1996, 2002). From the farm survey, an overall annual average population of 60 persons was estimated in the catchment, which is lower than the estimate obtained from the CSO Human Populations Census (109 persons in 2002). Each household was connected to a septic tank (Figure 5.12).

Despite contacting most farmers living within the catchment, data collated on field usages did not provide a complete coverage of the catchment; e.g. land, which was owned by farmers living outside the catchment, was not included in the field survey data, owing to difficulties to identify and contact these landowners at the time of the survey. These fields were mainly located in the east and covered about 15% of the catchment. Based on the farm survey, broadleaf forests covered 1.7% of the catchment area; coniferous forests, 14.8%; improved grasslands, 19.3%, mixed grasslands, 12.1%; unimproved grasslands, 21.8% and peatlands, 5.6%. In order to obtain a complete coverage of land use in the catchment, land parcels for which no data were collated were attributed land use based on the CORINE land covers updated by the forestry coverage (NFS, 1998). Based on CORINE, the eastern side of the catchment, which was not covered by the survey, comprised coniferous forests (6.6% of the catchment area), mixed grasslands (1.1%), unimproved grasslands (5.4%) and peatlands (1.9%).

For the whole catchment, combined land use data from the farm survey and CORINE showed that pasture was the main field use, covering 58% of the catchment area. Other land use comprised conifer plantations (21%) and peatlands (7%) (Table 5.5, Figure 5.13 – Associated CD-Rom: Appendix 4/Lickeen Land Uses). Data on fertiliser application rate and timing were variable and did not cover all the land parcels, and, thus, provided mainly a qualitative assessment of the spatial distribution of fertiliser application. Most farmers were applying fertilisers over the spring and summer periods.

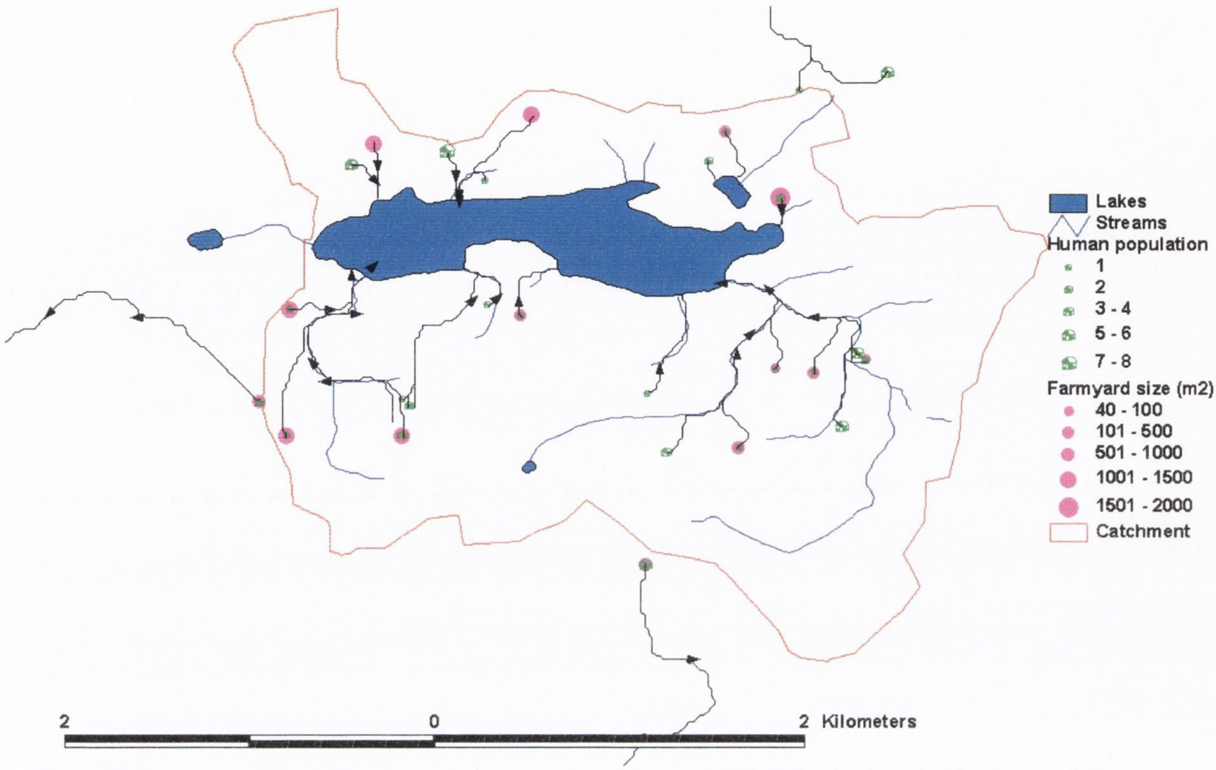

Figure 5.12: Location of houses and farms surveyed in March 2003 in the Lough Lickeen catchment, providing average number of persons per household and farmyard size. Modelled overland run-off pathways are also shown (black arrows).

Cattle number was estimated as 403, including 196 adult cattle, 7 calves, 135 suckling cows and 65 weanlings. There were 31 horses and ponies. Most cattle were housed during the winter period and cattle number in the catchment was usually greater during the winter. Assuming that livestock density was equally distributed among the fields that were pasture, the average cattle density in the catchment was estimated at 0.78 cattle ha^{-1}, which was lower than the density obtained from the CSO data. No sheep grazing activities were reported from the farm survey.

Table 5.5: Summary of field uses in the Lickeen catchment, based on farm survey results (March 2003), completed by CORINE and FIPS data

Final Field Usage	% Total Catchment Area
Conifer Forest	21.5
Broadleaf Forest	1.7
Total Peatlands	7.4
Unimproved Pasture	26.8
Mixed Pasture	26.7
Improved Pasture	4.9
Mixed Agriculture	0.8

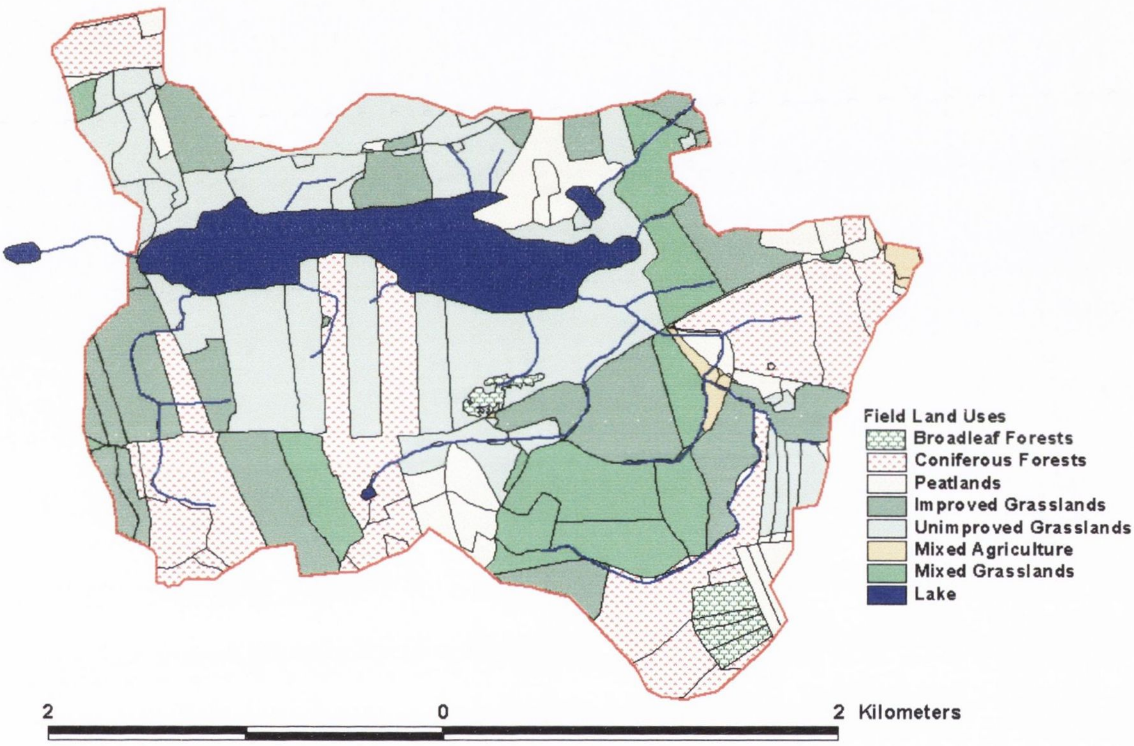

Figure 5.13: Summary of the Lickeen catchment agricultural field uses, based on the farm survey results (March 2003) and CORINE land covers updated by NFS data.

Overview of the sub-catchment descriptive variables

Owing to the large volume of data collated, sub-catchment descriptive variables are presented in the associated CD-Rom (Appendix 4/Lickeen sub-catchment variables) and summarised by stream basins in this section (Tables 5.6 and 5.7).

Stream 5 had the largest drainage basin with an area of 364 ha, comprising 41% of the total catchment area. It was sub-divided into 27 sub-catchments, including the upstream sub-catchment of Lough Ballard. It had the most complex stream network, with an overall channel length of 8.7

km. Field observations indicated that it had the greatest discharge rate during the monitoring period. Stream 1 had a drainage basin area of 101 ha, comprising 11% of the catchment area, a total channel length of 2.4 km and a less complex surface network than Stream 5. It was sub-divided into 6 sub-catchments and had the second greatest discharge rate in the catchment. The other streams were much smaller with no tributaries, and drainage basins comprising between <1% and 7% of the total catchment area.

Basins of streams 1, 5 and 2 had the greatest elevation. Streams 3, 4, 6, X and Y drained sub-catchments underlain by GI bedrock (100% of sub-catchment area) and covered principally by gley soils (> 70% of sub-catchment area). Stream 7 flows into the upstream Lake 9 (Lough Lickeen North-East). Its drainage basin was also underlain by GI (100%) bedrock but covered mainly by peat soils (> 60% of sub-catchment area). Streams 1, 2 and 5 were draining sub-catchments underlain by GI and CCG bedrock, with both gley and peat soils. Peat soils were usually found away from the inlet of each stream, with gley soils surrounding the lake. Pasture comprised more than 50% of individual sub-catchment land use, except for Stream 5. Conifer plantations were important in the catchments of stream 1 (42%), 3 (34%), 5 (28%) and 2 (25%). Broadleaf forests were present in the stream basin 4, and peat bogs, in the stream basins 5, 7 (L9) and Y.

Table 5.6: Descriptive variables of the ten stream drainage basins in the Lough Lickeen catchment, giving total sub-basin area, summary statistics of elevation and slope, expressed as minimum (Min.), maximum (Max.) and mean; bedrock geology composition (GI: Gull Island formation; CCG: Central Clare Group formation) and soil types expressed as % total catchment area; and soil P desorption index, as described by Daly (2000). Hydrological variables also described are total channel length, summary statistics of distance to Lough Lickeen, expressed as minimum (Min.), maximum (Max.) and mean. Land cover composition (expressed as % of total catchment area) and estimates of livestock numbers and human population are also described based on the farm surveys results of 2003

Stream Basins	**1**	**2**	**3**	**4**	**5**	**6**	**7 (L9)**	**X**	**Y**	**Z**
Sub-Basin area (km^2)	1.01	0.67	0.09	0.17	3.64	0.15	0.37	0.11	0.10	0.20
Topography										
Min Elev. (m)	67	67	70	67	67	67	69	67	67	67
Max Elev. (m)	162	160	104	121	160	92	88	101	101	102
Mean Elev. (m)	119	116	88	98	104	81	79	89	86	86
Max Slope (degree)	11.6	11.5	8.6	10.3	14.3	9.5	8.2	7.7	7.2	6.4
Mean Slope (degree)	4	4	5	5	3	4	3	4	4	3
Bedrock geology										
% GI	49	66	100	100	77	100	100	100	100	100
% CCG	51	34	0	0	23	0	0	0	0	0
Soil Types										
% Peats	42	49	0	0	54	15	68	0	28	19
% Gleys	58	51	100	100	46	85	32	100	72	81
Soil P desorption Index	1.52	1.46	1.90	1.90	1.41	1.76	1.29	1.90	1.65	1.73
Hydrology										
Total Channel Length (km)	2.39	0.71	0.24	0.63	8.69	0.31	0.95	0.37	0.27	0.41
Min dist-lickeen (km)							0.06			
Max dist-lickeen (km)	1.49	1.30	0.44	0.59	2.10	0.41	0.78	0.56	0.44	0.57
Mean dist-lickeen (km)	0.79	0.66	0.21	0.36	0.93	0.23	0.44	0.29	0.24	0.30
Farm Survey Land Uses										
% Improved Grassland	0	0	0	7	11	29	0	0	0	0
% Mixed Grassland	52	25	0	0	31	63	50	4	18	9
% Unimproved Grassland	6	50	66	75	13	7	19	96	73	88
% Total Pasture	58	75	66	82	54	100	70	100	91	98
% Total Peatlands	0	0	0	0	11	0	30	0	9	2
% Mixed Agriculture	0	0	0	0	2	0	0	0	0	0

Table 5.6 (continued)

Stream Basins	1	2	3	4	5	6	7 (L9)	X	Y	Z
% Conifers	42	25	34	0	28	0	0	0	0	0
% Broadleafs	0	0	0	17	3	0	0	0	0	0
Farm Survey Livestock										
Cattle No.	5	28	5	11	50	5	2	6	5	14
Horses No.	0	2	0	1	4	0	0	0	0	1
Farm Survey Population										
Total No. Persons	9	4	1	1	19	2	3	0	0	3

Table 5.7: Descriptive variables of the drainage basins of the six lake sites in the Lough Lickeen catchment, giving total sub-basin area, summary statistics of elevation and slope, expressed as minimum (Min.), maximum (Max.) and mean; bedrock geology composition (GI: Gull Island formation; CCG: Central Clare Group formation) and soil types expressed as % total catchment area; and soil P desorption index, as described by Daly (2000). Hydrological variables also described are total channel length, summary statistics of distance to Lough Lickeen, expressed as minimum (Min.), maximum (Max.) and mean. Land cover composition (expressed as % of total catchment area) and estimates of livestock numbers and human population are also described based on the farm surveys results of 2003

Drainage Basins	L2	L10	L11	L12	L13	L14
Sub-Basin area (km^2)	0.01	0.01	0.04	0.02	0.01	0.12
Topography						
Min Elev. (m)	74	67	67	67	67	67
Max Elev. (m)	103	80	89	92	82	121
Mean Elev. (m)	91	74	78	82	75	87
Min Slope (degree)	0	1	0	0	2	0
Max Slope (degree)	18.0	10.0	10.8	13.7	12.7	8.6
Mean Slope (degree)	11	6	3	7	7	4
Bedrock Geology						
% GI	100	100	100	100	100	100
% CCG	0	0	0	0	0	0
Soil Types						
% Peats	2	0	12	0	0	1
% Gleys	98	100	88	100	100	99

Table 5.7 (continued)

Drainage Basins	L2	L10	L11	L12	L13	L14
Soil P desorption index	1.88	1.90	1.79	1.90	1.90	1.89
Hydrology						
Max dist-lickeen (km)	0.19	0.13	0.43	0.22	0.10	0.66
Mean dist-lickeen (km)	0.09	0.06	0.13	0.10	0.04	0.30
Farm Survey Land Uses						
% Improved Grassland	0	0	0	0	0	0
% Mixed Grassland	0	0	2	100	0	65
% Unimproved Grassland	100	72	0	0	100	34
% Total Pasture	100	72	2	100	100	98
% Total Peatlands	0	28	98	0	0	2
% Mixed Agriculture	0	0	0	0	0	0
% Conifers	0	0	0	0	0	0
% Broadleafs	0	0	0	0	0	0
Farm Survey Livestock						
Cattle No.	1	1	0	0	1	3
Horses No.	0	0	0	0	0	0
Farm Survey Population						
Total No. Persons	0	0	0	0	0	10

V-3.2 Monitoring results 2002-03

Full monitoring results are provided in the associated CD-Rom (Appendix 4/LRA Monitoring Results 2002-03). Summaries of water quality are provided in this section.

Water quality of Loughs Lickeen, Ballard, Northeast Lickeen and Cloonmora:

Lakes in the Lickeen catchment and the downstream lake (Lough Cloonmara) were nutrient enriched and, based on the OECD scheme (OECD, 1982), classified as eutrophic. Over the monitoring period 2002-03, mean TP concentrations ranged from 36 $\mu g\ l^{-1}$ (L. Lickeen) to 91 $\mu g\ l^{-1}$ (L. North-east Lickeen). Maximum chlorophyll-*a* concentrations ranged from 37 $\mu g\ l^{-1}$ (L. North-east Lickeen and L. Cloonmara) to 72 $\mu g\ l^{-1}$ (L. Ballard). The lowest mean pH of 6.47 was recorded for L. Ballard, which drains a peatland area planted by conifer plantations (Table 5.8). No distinct seasonal patterns of P fractions, TN and chlorophyll-*a* concentrations and alkalinity levels were observed in any of the lakes. NO_3-N concentrations and colour decreased during the spring and summer, with maximum values in the winter (Figures 5.14 to 5.18). Colour in Lough Ballard, however, increased during the summer and decreased during the winter (Figure 5.19).

Significant difference (M-ANOVA, $p \leq 0.05$, Appendix 4 – Table 1) were observed between summer and winter NO_3-N, TN, SRP concentrations among the four lakes, with lower summer concentrations, except for Lough Northeast Lickeen. Significant differences ($p \leq 0.05$) were found between summer and winter chlorophyll-*a* concentrations among the four lakes with higher concentrations recorded during the summer. Summer and winter colour levels were also significantly different ($p \leq 0.05$) among the lakes with low colour levels recorded during the summer, except for Lough Ballard. Greatest variations between summer and winter water chemistry was found in Lough Cloonmara.

Among the lakes, the ratio NO_3-N/SRP (Figure 5.20) was lower than 10 for Lough Northeast Lickeen (L9) during the whole monitoring period, Lough Ballard, except in February 2002 and 2003 and Lough Cloonmara between July (no data for previous months) and November 2002. The ratio was more variable for Lough Lickeen (estimated based on mean concentrations from all the lake sampling sites) and was lower than 10 in July 2002 and between September and November 2002. The four lakes showed similar variations in the NO_3-N/SRP ratio, with minimum summer values and maximum reached during the winter months.

Table 5.8: Lickeen catchment average lake water chemistry recorded between February 2002 and March 2003 in the main lake: Lough Lickeen, upstream lakes: Loughs Ballard (L7) and North-east Lickeen (L9) and downstream lake: Lough Cloonmara, also giving 95% CI (in italics) (n=15 for Loughs Lickeen, Ballard and North-east Lickeen; n=9 for Lough Cloonmara). Maximum chlorophyll-*a* concentrations reached during the monitoring period are also provided (Max. Chl-*a*)

Lake		**NO_3-N**	**TN**	**TP**	**TDP**	**SRP**	**Chl-*a***	**Max Chl-*a***	**TDOC**	**pH**	**Alk.**	**Cond.**	**Colour**	**Turb.**
Units		mg l^{-1}	mg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	mg l^{-1}		mgCaCO$_3$ l^{-1}	µS cm^{-1}	PtCo	NTU
Lickeen		0.08	0.86	35.7	15.6	4.0	12.1	60.9	9.7	6.47	24.6	133.4	78	3.9
	95% CI	*0.01*	*0.07*	*7.9*	*1.9*	*1.0*	*4.6*		*1.7*	*0.20*	*2.7*	*7.5*	*43*	*3.1*
Ballard		0.03	0.87	53.5	34.9	10.3	20.0	72.2	15.4	6.04	6.3	111.7	195	4.1
	95% CI	*0.02*	*0.18*	*16.9*	*11.4*	*3.4*	*12.5*		*3.5*	*0.23*	*4.4*	*14.3*	*57*	*2.3*
North-East Lickeen		0.07	1.19	91.1	64.7	34.4	15.8	36.7	20.5	7.14	29.1	145.5	243	11.6
	95% CI	*0.04*	*0.30*	*19.6*	*11.8*	*8.7*	*5.8*		*2.6*	*0.10*	*2.2*	*7.0*	*43*	*8.2*
Cloonmara		0.08	0.99	49.3	17.8	5.1	18.8	36.7	8.8	7.25	28.6	147.4	98	9.1
	95% CI	*0.05*	*0.20*	*21.1*	*5.6*	*2.3*	*9.4*		*0.5*	*0.08*	*5.7*	*20.2*	*69*	*7.3*

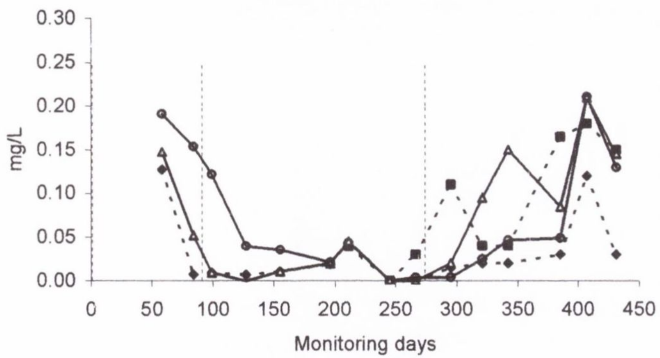

Figure 5.14: Variations in NO_3-N concentrations (mg l^{-1}) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Loughs Ballard (-- ♦ --); Cloonmara (-- ■ --); north-east Lickeen (– Δ –) and Lickeen (– ○ –). Lough Lickeen data represents the averages of the concentrations recorded at each sampling sites on the lake. Winter and summer periods are also differentiated by the vertical lines (---).

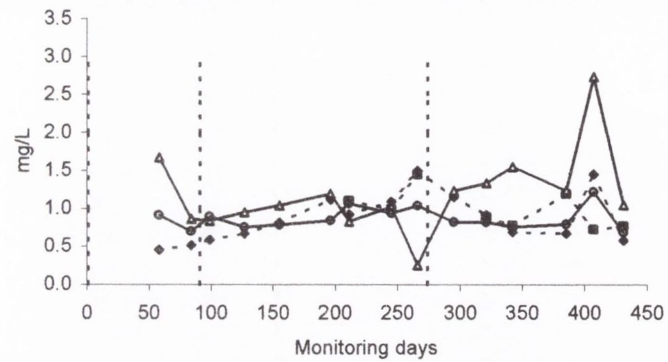

Figure 5.15: Variations in TN concentrations (mg l^{-1}) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Loughs Ballard (-- ♦ --); Cloonmara (-- ■ --); north-east Lickeen (– Δ –) and Lickeen (– ○ –). Lough Lickeen data represents the averages of the concentrations recorded at each sampling sites on the lake. Winter and summer periods are also differentiated by the vertical lines (---).

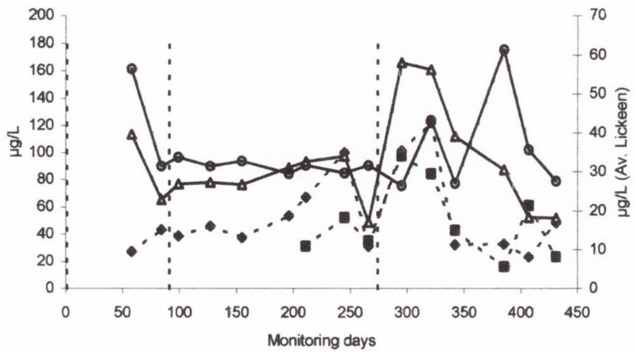

Figure 5.16: Variations in TP concentrations (µg l^{-1}) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Loughs Ballard (-- ♦ --); Cloonmara (-- ■ --); north-east Lickeen (— Δ —) and Lickeen (— ○ —). Lough Lickeen data represents the averages of the concentrations recorded at each sampling sites on the lake. Winter and summer periods are also differentiated by the vertical lines (---).

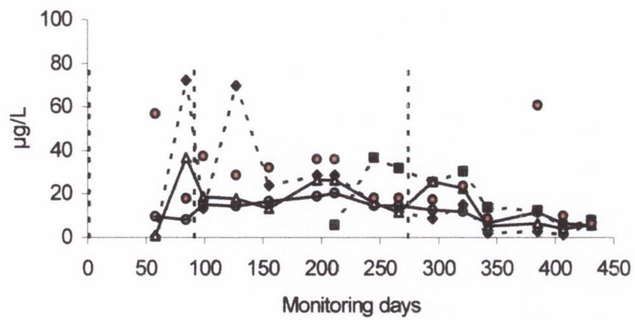

Figure 5.17: Variations in chlorophyll-*a* concentrations (µg l^{-1}) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Loughs Ballard (-- ♦ --); Cloonmara (-- ■ --); north-east Lickeen (— Δ —) and Lickeen (— ○ —). Lough Lickeen data represents the averages of the concentrations Lickeen are also shown recorded at each sampling sites on the lake. Maximum concentrations recorded in the different sampling stations on Lough for each sampling occasions (●). Winter and summer periods are also differentiated by the vertical lines (---).

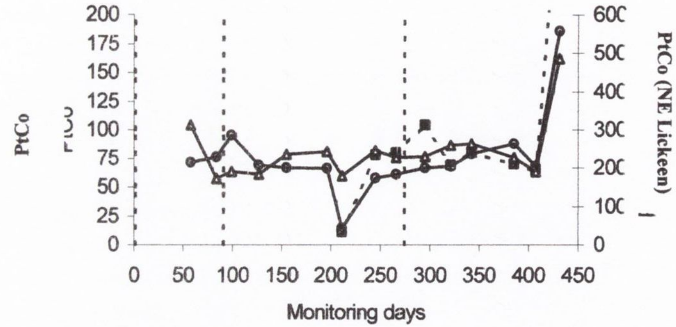

Figure 5.18: Variations in colour levels (PtCo) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Loughs Cloonmara (-- ■ --); north-east Lickeen (— Δ —) and Lickeen (— ○ —). Lough Lickeen data represents the averages of the concentrations recorded at each sampling sites on the lake. Winter and summer periods are also differentiated by the vertical lines (---).

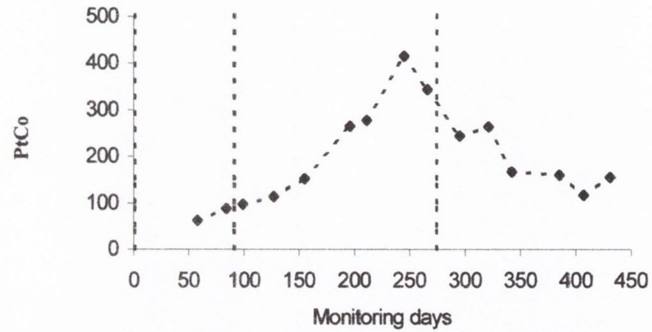

Figure 5.19: Variations in colour levels (PtCo) during the monitoring period (on the x-axis: day 1 = 01/01/02 and day 366 = 01/01/03) in Lough Ballard (-- ♦ --). Winter and summer periods are also differentiated by the vertical lines (---).

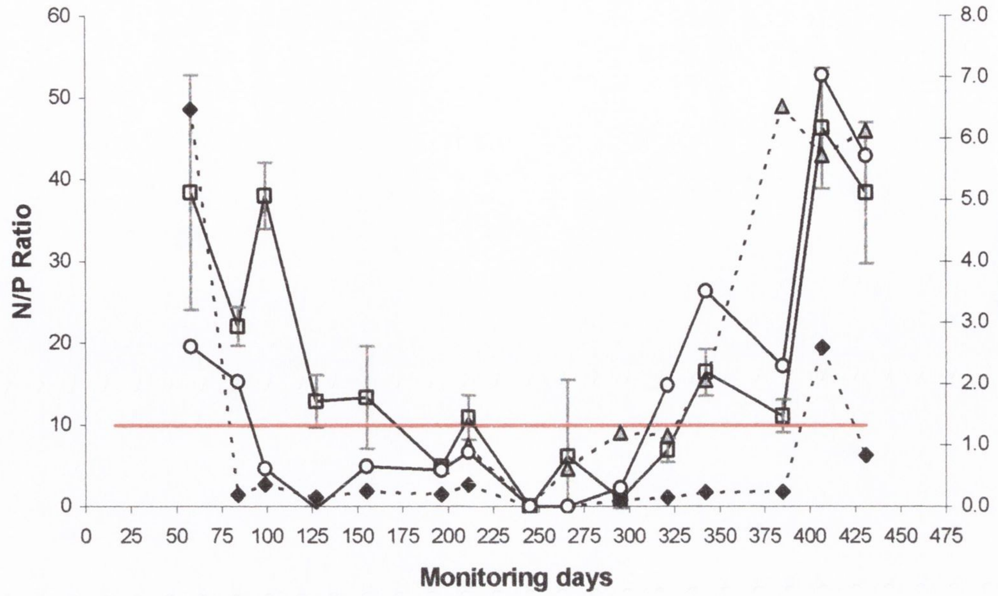

Figure 5.20: Variations in N/P Ratio calculated as NO_3-N/SRP ratio during the monitoring period (X-axis: day 1=01/01/02 and day 366=01/01/03) in Loughs Ballard (-- ♦--), Cloonmara (- ▲ --), Lickeen (— □—) and Northeast Lickeen (— ○ —). For clarity of the graph, the main Y-axis (0-60) refers to ratios calculated for Loughs Ballard, Cloonmara and Lickeen, while the secondary Y-axis (0.0-8.0) refers to ratios calculated for Lough Northeast Lickeen (L9), which had lower ratios. Lickeen ratio are based on means calculated on all the lake sampling stations, 95% CI are shown (error bars). The red line shows the ratio limit of 10

Lough Lickeen water chemistry

Lickeen water chemistry data are summarised in Table 5.9 and Figures 5.21 to 5.25.

-Inter-annual seasonal variations

In-lake NO_3-N concentrations decreased during the spring, with minima over the summer. No obvious seasonal patterns were observed in the variations in in-lake TN and TP concentrations. Colour showed a steady but slight decline over the spring period. Chlorophyll-*a* concentrations reached maximum value during the summer (July/August) with a secondary peak in September 2001. Alkalinity values remained within a small and fairly constant range: 20-29 mg $CaCO_3$ l^{-1}. Over the monitoring period 2000-2003, annual mean TP and maximum chlorophyll-*a* in-lake concentrations increased. Annual mean chlorophyll-*a* concentrations were higher in 2001 (Figure 5.26).

Table 5.9: Means of lake chemical variables recorded between February 2002 and March 2003 in the different sampling locations in Lough Lickeen (n=16)., also giving 95% CI (in italics) and total number of samples per site (n). Maximum chlorophyll-*a* concentrations reached during the monitoring period are also provided (Max. Chl-*a*)

Lake	**n**	**NO_3-N**	**TN**	**TP**	**TDP**	**SRP**	**Chl-*a***	**Max Chl-*a***	**TDOC**	**pH**	**Alk.**	**Cond.**	**Colour**	**Turb.**
Units		mg l^{-1}	mg l^{-1}	μg l^{-1}	μg l^{-1}	μg l^{-1}	μg l^{-1}	μg l^{-1}	mg l^{-1}		mgCaCO$_3$ l^{-1}	μS cm^{-1}	PtCo	NTU
Shore samples:	-													
L1	15	0.07	0.78	27.3	16.3	5.5	11.0	26.0	9.7	7.30	24.0	135.8	69	3.6
		0.03	*0.07*	*2.6*	*3.9*	*2.6*	*4.2*		*1.3*	*0.14*	*2.4*	*6.4*	*14*	*1.1*
L2	15	0.07	0.81	26.9	14.4	3.9	10.7	17.2	9.0	5.49	24.5	131.7	64	3.2
		0.04	*0.05*	*3.0*	*2.5*	*0.9*	*2.2*		*1.5*	*0.44*	*0.7*	*3.3*	*9*	*0.9*
L3	15	0.06	0.80	30.9	14.8	3.8	11.4	25.8	9.6	7.34	23.6	135.2	68	4.2
		0.03	*0.10*	*4.9*	*2.6*	*1.0*	*4.1*		*2.2*	*0.07*	*2.1*	*6.4*	*13*	*1.6*
L4	15	0.07	1.10	50.4	14.7	3.5	15.4	60.9	9.0	7.31	24.1	132.1	68	6.4
		0.04	*0.30*	*27.8*	*2.6*	*0.9*	*7.6*		*1.7*	*0.12*	*1.2*	*3.5*	*11*	*3.3*
L5	15	0.08	0.92	29.7	14.4	3.2	13.3	36.0	9.3	7.38	24.9	133.5	67	3.6
		0.05	*0.16*	*5.0*	*3.0*	*0.8*	*5.5*		*0.6*	*0.16*	*0.7*	*3.6*	*11*	*0.9*
L6	15	0.08	0.99	47.6	18.4	5.1	13.4	56.7	10.8	7.36	27.3	141.1	87	4.9
		0.04	*0.23*	*30.5*	*2.9*	*1.8*	*7.2*		*1.9*	*0.09*	*2.2*	*7.8*	*19*	*3.2*
L8	15	0.08	0.91	34.1	16.2	3.8	11.5	19.5	9.6	7.29	23.4	132.6	88	3.0
		0.06	*0.19*	*6.1*	*2.8*	*0.9*	*3.0*		*1.0*	*0.05*	*2.7*	*3.5*	*51*	*0.9*
L10	4	0.11	0.72	32.9	20.6	5.0	9.4	12.8	12.2	7.38	21.2	126.3	82	3.4
		0.09	*0.09*	*5.4*	*10.4*	*3.7*	*6.0*		*5.5*	*0.21*	*9.8*	*2.0*	*17*	*2.6*
L11	4	0.11	0.74	33.3	18.4	3.8	11.0	19.2	12.2	7.35	24.2	126.5	91	3.1
		0.08	*0.14*	*6.6*	*7.2*	*2.8*	*10.8*		*8.5*	*0.21*	*1.4*	*0.9*	*71*	*3.0*
L12	4	0.11	0.72	36.7	18.8	4.0	12.7	17.8	12.6	7.31	24.0	126.0	81	2.7
		0.09	*0.23*	*6.9*	*7.6*	*2.9*	*9.0*		*6.8*	*0.14*	*5.1*	*1.3*	*36*	*1.3*
L13	4	0.12	0.74	39.1	19.3	4.5	13.5	28.6	10.9	7.41	24.3	126.3	88	3.2
		0.10	*0.30*	*14.2*	*5.4*	*3.2*	*17.2*		*4.9*	*0.16*	*1.6*	*2.0*	*47*	*1.7*
L14	15	0.07	0.88	31.4	16.5	3.9	14.3	37.5	9.8	7.34	26.4	134.2	80	3.4
		0.04	*0.18*	*3.7*	*2.4*	*0.8*	*5.6*		*1.4*	*0.06*	*3.0*	*4.8*	*27*	*0.9*
Middle Lake Samples	-													
L .Middle A	6	0.09	0.79	44.9	12.9	3.3	9.5	13.3	8.7	7.28	24.3	131.2	117	5.0
		0.09	*0.14*	*37.9*	*1.9*	*0.5*	*3.6*		*0.9*	*0.06*	*1.0*	*5.0*	*119*	*3.1*
L. Middle B	10	0.06	0.84	40.5	13.6	3.1	12.2	17.0	8.9	7.38	24.8	133.6	72	3.6

Table 5.9 (continued)

Lake	n	NO_3-N	TN	TP	TDP	SRP	Chl-*a*	Max Chl-*a*	TDOC	pH	Alk.	Cond.	Colour	Turb.
Units		mg l^{-1}	mg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}	mg l^{-1}		mgCaCO$_3$ l^{-1}	µS cm^{-1}	PtCo	NTU
		0.05	*0.11*	*18.6*	*1.6*	*0.7*	*3.3*		*0.5*	*0.06*	*0.7*	*4.7*	*35*	*1.4*
L. Middle C	6	0.08	0.76	41.7	12.7	3.1	8.7	13.0	9.1	7.35	24.3	131.1	88	3.1
		0.10	*0.09*	*16.8*	*2.0*	*0.5*	*3.2*		*0.8*	*0.08*	*1.0*	*4.8*	*51*	*1.4*
L. Middle D	6	0.09	0.73	33.4	12.5	3.4	8.6	13.0	9.2	7.36	24.2	131.4	93	2.7
		0.09	*0.07*	*11.3*	*1.1*	*1.3*	*3.6*		*0.6*	*0.05*	*1.0*	*4.9*	*63*	*0.8*

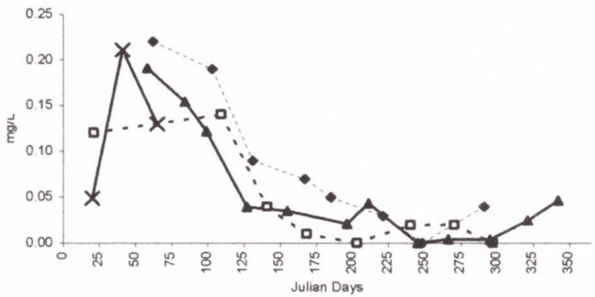

Figure 5.21: Variation in in-lake NO_3-N concentrations (mg l^{-1}) recorded in Lough Lickeen in 2000 (--♦--), 2001 (--□--), 2002 (–▲–) and 2003 (–*–). Concentrations for 2002 and 2003 refer to mean values of the concentrations recorded at the different sampling sites in the lake.

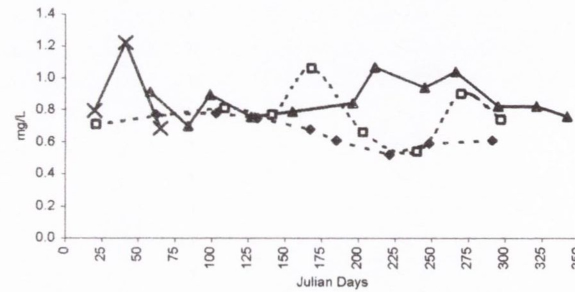

Figure 5.22: Variation in in-lake TN concentrations (mg l^{-1}) recorded in Lough Lickeen in 2000 (--♦--), 2001 (--□--), 2002 (–▲–) and 2003 (–*–).Concentrations for 2002 and 2003 refer to mean values of the concentrations recorded at the different sampling sites in the lake

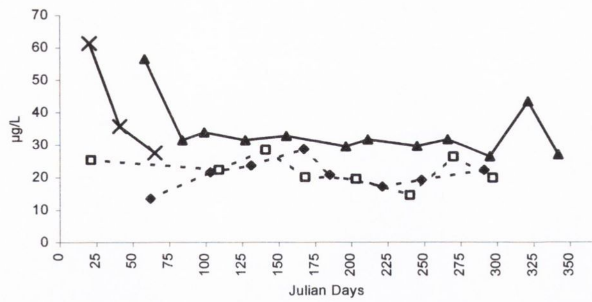

Figure 5.23: Variation in in-lake TP concentrations (µg l^{-1}) recorded in Lough Lickeen in 2000 (--♦--), 2001 (--□--), 2002 (—▲—) and 2003 (—*—). Concentrations for 2002 and 2003 refer to mean values of the concentrations recorded at the different sampling sites in the lake

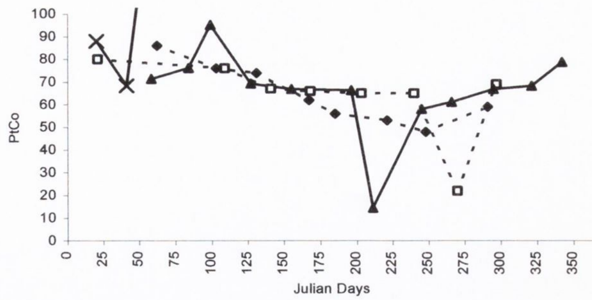

Figure 5.25: Variation in in-lake colour (PtCo) recorded in Lough Lickeen in 2000 (--♦--), 2001 (--□--), 2002 (—▲—) and 2003 (—*—). Concentrations for 2002 and 2003 refer to mean values of the concentrations recorded at the different sampling sites in the lake.

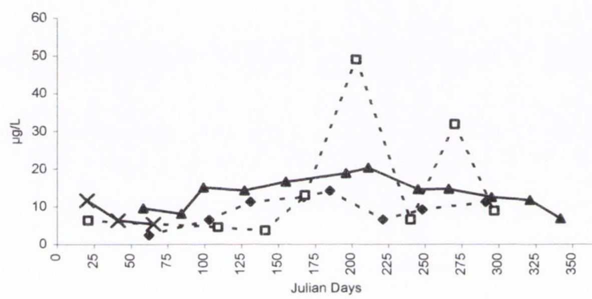

Figure 5.24: Variation in in-lake Chlorophyll-*a* concentrations (µg l^{-1}) recorded in Lough Lickeen in 2000 (--♦--), 2001 (--□--), 2002 (—▲—) and 2003 (—*—). Concentrations for 2002 and 2003 refer to mean values of the concentrations recorded at the different sampling sites in the lake

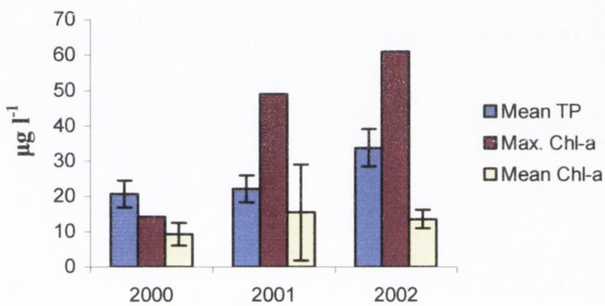

Figure 5.26: Variations in annual mean TP, chlorophyll-*a* and maximum chlorophyll-*a* concentrations recorded in 2000, 2001 and 2002 in Lough Lickeen. 95% confidence intervals are also shown.

- Seasonal variations 2002-03

Based on the data recorded in 2002-03, when more intensive monitoring was carried out, no effect of rainfall was found on TN, chlorophyll-*a* concentrations and colour. Increasing in-lake concentrations of P fractions were, however, related positively with rainfall (Figures 5.27 to 5.30), although this could not account for the higher concentrations of TP recorded in 2002 compared with the previous two years. Log(daily rainfall) was significantly positively correlated with Log(TDP) ($n=15$, $r_p=0.76$, $p<0.05$), while no significant correlations were found with Log(TP) and Log(SRP).

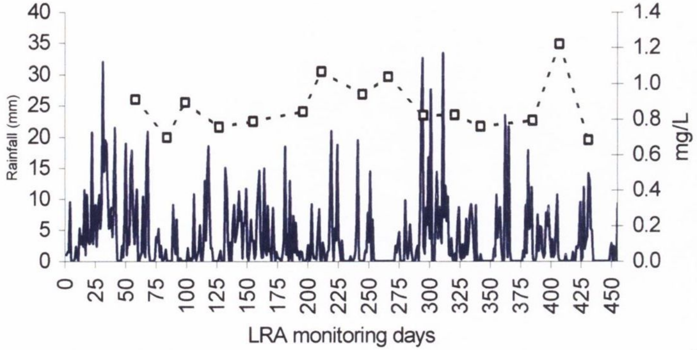

Figure 5.27: Variations in in-lake TN concentrations (mg l^{-1}) (--□--) recorded in Lough Lickeen between February 2002 and March 2003, also showing daily rainfall (mm) (–) recorded in Ennistymon. On the X-Axis: Day 1: 1st January 2002; Day 366: 1st January 2003

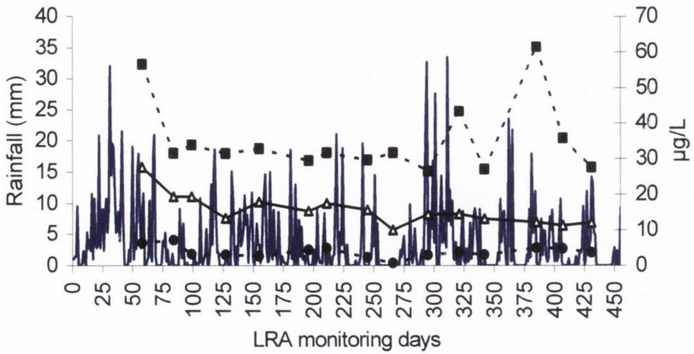

Figure 5.28: Variations in in-lake P fractions concentrations (µg l^{-1}) with TP (--■--), TDP (–Δ–) and SRP (--●--) recorded in Lough Lickeen between February 2002 and March 2003, also showing daily rainfall (mm) (–) recorded in Ennistymon. On the X-Axis: Day 1: 1st January 2002; Day 366: 1st January 2003

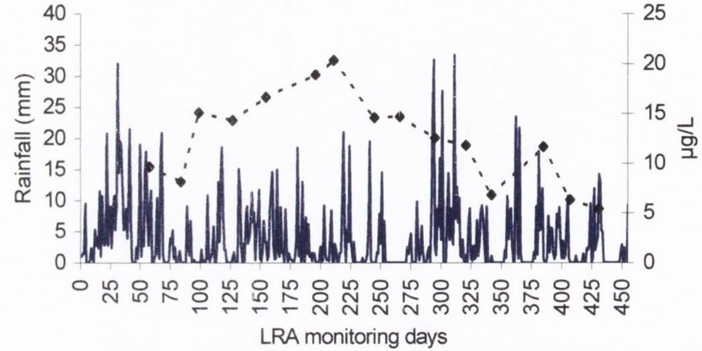

Figure 5.29: Variations in in-lake chlorophyll-*a* concentrations (µg l^{-1}) (--♦--), also showing daily rainfall (mm) (–) recorded in Ennistymon. On the X-Axis: Day 1: 1st January 2002; Day 366: 1st January 2003

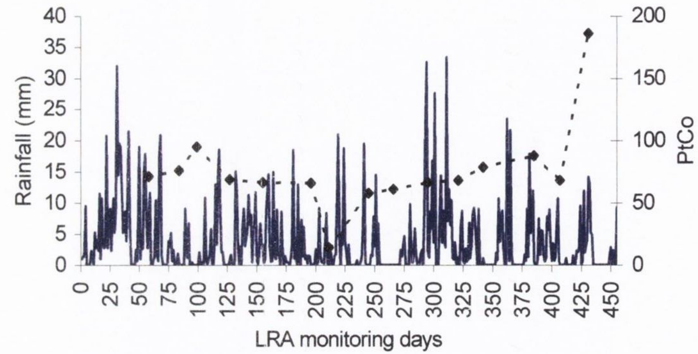

Figure 5.30: Variations in in-lake colour (PtCo) (--♦--), also showing daily rainfall (mm) (–) recorded in Ennistymon. On the X-Axis: Day 1: 1st January 2002; Day 366: 1st January 2003

- Comparison lakeshore and middle-lake samples

Initial monitoring (February – May 2002, n=4 sampling occasions), suggested differences among lakeshore samples in Lough Lickeen (M-ANOVA, $p<0.05$, Appendix 4 – Table 2). From July 2002, middle-lake samples were included in the monitoring. Significant differences were found (M-ANOVA, $p<0.05$, Appendix 4 – Table 3) between lakeshore (8 sites, 10 sampling occasions) and middle-lake samples (4 sites, 10 sampling occasions). For each sampling occasion, lakeshore and middle-lake colour levels and TN concentrations were significantly different ($p\leq0.05$), with lower colour levels recorded for the middle-lake samples. No significant differences were found for TP and chlorophyll-*a* concentrations between lakeshore and middle-lake samples. Nevertheless, maximum chlorophyll-*a* was usually recorded among lakeshore samples.

- Comparison of overall lake chemistry and "near-outlet" lake chemistry

The assumption made in Chapter 3, that water chemistry measured near the lake outlet was representative of the overall lake chemistry, was tested for Lough Lickeen. Water chemistry obtained for the sampling site Lake middle B, located near the sampling station used in the monitoring 2000-01 and close to the outlet, was not significantly different from the overall lake average chemistry recorded between July 2002 and March 2003. No seasonal effects were found (M-ANOVA, Appendix 4 – Table 4).

While no significant difference was found between mean TP and chlorophyll-*a* concentrations between overall lake average data and lake middle B values, maximum chlorophyll-*a* concentrations recorded among the two datasets differed greatly, with 60.9 $\mu g\ l^{-1}$ for the overall lake sites and 17.0 $\mu g\ l^{-1}$ for the site Lake Middle B. When compared with the overall lake average chemistry, means of the different chemical variables recorded near the lake outlet were included within the overall lake mean ± 95% CI (Table 5.10). Excluding an outlying value of pH, recorded for the site L2 in December 2002 (pH=4.32), the overall mean pH of the lake was similar to the pH levels measured near the lake outlet.

- Spatial assessment of eutrophication

Influence of inflowing stream on lakeshore samples

P concentrations recorded for lakeshore sites close to stream inlets were significantly positively correlated with P concentrations at the stream inlets in streams 1, 2, and 3, but were significantly negatively correlated ($n=15$, $p\leq0.05$) in Stream 5 (Table 5.11).

Table 5.10: Means of chemical variables found in Lough Lickeen over the monitoring period 2002-03 and for the site lake Middle B. 95% CI are also provided.

	Lickeen (n=109)		Middle B (n=10)	
	Mean	**95% CI**	**Mean**	**95% CI**
NO_3-N (mg l^{-1})	0.06	0.01	0.06	0.05
TN (mg l^{-1})	0.89	0.05	0.84	0.11
TP (μg l^{-1})	34.8	4.5	40.5	18.6
TDP (μg l^{-1})	13.5	0.6	13.6	1.6
SRP (μg l^{-1})	3.6	0.4	3.1	0.7
Chla (μg l^{-1})	11.8	1.5	12.2	3.3
Max Chla (μg l^{-1})	60.9		17.0	
TDOC (mg l^{-1})	8.8	0.3	8.9	0.5
pH	6.32	0.06	7.38	0.06
Alk. (mg$CaCO_3$ l^{-1})	25.0	0.6	24.8	0.7
Cond. (μS cm^{-1})	134.7	1.4	133.6	4.7
Colour (PtCo)	78	10	72	35
Turb. (NTU)	3.5	0.4	3.6	1.4

Table 5.11: Summary of significant Pearson's Product-Moment correlation coefficients between in-lake and inlet P concentrations (n=15, $p \leq 0.05$) among the monitored streams of the Lough Lickeen Catchment

	Log(In-lake TP)	Log(In-lake TDP)
Log(Inlet TP)	Stream 2 (r_p=0.74)	Stream 1 (r_p=0.66)
Log(Inlet TDP)		Stream 2 (r_p=0.52)
Log(Inlet SRP)	Stream 3 (r_p=0.59) Stream 5 (r_p=-0.67)	

Positive significant relationships were found between in-lake and inlet N concentrations, with significant positive correlations (n=15, $p \leq 0.05$) between Log(in-lake NO_3-N) and Log(inlet NO_3-N) in streams 4 (r_p=0.61) and 6 (r=0.55); and between Log(in-lake TN) and Log(inlet TN) in stream 2 (r_p=0.74). Except for stream 3, in-lake chlorophyll-*a* concentrations were usually positively correlated (n=15, $p \leq 0.05$) with inlet P and TDOC concentrations (Figure 5.31, Table 5.12). The stronger correlations were observed between in-lake and inlet pH values (Table 5.13, Figure 5.32), except for stream 4 where no relationship was observed. In-lake pH levels were also positively correlated with alkalinity and colour at the inlets.

Table 5.12: Pearson's Product-Moment correlation coefficients (n=15) between in-lake Log(Chlorophyll-*a* concentrations) and chemical variables measured at the inlet of the associated streams in 2002-03 in the Lough Lickeen Catchment. Coefficients significant at $p \leq 0.05$ are in bold and underlined for $p \leq 0.01$.

	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	Stream 6
Log(TP)	0.18	0.49	0.02	**0.54**	**0.52**	**0.62**
Log(TDP)	0.46	**0.55**	0.12	0.51	**0.56**	**0.60**
Log(SRP)	<u>**0.75**</u>	0.37	0.38	**0.59**	-0.01	**0.60**
Log(NO_3-N)	0.41	-0.32	0.11	**-0.57**	0.30	-0.23
Log(TDOC)	<u>**0.71**</u>	<u>**0.72**</u>	-0.20	<u>**0.69**</u>	0.39	0.50
pH	<u>**0.73**</u>	<u>**0.86**</u>	-0.08	<u>**0.64**</u>	0.04	0.48
Log(Alkalinity)	<u>**0.68**</u>	<u>**0.79**</u>	-0.02	0.44	0.23	0.45
Log(Colour)	<u>**0.73**</u>	**0.59**	0.02	<u>**0.82**</u>	0.38	**0.63**

Table 5.13: Pearson's Product-Moment correlation coefficients (n=15) between in-lake pH and chemical variables measured at the inlet of the associated streams in 2002-03 in the Lough Lickeen Catchment. Coefficients significant at $p \leq 0.05$ are in bold and underlined for $p \leq 0.01$.

	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	Stream 6
pH	<u>**0.74**</u>	<u>**0.75**</u>	<u>**0.79**</u>	0.23	<u>**0.79**</u>	<u>**0.87**</u>
Log(Alkalinity)	<u>**0.83**</u>	<u>**0.90**</u>	<u>**0.75**</u>	0.17	<u>**0.77**</u>	**0.60**
Log(Colour)	<u>**0.68**</u>	0.48	<u>**0.80**</u>	0.26	0.41	0.12

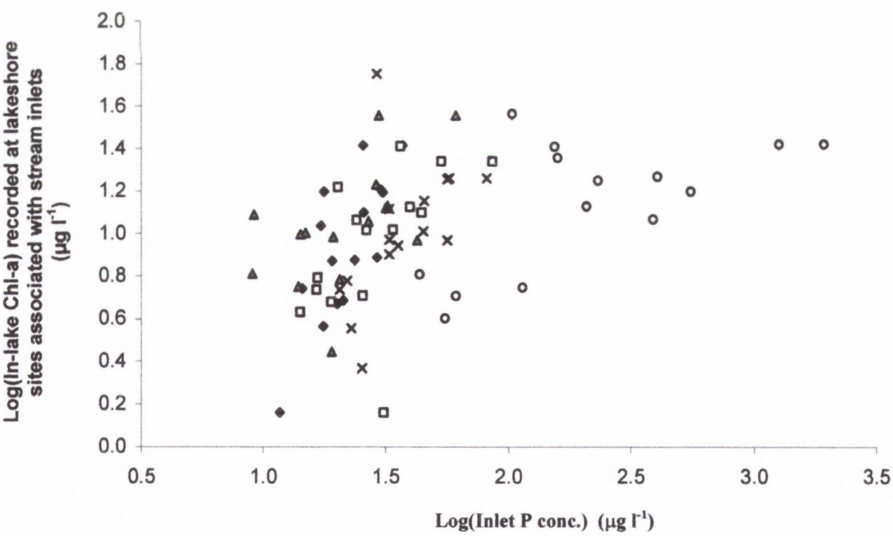

Figure 5.31: Comparison Log(In-lake chlorophyll-*a*) ($\mu g\ l^{-1}$) recorded at lakeshore sites associated with stream inlets against Log(Inlet SRP) in stream 1 (♦), Log(Inlet TDP) in stream 2 (□) and Log(Inlet TP) in streams 4 (▲), 5 (x) and 6 (○) recorded in 2002-03 in the Lough Lickeen catchment. P concentrations are in $\mu g\ l^{-1}$.

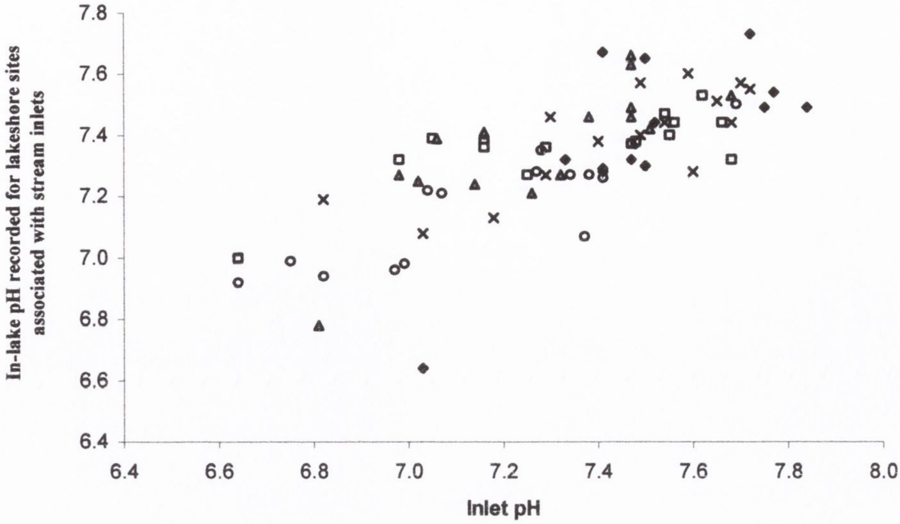

Figure 5.32: Comparison In-lake pH recorded at lakeshore sites associated with stream inlets against Inlet pH in stream 1 (♦), 2 (□), 3 (▲), 5 (x) and 6 (○) recorded in 2002-03 in the Lough Lickeen catchment.

No significant differences in the overall water chemistry were found between lakeshore sites associated with stream inlets ("inlet stream") and those where the influence of a stream was unlikely ("no stream") (M-ANOVA, Appendix 4 – Table 5). However, water chemical variables recorded among the "inlet stream" lakeshore sites covered a greater range of values compared with the "no stream" sites (Figure 5.33 to 5.39).

Statistical modelling of variations in chlorophyll-a concentrations

Stepwise multiple regressions were carried out on the original lake datasets in order to predict in-lake chlorophyll-*a* concentrations based on recorded concentrations of other lake chemical variables (Appendix 4 – Table 6). The best linear model describing the variations of Log(chlorophyll-*a*) (R^2=0.52, n=141, p≤0.001; Figure 5.40) was based on Log(NO_3-N), Log(colour), Log(TP) and Log(Alkalinity) (Equation 5.5), with:

Predicted Log(Chl-a) =

-0.26 * Log(NO_3-N) - 0.25 * Log(colour) + 0.69 * Log(TP) + 1.64 * Log(Alk.) –2.19

Equation 5.5

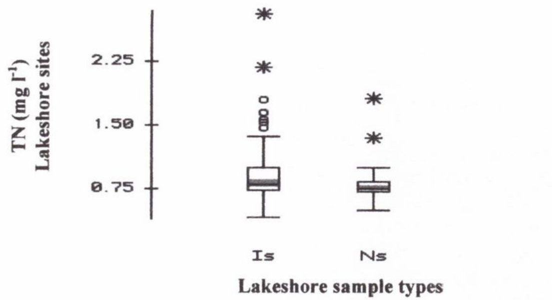

Figure 5.33: Comparison of TN concentrations (mg l^{-1}) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

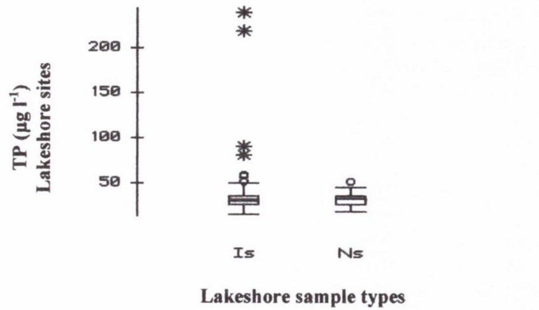

Figure 5.34: Comparison of TP concentrations (µg l^{-1}) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

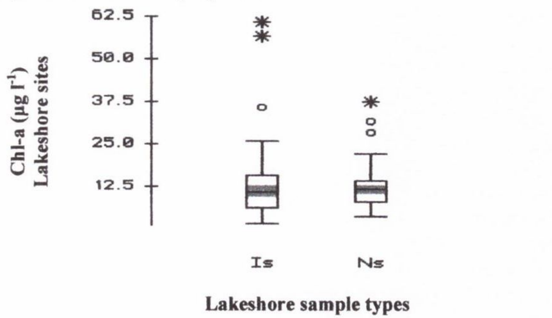

Figure 5.35: Comparison of chlorophyll-*a* concentrations (µg l^{-1}) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

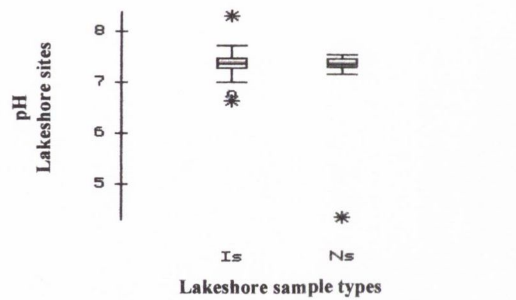

Figure 5.36: Comparison of pH in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

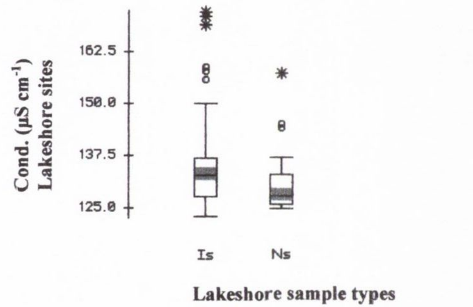

Figure 5.37: Comparison of conductivity (µS cm^{-1}) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

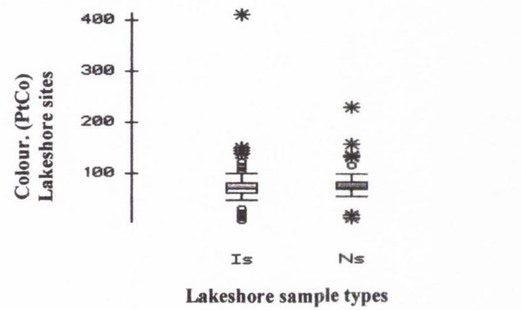

Figure 5.37: Comparison of colour (PtCo) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

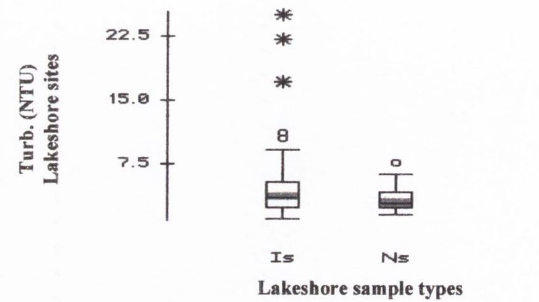

Figure 5.39: Comparison of turbidity (NTU) in lakeshore samples in 2002-03, recorded in “inlet stream” (Is) and “no stream” (Ns) sites [(1)]

<u>Note (1):</u>
The box depicts the central half of the data between the 25% and 75% points. The line across the box displays the median value. The whiskers extend from the top and the bottom of the box to depict the extent of the main body of the data. Extreme values are plotted with a circle. Very extreme data values are plotted with a starburst. The shaded area superimposed on each box is a 95% confidence interval around the median.

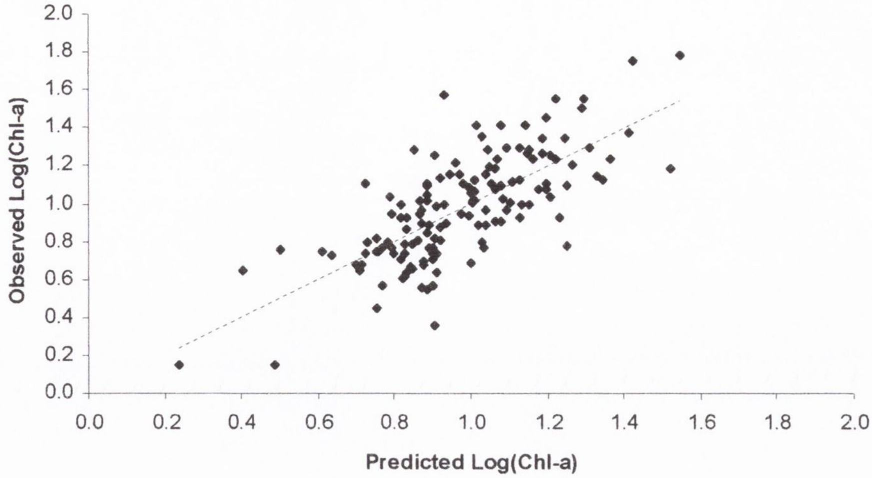

Figure 5.40: Comparison of calculated and predicted Log(Chlorophyll-*a* concentrations) (μg l^{-1}) obtained for Lough Lickeen when applying the equation: *Predicted Log(Chl-a) = -0.26 * Log(NO₃-N) - 0.25 * Log(colour) + 0.69 * Log(TP) + 1.64 * Log(Alk.) – 2.19* (R^2=0.53, df=139, p≤0.001).

Spatial analysis of eutrophication in Lough Lickeen

Spatial distribution of TN, TP, chlorophyll-*a* concentrations and colour within Lough Lickeen were interpolated from monitoring averages using inverse distance weighted (IDW) interpolation method with the *Spatial Analyst* extension of *ArcView 3.2*. Higher NO_3-N concentrations were found mainly on the east side of the lake, especially on the northern shore, while higher TN concentrations were estimated for the southern shore around the inlets of Streams 3, 4 and 5. TP concentrations were higher in the middle part of the lake. The highest chlorophyll-*a* mean and maximum concentrations were found along the southern (between streams 3 and 6) and northeastern shore (near L14 site). Estimates of the lake mean concentrations were calculated based on the GIS interpolations, were found to be very similar to the average concentrations based on the monitoring data (Table 5.14).

Table 5.14: Comparison of lake mean NO_3-N, TN, TP and chlorophyll-*a* concentrations based on GIS interpolations and based on monitoring 2002-03 data.

	GIS Estimates	Monitoring Estimates
NO_3-N	0.08	0.08 ± 0.01
TN	0.81	0.86 ± 0.07
TP	36.5	35.7 ± 7.9
Chlorophyll-*a*	11.3	12.1 ± 4.6

A GIS-based method of the lake eutrophication assessment was undertaken to derive a spatial trophic state index (TSI), that incorporated mean TN, mean TP, mean and maximum chlorophyll-*a* concentrations. A 0-100 eutrophication scale was developed (Table 5.15) to categorise the trophic status within the lake. For each indicator, Equation 5.6 was used to estimate the spatial distribution of trophic status (TS) (OECD, 1982; Xu *et al*, 2001) using the IDW interpolation method with GIS (Figures 5.41 to 5.44).

$$\mathbf{TSI_i = TSI_{i,\,k-1} + (C_i - S_{i,\,k-1}) \,/\, (S_{i,\,k} - S_{i,\,k-1}) * (TSI_{i,\,k} - TSI_{i,\,k-1})}$$

Equation 5.6

Where:
C_i: measured concentrations of the i-th indicator (I=mean TN, mean TP, mean and maximum chlorophyll-*a* concentrations);
$TSI_{i,\,k}$ and $TSI_{i,\,k-1}$: k-th and (k-1)-th scales of the i-th indicator
$S_{i,\,k}$ and $S_{i,\,k-1}$: upper limit concentrations of the k-th and (k-1)-th scales of the i-th indicator.

Each cell (5*5 m^2) of each thematic map was assigned a value from 0 to 100 based on a comparison between its initial value (TS based on recorded concentrations) and the eutrophication scales (Table 5.15, Equation 5.6).

Table 5.15: Scale of trophic state index (TSI) (OECD, 1982, Xu *et al*, 2001), based on mean TP, mean TN, mean and maximum chlorophyll-*a* (Chla) concentrations.

TSI	Mean TP ($\mu g\ l^{-1}$)	Mean Chla ($\mu g\ l^{-1}$)	Max Chla ($\mu g\ l^{-1}$)	Mean TN ($mg\ l^{-1}$)	
0	<4	<1	<2.5	<0.01	Ultra-Oligotrophic
10	4-5.5	1.0-1.3	2.5-3.9	0.01-0.15	Oligotrophic
20	5.5-7	1.3-1.7	3.9-5.2	0.15-0.30	Oligotrophic
30	7-8.5	1.7-2.1	5.2-6.6	0.30-0.45	Oligotrophic
40	8.5-10	2.1-2.5	6.6-8	0.45-0.60	Oligotrophic
50	10-23	2.5-5.3	8-16.5	0.6-0.8	lower Mesotrophic
60	23-35	5.3-8	16.5-25	0.8-1.0	higher Mesotrophic
70	35-56.7	8-13.7	25-35	1.0-1.7	moderately Eutrophic
80	56.7-78.4	13.7-19.4	35-55	1.7-2.4	strongly-Eutrophic
90	78.4-100	19.4-25	55-75	2.4-3	highly-Eutrophic
100	>100	>25	>75	>3	Hypertrophic

The four thematic maps were analysed on a cell-by-cell basis to produce a final map (Figure 5.45 – Appendix 4/Lickeen Spatial TSI) of trophic state of Lough Lickeen. Equation 5.7 was used in the overlay operation to produce the TSI values:

$$\mathbf{TSI = TSI_{TP} * W_{TP} + TSI_{TN} * W_{TN} + TSI_{Chl\text{-}a} * W_{Chl\text{-}a} + TSI_{MxChl\text{-}a} * W_{MxChl\text{-}a}}$$

Equation5.7

where TSI_{TP}, TSI_{TN}, $TSI_{Chl\text{-}a}$ and $TSI_{MxChl\text{-}a}$ are the eutrophication levels for mean TP, TN, chlorophyll-*a* concentrations and maximum chlorophyll-*a* concentrations on the six thematic layers and W_{TP}, W_{TN}, $W_{Chl\text{-}a}$ and $W_{MxChl\text{-}a}$ are the weighting factors for each indicator (assumed as ¼ in this case).

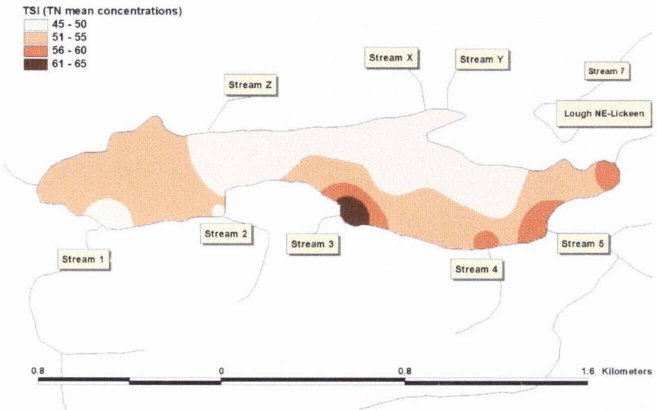

Figure 5.41: Spatial distribution of the lake trophic state index (scale 0-100) based on mean TN concentrations in Lough Lickeen

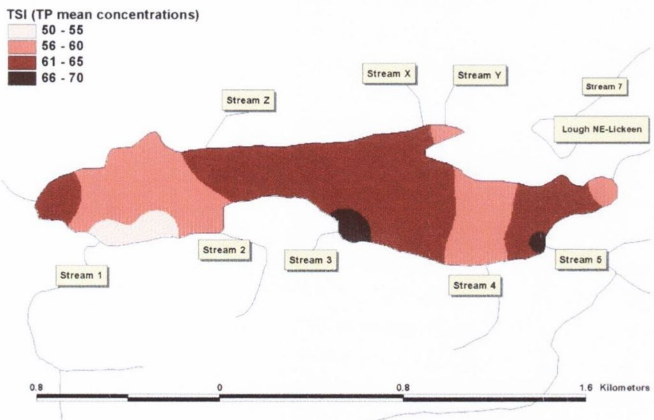

Figure 5.42: Spatial distribution of the lake trophic state index (scale 0-100) based on mean TP concentrations in Lough Lickeen

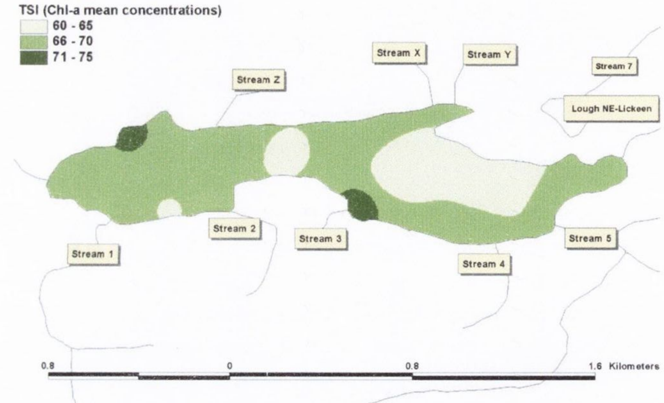

Figure 5.43: Spatial distribution of the lake trophic state index (scale 0-100) based on mean chlorophyll-*a* concentrations in Lough Lickeen

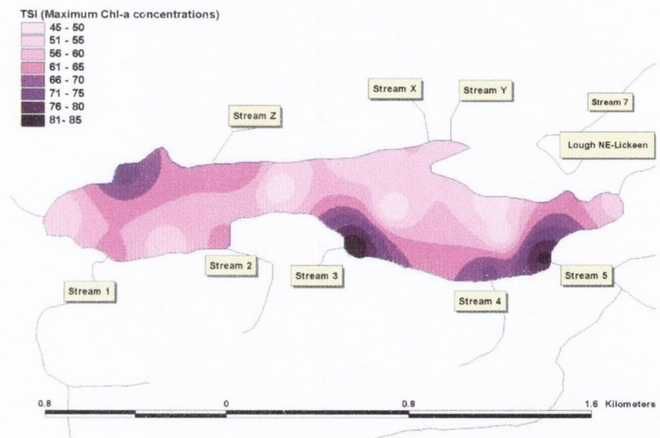

Figure 5.44: Spatial distribution of the lake trophic state index (scale 0-100) based on maximum chlorophyll-*a* concentrations in Lough Lickeen

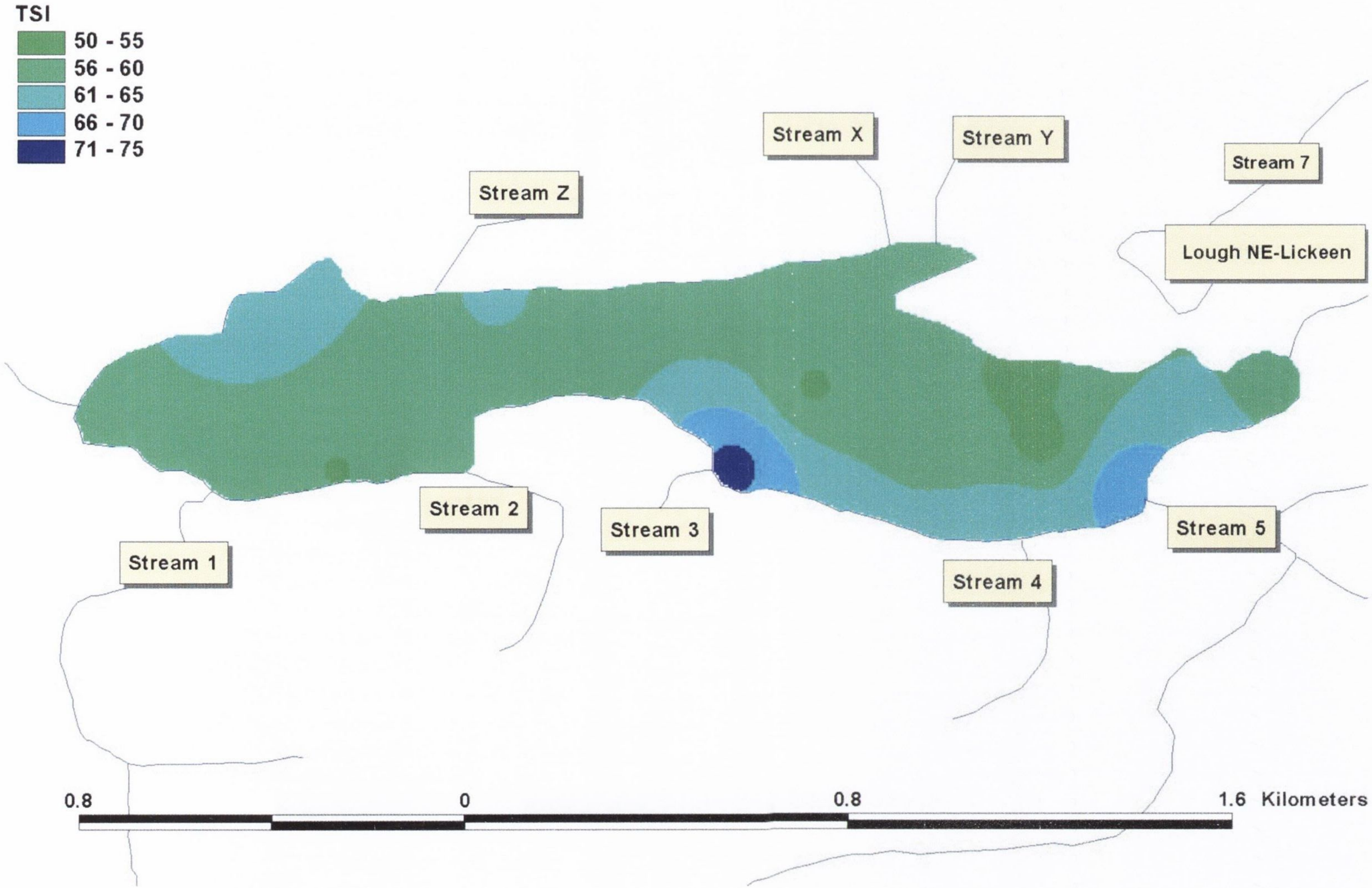

Figure 5.45: Spatial distribution of the eutrophication (scale 0-100) in Lough Lickeen based on overlay technique using mean TN, TP, chlorophyll-*a* and maximum chlorophyll-*a* concentrations as indicators.

The overall TSI ranged from 53 (lower mesotrophic) to 71 (strongly eutrophic) within Lough Lickeen, with a mean value of 59 (lower mesotrophic). Trophic states based on mean TP and chlorophyll-*a* concentrations gave a greater overall mean of, respectively, 60 and 66 (higher mesotrophic), but showed a lower range of variations. Based on the mean TN concentrations, the overall mean was lower (51). Maximum chlorophyll-*a* concentrations gave a similar mean to the overall TSI, but showed a greater range of variations (46: oligotrophic to 83: strongly-eutrophic).

Based on overall TSI spatial distribution, mesotrophic conditions (TSI 50-60) predominate in Lough Lickeen, with eutrophic conditions (TSI 60-70) observed mainly on the southeastern shore along the inlets of streams 3, 4 and 5. Eutrophic conditions were also prevalent along the northern shore, likely associated with overland run-off from nearby farmyards (Figure 5.46). No obvious surface connection between Lough Northeast Lickeen and the main lake were observed in low flow conditions, but during high water-level conditions, the two lakes were linked. Potential overland run-off/surface drainage pathways were modelled between the two lakes and could explain the eutrophic conditions observed on the northeastern shore (Figure 5.47). Hypertrophic conditions (TSI 70-80) were observed at the inlet of stream 3, which drains conifer plantations.

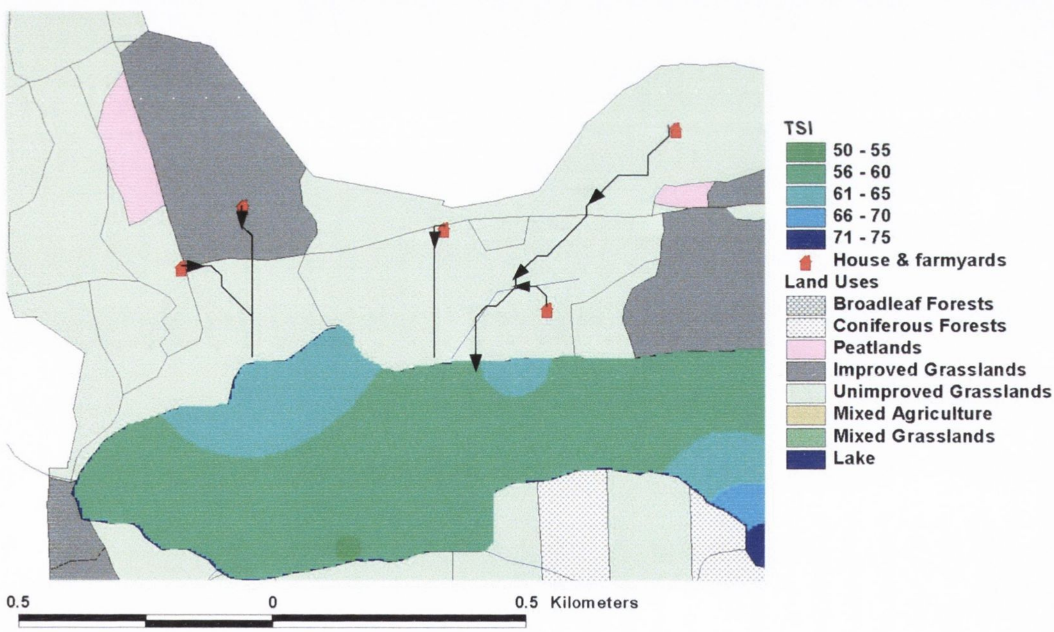

Figure 5.46: Modelled overland run-off pathways from house and farmyards into Lough Lickeen – northwestern shore (black arrows). Catchment land uses and lake TSI are also shown.

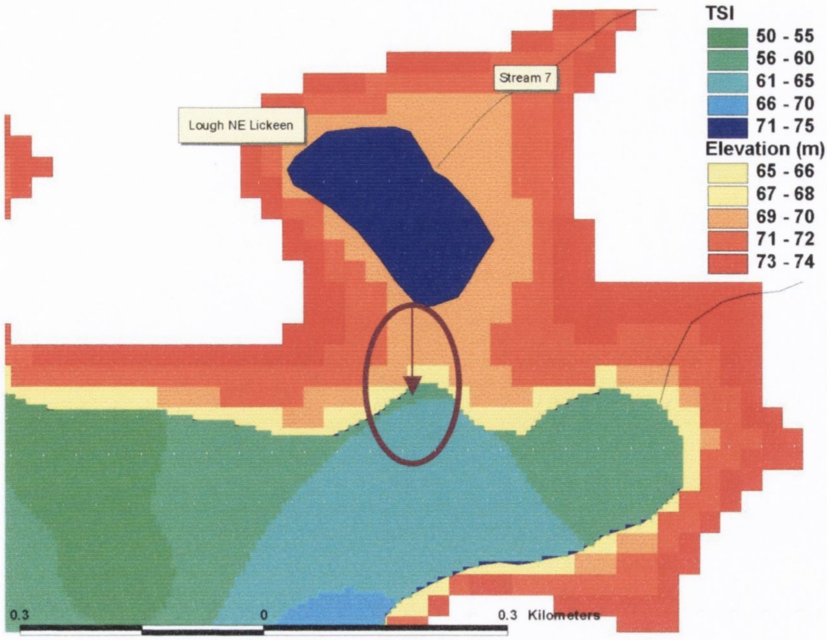

Figure 5.47: Modelled overland run-off pathways / surface connection between Lough Northeast Lickeen and Lough Lickeen. Catchment DEM and lake TSI are also shown.

Stream water chemistry

- Stream basin water chemistry

Generally, low concentrations of nitrogen were recorded in the inflowing streams. Highest mean concentrations of 0.38 mg l^{-1} NO_3-N and 2.16 mg l^{-1} TN were found in Stream 7. Average TP concentrations were highly variable, ranging from 23.5 µg l^{-1} (Stream 4) to 313.1 µg l^{-1} (Stream 7). Three streams (Streams 2, 5 and 7) had an average pH lower than 6.3, with a minimum value of 4.67 recorded in Stream 7. Except for the outflow and Stream 4, average concentrations of total dissolved organic carbon (TDOC) were moderate to high, and the water highly coloured. A maximum mean value of 407 PtCo was found in Stream 7. Streams 6, 7 and Y had the highest mean values of nutrient concentrations, TDOC, conductivity, colour and turbidity. Generally low values were recorded for Streams 4, Z and the lake outflow (Tables 5.16 and 5.17; Figures 5.48 to 5.50).

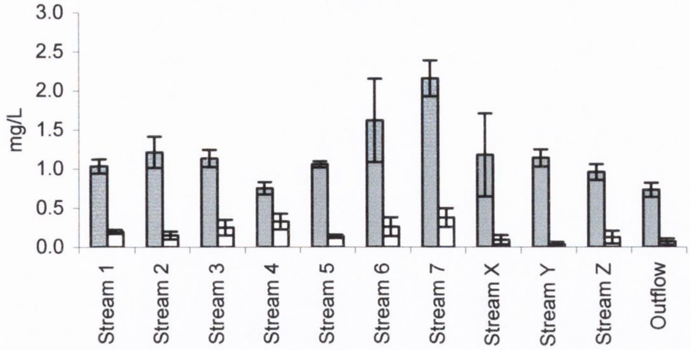

Figure 5.48: Distribution of TN (grey shade) and NO_3-N (white shade) mean concentrations (mg l^{-1}) among the stream basins of Lough Lickeen catchment. Means are calculated based on data recorded between February 2002 and March 2003 ($n \leq 15$) for all sites on each inflowing stream - 95 % confidence intervals are also shown.

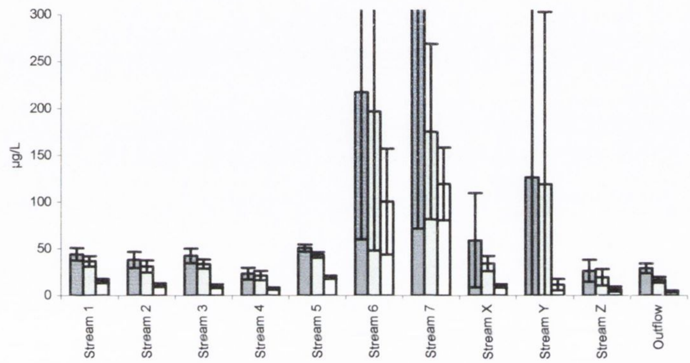

Figure 5.49: Distribution of TP (grey shade), TDP (grey stripes) and SRP (white shade) average concentrations (µg l^{-1}) among the stream basins of Lough Lickeen catchment. Means are calculated based on data recorded between February 2002 and March 2003 ($n \leq 15$) for all sites on each inflowing stream - 95 % confidence intervals are also shown.

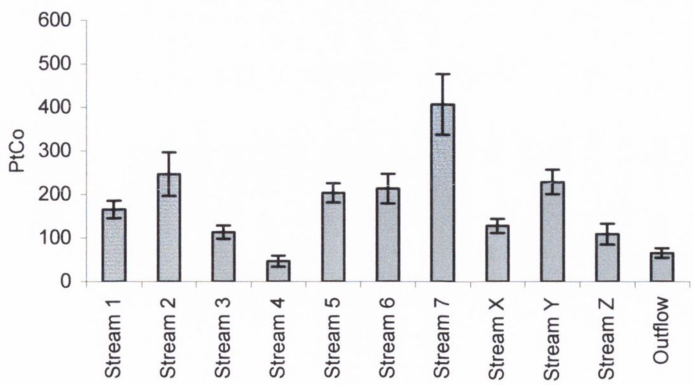

Figure 5.50: Distribution of colour average concentrations (PtCo) among the stream basins of Lough Lickeen catchment. Means are calculated based on data recorded between February 2002 and March 2003 ($n \leq 15$) for all sites on each inflowing stream - 95 % confidence intervals are also shown.

Table 5.16: Summary overall mean chemistry by stream basin in Lough Lickeen catchment monitoring February 2002 – March 2003, providing mean concentrations of N fractions (NO_3-N, TN); P fractions (TP, TDP, SRP) and TDOC – 95% confidence intervals (95% CI) in italics and total number of samples per stream basin (n) are also given.

Stream	n	NO_3-N mg l^{-1}	*95% CI*	TN mg l^{-1}	*95% CI*	TP µg l^{-1}	*95% CI*	TDP µg l^{-1}	*95% CI*	SRP µg l^{-1}	*95% CI*	TDOC mg l^{-1}	*95% CI*
1	64	0.20	*0.02*	1.04	*0.09*	44.3	*6.8*	36.8	*5.6*	15.4	*2.2*	15.2	*1.3*
2	29	0.15	*0.05*	1.21	*0.2*	38.2	*8.6*	31.5	*6.4*	11.2	*2.0*	21.3	*3.2*
3	29	0.25	*0.1*	1.13	*0.11*	42.5	*7.7*	33.7	*4.9*	10.0	*2.0*	13.6	*1.5*
4	19	0.33	*0.1*	0.75	*0.08*	23.5	*6.2*	21.2	*5.0*	7.4	*1.3*	6.7	*1.9*
5	239	0.14	*0.02*	1.06	*0.04*	51.0	*3.7*	43.5	*3.1*	19.5	*1.7*	19.3	*1.1*
6	29	0.26	*0.12*	1.62	*0.53*	217.3	*157.3*	196.9	*148.8*	100.6	*56.5*	19.2	*2.8*
7	27	0.38	*0.12*	2.16	*0.23*	313.1	*241.3*	175.3	*93.5*	119.7	*38.9*	35.9	*4.1*
X	15	0.09	*0.06*	1.18	*0.53*	59.1	*50.4*	34.2	*8.2*	10.2	*1.9*	16.5	*2.1*
Y	15	0.04	*0.03*	1.14	*0.11*	126.5	*192.2*	119.2	*183.6*	11.5	*6.1*	24.2	*2.9*
Z	8	0.13	*0.08*	0.96	*0.1*	26.3	*11.7*	19.4	*8.8*	6.8	*2.7*	12.3	*1.8*
Outflow	15	0.07	*0.04*	0.73	*0.09*	29.0	*5.3*	16.6	*3.2*	4.1	*1.0*	10.4	*1.7*

Table 5.17: Summary overall mean chemistry by stream basin in Lough Lickeen catchment monitoring February 2002 – March 2003, providing mean values of pH, alkalinity (Alk.), conductivity (Cond.) and turbidity (Turb.) – 95% confidence intervals (95% CI) in italics and total number of samples per stream basin (n) are also given.

Stream	n	pH	*95% CI*	Alk. mgCaCO$_3$ l^{-1}	*95% CI*	Cond. µS cm^{-1}	*95% CI*	Colour PtCo	*95% CI*	Turb. NTU	*95% CI*
1	64	6.96	*0.10*	35.8	*5.5*	170.3	*9.3*	165	*20*	5.7	*1.3*
2	29	6.29	*0.25*	26.3	*6.3*	164.4	*11.7*	247	*50*	7.0	*2.4*
3	29	6.83	*0.17*	30.7	*4.4*	149.7	*9.3*	114	*15*	8.4	*4.3*
4	19	7.42	*0.10*	39.7	*7.5*	169.7	*9.5*	47	*13*	3.9	*1.5*
5	239	6.01	*0.10*	41.1	*4.7*	139.9	*15.9*	203	*22*	7.6	*4.7*
6	29	6.95	*0.12*	40.9	*13.1*	177.8	*32.4*	213	*34*	5.5	*2.3*
7	27	4.61	*0.35*	60.4	*8.3*	207.5	*15.6*	407	*70*	41.0	*25.2*
X	15	7.63	*0.16*	71.8	*16.3*	216.6	*25.9*	128	*16*	14.5	*20.0*
Y	15	7.32	*0.15*	49.4	*6.5*	179.4	*11.8*	229	*28*	11.8	*5.7*
Z	8	7.23	*0.28*	58.5	*23.1*	216.6	*42.0*	109	*24*	7.1	*5.3*
Outflow	15	7.30	*0.11*	23.1	*2.8*	135.9	*6.5*	66	*11*	3.4	*1.0*

Streams with high mean nutrient concentrations were associated with high colour, TDOC concentrations and low pH values (Table 5.18).

Table 5.18: Pearson's Product-Moment correlation coefficients between stream monthly averages (n=11). Correlation coefficients significant at $p \leq 0.05$ are in bold and at $p \leq 0.01$ are underlined.

	LogTN	LogTP	LogTDP	LogSRP	LogTDOC	pH	LogColour
LogTN	1.00						
LogTP	**0.89**	1.00					
LogTDP	**0.85**	**0.97**	1.00				
LogSRP	**0.90**	**0.89**	**0.89**	1.00			
LogTOC	**0.86**	**0.81**	**0.77**	<u>**0.70**</u>	1.00		
pH	<u>**-0.70**</u>	-0.54	-0.48	<u>**-0.68**</u>	<u>**-0.69**</u>	1.00	
LogColour	**0.87**	**0.77**	**0.77**	**0.74**	**0.98**	**-0.71**	1.00

- Monitoring sites water chemistry

TN mean concentrations over the monitoring period (February 02 - March 03) ranged from 0.73 mg l^{-1} (outflow) to 2.39 mg l^{-1} (site 7a), while NO_3-N mean concentrations ranged from 0.02 mg l^{-1} (site 5e) to 0.41 mg l^{-1} (site 7a) (Table 5.19). TP mean concentrations ranged from 25 μg l^{-1} (site 4a) to 416 μg l^{-1} (site 7b), TDP mean concentrations from 17 μg l^{-1} (outflow) to 348 μg l^{-1} (site 6a) and SRP mean concentrations from 4 μg l^{-1} (outflow) to 186 μg l^{-1} (site 6a) (Table 5.19). Significant positive correlations (n=489, $p \leq 0.05$) were found between Log(TP) and Log(TDP) (r_p=0.92) and Log(SRP) (r_p=0.77). Log (TDP) and Log(SRP) were also positively correlated (n=489, $p \leq 0.05$, r_p=0.84).

Stream mean colour values were high, with a minimum value of 53 obtained for site 4a and a maximum of 475 PtCo for site 5m. Streams had moderate to high TDOC mean concentrations, ranging from 7.4 mg l^{-1} (site 4a) to 37.1 mg l^{-1} (site 7a) (Table 5.19). Finally Log(Colour) was positively correlated (n=489, $p \leq 0.05$) with Log(TP) (r_p=0.50), Log(TDP) (r_p=0.53) and Log(SRP) (r_p=0.52). Stream mean pH also covered a wide range with a minimum value of 4.35 for site 7a, while maximum mean pH was obtained for site 5s with 7.72 (Table 5.19).

Table 5.19: Summary of mean water chemistry of the sites monitored in the Lough Lickeen catchment between February 2002 and March 2003 – Total number of samples (n) and 95% confidence intervals (95% CI) are provided.

Sites	n	NO_3-N mg l^{-1}	TN mg l^{-1}	TP µg l^{-1}	TDP µg l^{-1}	SRP µg l^{-1}	TDOC mg l^{-1}	pH	Alk . mg$CaCO_3$ l^{-1}	Cond. µS cm^{-1}	Colour PtCo	Turb. NTU
1a	15	0.27	1.07	52.6	45.6	22.7	14.0	7.47	47.2	191.2	157	5.9
95% CI		*0.04*	*0.14*	*15.8*	*12.1*	*3.8*	*2.6*	*0.11*	*10.2*	*17.7*	*38*	*3.8*
1b	4	0.26	1.04	51.1	36.0	18.0	10.9	7.16	50.4	200.5	106	9.3
95% CI		*0.14*	*0.84*	*51.2*	*18.7*	*17.3*	*18.5*	*2.25*	*138.7*	*112.6*	*212*	*69.5*
1c	15	0.18	1.01	38.3	34.9	12.9	14.9	7.22	38.0	166.7	163	5.4
95% CI		*0.05*	*0.21*	*11.9*	*11.2*	*3.6*	*2.7*	*0.16*	*11.4*	*18.4*	*43*	*1.9*
1d	15	0.12	0.95	33.3	24.6	8.0	18.3	6.53	11.1	131.2	211	4.3
95% CI		*0.04*	*0.26*	*13.7*	*8.6*	*1.7*	*3.4*	*0.20*	*3.6*	*8.6*	*58*	*2.5*
1e	15	0.20	1.12	51.1	42.2	17.4	14.5	7.20	43.0	184.1	145	6.4
95% CI		*0.06*	*0.22*	*19.4*	*17.0*	*5.9*	*2.7*	*0.13*	*10.9*	*21.0*	*38*	*2.7*
2a	15	0.20	1.14	38.7	32.4	11.6	16.3	7.23	33.7	177.6	158	4.9
95% CI		*0.08*	*0.25*	*11.7*	*10.2*	*3.2*	*2.6*	*0.17*	*7.6*	*14.7*	*35*	*1.1*
2b	14	0.09	1.29	37.8	30.6	10.8	26.5	6.00	18.4	150.3	342	9.2
95% CI		*0.04*	*0.35*	*14.3*	*9.1*	*2.8*	*5.0*	*0.35*	*9.4*	*16.8*	*70*	*4.8*
3a	15	0.40	1.26	43.5	38.2	12.9	12.9	7.21	32.9	162.2	98	4.6
95% CI		*0.15*	*0.19*	*6.8*	*6.1*	*2.9*	*2.1*	*0.13*	*7.6*	*12.5*	*16*	*2.2*
3b	14	0.09	1.00	41.4	28.9	6.9	14.3	6.62	28.3	136.4	130	12.4
95% CI		*0.05*	*0.10*	*15.6*	*7.9*	*2.0*	*2.5*	*0.28*	*4.8*	*11.1*	*24*	*8.6*
4a	15	0.27	0.74	24.8	22.3	8.4	7.4	7.44	40.9	173.0	53	2.8
95% CI		*0.08*	*0.07*	*7.6*	*6.2*	*1.3*	*2.4*	*0.11*	*8.3*	*11.1*	*15*	*1.1*
4b	4	0.52	0.80	18.7	17.1	4.0	4.1	7.35	35.0	157.3	24	7.8
95% CI		*0.47*	*0.62*	*20.3*	*15.9*	*4.5*	*4.5*	*0.97*	*96.1*	*72.7*	*91*	*23.9*
5a	15	0.14	0.89	39.6	34.6	13.1	16.4	7.34	43.1	291.6	172	3.3
95% CI		*0.04*	*0.11*	*9.4*	*8.9*	*2.6*	*2.7*	*0.15*	*9.8*	*243.7*	*31*	*0.6*
5b	4	0.18	0.78	49.0	31.3	11.9	14.6	7.38	43.2	213.7	126	3.6
95% CI		*0.11*	*0.21*	*39.8*	*15.6*	*12.2*	*13.2*	*1.37*	*61.3*	*252.0*	*135*	*7.0*
5c	4	0.18	1.04	34.7	19.1	3.6	15.0	7.44	56.6	208.3	93	9.6

Table 5.19 (continued)

Sites	n	NO_3-N mg l^{-1}	TN mg l^{-1}	TP µg l^{-1}	TDP µg l^{-1}	SRP µg l^{-1}	TDOC mg l^{-1}	pH	Alk . mg$CaCO_3$ l^{-1}	Cond. µS cm^{-1}	Colour PtCo	Turb. NTU
95% CI		*0.26*	*0.30*	*38.0*	*14.0*	*3.9*	*14.0*	*1.43*	*96.3*	*95.6*	*136*	*57.7*
5d	15	0.13	0.84	40.3	34.7	10.8	14.2	6.90	32.3	155.6	150	4.3
95% CI		*0.06*	*0.12*	*10.3*	*8.4*	*3.0*	*2.6*	*0.25*	*8.4*	*17.4*	*34*	*1.6*
5e	15	0.02	0.76	39.8	35.6	10.4	16.2	6.16	4.4	112.7	192	2.7
95% CI		*0.01*	*0.13*	*9.7*	*8.7*	*1.9*	*3.7*	*0.19*	*1.6*	*13.8*	*51*	*0.8*
5f	13	0.02	0.90	59.4	38.6	17.3	16.4	5.73	4.1	116.1	206	5.6
95% CI		*0.01*	*0.15*	*19.7*	*11.3*	*8.1*	*4.2*	*0.25*	*2.0*	*16.0*	*68*	*4.2*
5g	15	0.13	1.03	47.4	41.6	18.5	18.7	6.63	40.3	186.4	206	4.2
95% CI		*0.03*	*0.12*	*11.8*	*11.0*	*3.0*	*2.8*	*0.29*	*10.4*	*17.8*	*40*	*1.3*
5h	15	0.04	1.08	45.5	41.6	17.0	25.4	6.20	9.3	169.1	363	7.8
95% CI		0.02	0.20	16.8	15.6	5.8	6.2	0.26	4.5	11.3	214	7.7
5j	15	0.14	1.00	46.1	41.0	18.1	19.6	6.01	43.9	183.6	206	3.6
95% CI		*0.04*	*0.11*	*10.7*	*10.6*	*3.5*	*4.3*	*0.39*	*11.1*	*14.8*	*35*	*0.7*
5k	4	0.20	1.02	39.2	35.4	15.2	17.8	7.21	40.1	175.5	189	4.2
95% CI		*0.05*	*0.50*	*15.6*	*10.4*	*8.2*	*10.6*	*1.50*	*60.1*	*10.7*	*152*	*8.7*
5l	4	0.15	0.90	39.1	34.9	14.6	20.2	7.25	37.9	172.0	194	3.6
95% CI		*0.04*	*0.31*	*19.9*	*10.4*	*7.2*	*20.8*	*1.60*	*55.5*	*9.1*	*177*	*8.4*
5m	15	0.02	1.24	85.8	72.9	40.1	35.6	5.62	13.9	167.1	475	4.7
95% CI		*0.01*	*0.17*	*24.2*	*21.7*	*13.5*	*7.1*	*0.42*	*16.9*	*14.2*	*210*	*4.1*
5n	4	0.02	0.94	76.4	61.3	34.0	32.3	4.56	-0.4	208.8	272	11.9
95% CI		*0.04*	*0.35*	*90.4*	*17.9*	*30.7*	*13.1*	*3.07*	*16.5*	*143.1*	*371*	*83.9*
5o	15	0.15	1.07	47.6	44.0	22.8	18.7	7.26	38.1	165.7	195	4.5
95% CI		*0.06*	*0.12*	*10.8*	*10.0*	*4.4*	*2.5*	*0.12*	*8.0*	*12.7*	*34*	*1.5*
5p	15	0.12	1.19	51.0	47.6	30.9	20.2	7.09	38.3	166.2	215	3.3
95% CI		*0.03*	*0.23*	*11.1*	*10.1*	*10.2*	*2.3*	*0.15*	*8.4*	*13.9*	*34*	*0.6*
5q	12	0.08	1.06	48.6	26.8	7.9	16.9	5.90	11.0	115.9	172	52.5
95% CI		*0.06*	*0.52*	*31.0*	*8.1*	*2.5*	*4.3*	*0.39*	*9.0*	*27.5*	*47*	*103.2*
5r	15	0.22	1.26	53.2	49.0	21.2	16.6	7.19	73.2	234.0	140	7.3
95% CI		*0.07*	*0.23*	*16.2*	*13.9*	*6.4*	*3.7*	*0.25*	*20.5*	*36.4*	*38*	*3.8*

Table 5.19 (continued)

Sites	n	NO_3-N mg l^{-1}	TN mg l^{-1}	TP µg l^{-1}	TDP µg l^{-1}	SRP µg l^{-1}	TDOC mg l^{-1}	pH	Alk . mg$CaCO_3$ l^{-1}	Cond. µS cm^{-1}	Colour PtCo	Turb. NTU
5s	15	0.26	1.22	54.8	50.3	21.9	18.3	7.72	88.0	253.9	125	6.7
95% CI		*0.12*	*0.14*	*16.8*	*15.3*	*7.2*	*5.3*	*0.14*	*21.9*	*39.7*	*15*	*3.5*
5t	15	0.21	1.23	54.0	48.3	20.9	17.1	7.70	89.1	253.6	128	5.4
95% CI		*0.06*	*0.14*	*17.0*	*15.5*	*5.4*	*3.0*	*0.15*	*22.7*	*39.1*	*20*	*1.2*
5u	14	0.35	1.26	57.2	51.9	23.7	17.0	7.67	87.4	249.5	132	7.9
95% CI		*0.27*	*0.16*	*20.1*	*18.5*	*8.1*	*2.8*	*0.14*	*24.2*	*39.2*	*17*	*6.6*
6a	15	0.33	1.96	381.4	348.3	185.5	17.5	7.07	62.0	227.8	192	6.1
95% CI		*0.23*	*1.02*	*293.9*	*279.5*	*92.8*	*4.0*	*0.16*	*20.2*	*51.0*	*54*	*4.3*
6b	14	0.19	1.26	41.6	34.6	9.6	21.0	6.85	18.3	124.3	237	4.8
95% CI		*0.11*	*0.29*	*17.4*	*13.4*	*2.9*	*4.2*	*0.17*	*4.8*	*13.3*	*44*	*1.9*
7a	15	0.41	2.39	230.5	198.7	112.5	37.0	4.35	4.2	193.6	463	38.9
95% CI		*0.21*	*0.35*	*176.4*	*166.8*	*65.8*	*5.7*	*0.58*	*12.2*	*19.6*	*110*	*28.3*
7b	12	0.35	1.87	416.3	143.3	128.7	34.4	6.88	68.1	224.9	337	43.6
95% CI		*0.14*	*0.22*	*542.5*	*46.7*	*43.8*	*6.9*	*0.34*	*11.0*	*24.6*	*76*	*50.3*
X	15	0.09	1.18	59.1	34.2	10.2	16.5	7.63	71.8	216.6	128	14.5
95% CI		*0.06*	*0.53*	*50.4*	*8.2*	*1.9*	*2.1*	*0.16*	*16.3*	*25.9*	*16*	*20.0*
Y	15	0.04	1.14	126.5	119.2	11.5	24.2	7.32	49.4	179.4	229	11.8
95% CI		*0.03*	*0.11*	*192.2*	*183.6*	*6.1*	*2.9*	*0.15*	*6.5*	*11.8*	*28*	*5.7*
Z	8	0.13	0.96	26.3	19.4	6.8	12.3	7.23	58.5	216.6	109	7.1
95% CI		*0.08*	*0.14*	*21.7*	*20.0*	*7.2*	*5.6*	*0.99*	*91.7*	*183.9*	*113*	*27.6*
Outflow	15	0.07	0.73	29.0	16.6	4.1	10.4	7.30	23.1	135.9	66	3.4
95% CI		*0.04*	*0.09*	*5.3*	*3.2*	*1.0*	*1.7*	*0.11*	*2.8*	*6.5*	*11*	*1.0*

Higher nutrient and colour concentrations were located mainly in the streams of the northeastern side of the catchment and in the southeast (Figures 5.51 to 5.54).

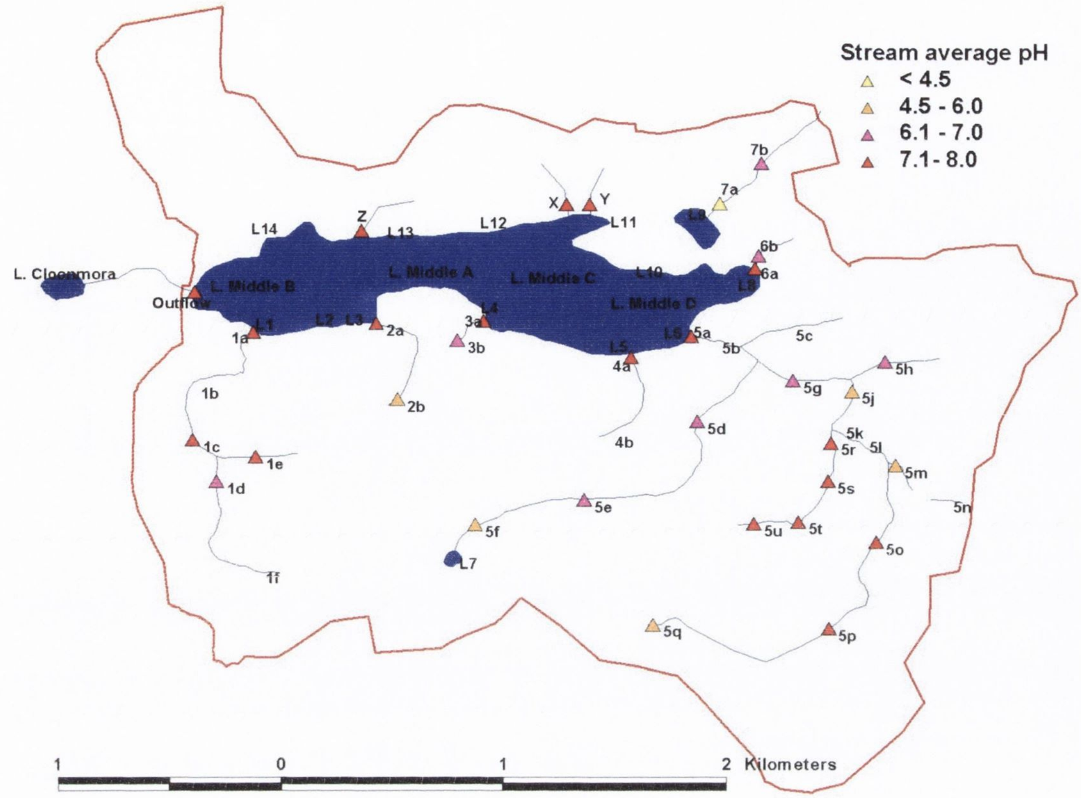

Figure 5.51: Spatial variation in stream mean pH, recorded between February 2002 and March 2003 in Lough Lickeen catchment.

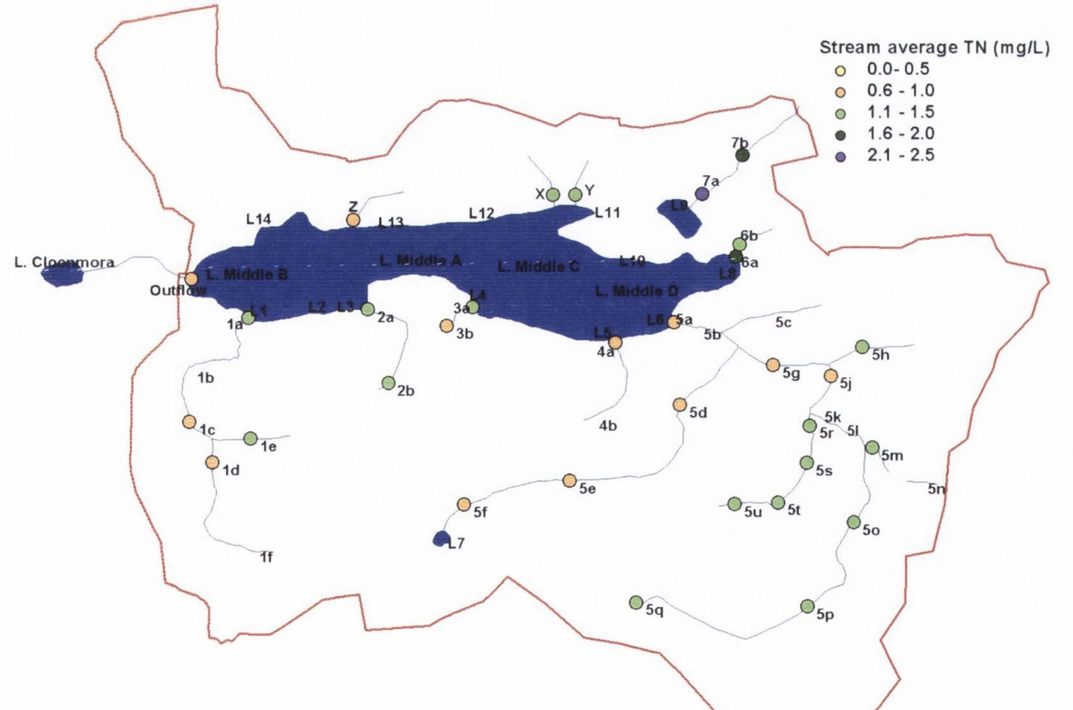

Figure 5.52: Spatial variation in stream mean TN concentrations (mg l^{-1}), recorded between February 2002 and March 2003 in Lough Lickeen catchment.

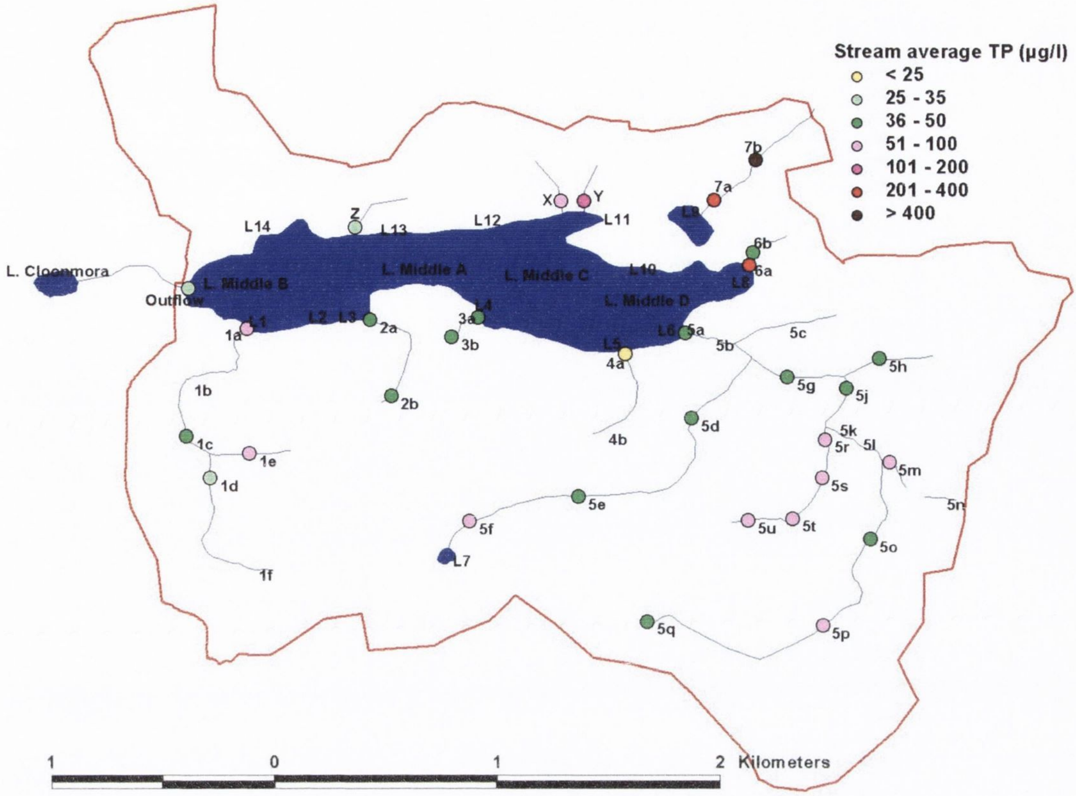

Figure 5.53: Spatial variation in stream mean TP concentrations, ($\mu g\ l^{-1}$), recorded between February 2002 and March 2003 in Lough Lickeen catchment.

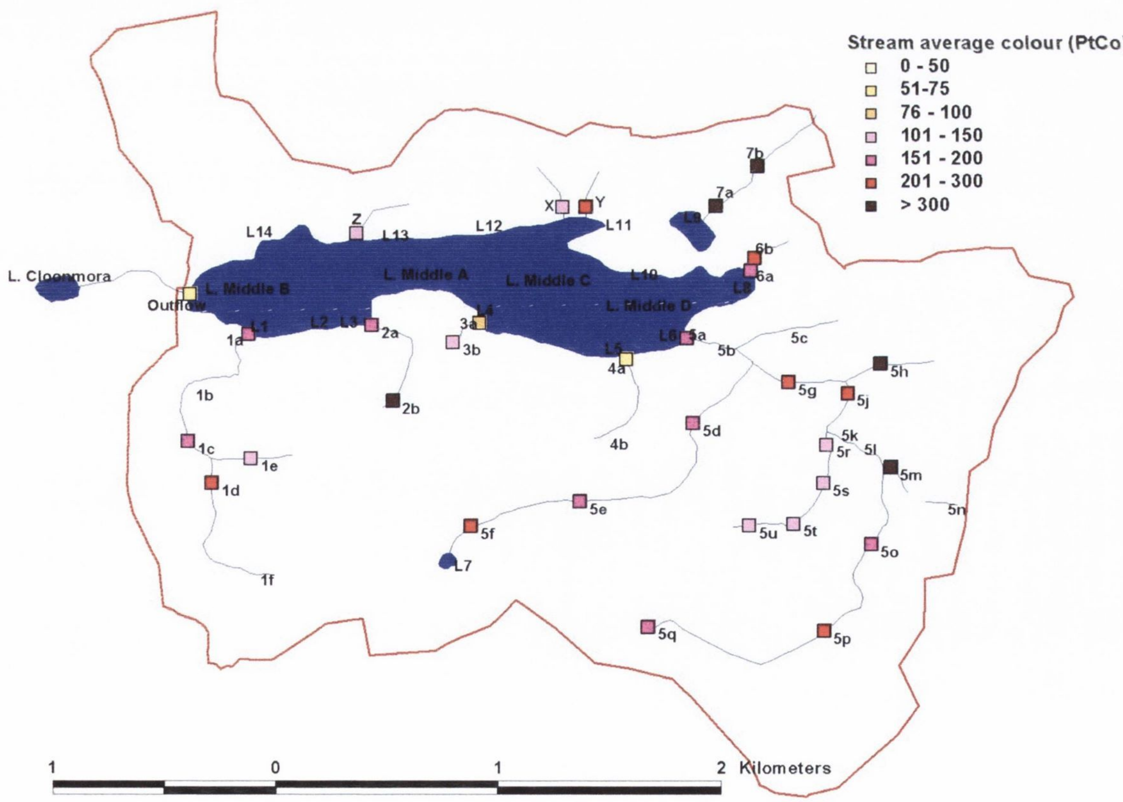

Figure 5.54: Spatial variation in stream mean colour (PtCo), recorded between February 2002 and March 2003 in Lough Lickeen catchment.

Three main groups among the sampling sites most intensively monitored between February 2002-March 2003 (n=31) were identified (Cluster analysis and PCA, Figure 5.55):

- A: High alkalinity streams associated with very high nutrient concentrations, with low turbidity levels (Site 6a) or with high turbidity levels (Sites 7a and 7b),
- B: Streams with lower alkalinity and nutrient concentrations, with very high turbidity levels (Site 5q) and with low colour levels (Sites 3a and 4a),
- C: Streams with lower alkalinity and nutrient concentrations, and high colour (>98 PtCO), with high TP and TDP concentrations (Site Y), with low NO_3-N and high TDOC concentrations, low pH, alkalinity and conductivity levels (Sites 1d, 2b, 5e, 5f, 5h, 5m and 6b) and finally with high NO_3-N and low TDOC concentrations, high pH and alkalinity levels (Sites 5a, 5r, 5s, 5t, 5u, X, Z, 1a, 1c, 1e, 2a, 3b, 5a, 5d, 5g, 5j and 5o).

Significant differences (M-ANOVA, $p \leq 0.05$, Appendix 5 – Table 7) were found among the stream TN, TP, SRP and TDOC concentrations, between winter and summer and among sampling occasions. Higher concentrations were observed for the summer months, except for streams 3 and Y, which had lower summer SRP concentrations. Seasonal variations of chemical variables are exemplified by an analysis of stream 1. NO_3-N concentrations appeared to be very variable over time and no clear seasonal patterns were observed. Daily variations in rainfall in the catchment did not appear to influence the variations in NO_3-N concentrations (Figure 5.56).

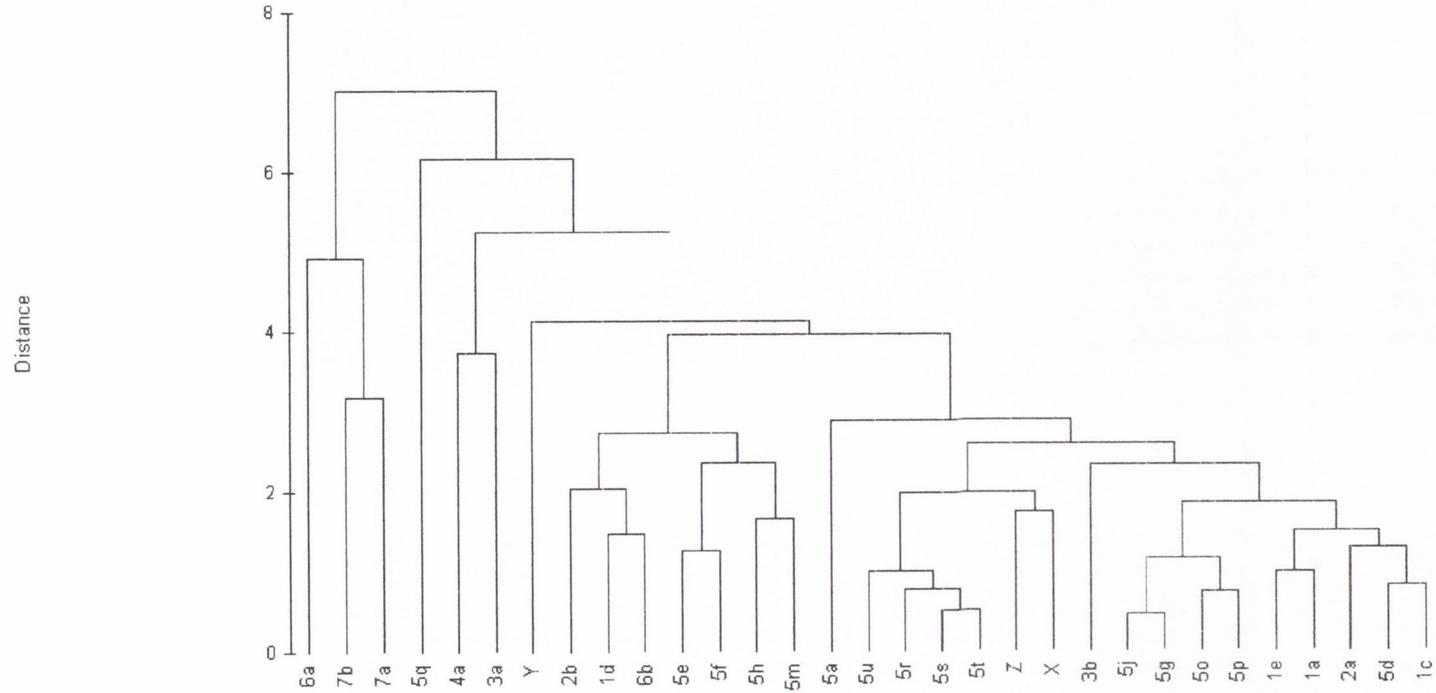

Figure 5.55: Cluster analysis results carried out with *Primer* software on the stream mean chemistry 2002-03 in Lough Lickeen catchment.

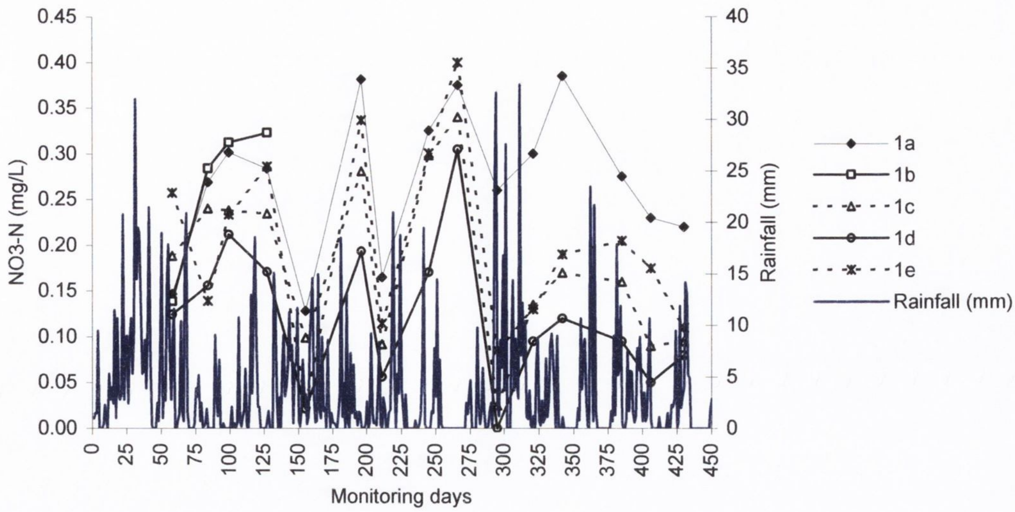

Figure 5.56: Seasonal variations in stream NO_3-N concentrations (mg l^{-1}) among the sites monitored in Stream 1 - February 2002 – March 2003. Daily variations in rainfall recorded in Ennistymon weather station are shown. On the X-Axis: Day 1=1st January 2002 and Day 366=1st January 2003.

Rainfall pattern did not appear to affect in-stream TN concentrations. Generally, TN concentrations decreased over the winter and increased during the spring, with maximum values recorded during the summer (Figure 5.57). TP concentrations in stream 1 were maximum during the summer. Site 1d had a secondary maximum concentration in May 2002 (Figure 5.58). Variations in stream TDP and SRP concentrations were assumed to follow the same seasonal patterns as significant positive correlations were found previously between TP, SRP and TDP concentrations in the inflowing streams.

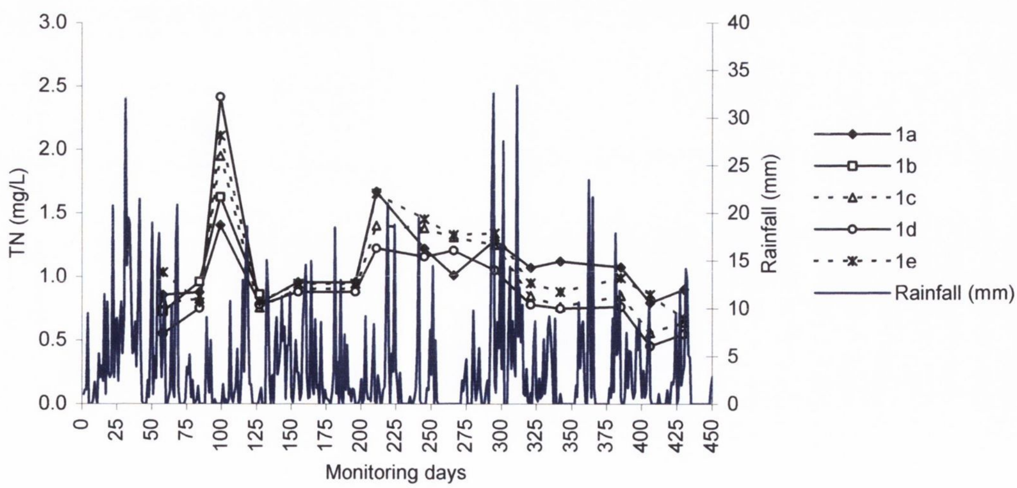

Figure 5.57: Seasonal variations in stream TN concentrations (mg l^{-1}) among the sites monitored in Stream 1 - February 2002 – March 2003. Daily variations in rainfall recorded in Ennistymon weather station are shown. On the X-Axis: Day 1=1st January 2002 and Day 366=1st January 2003.

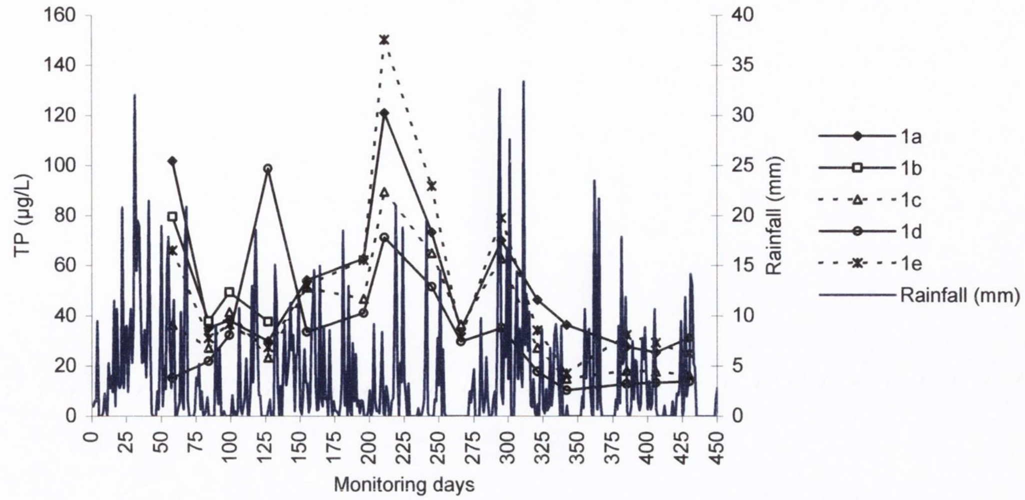

Figure 5.58: Seasonal variations in stream TP concentrations (µg l^{-1}) among the sites monitored in Stream 1 - February 2002 – March 2003. Daily variations in rainfall recorded in Ennistymon weather station are shown. On the X-Axis: Day 1=1st January 2002 and Day 366=1st January 2003.

Alkalinity recorded among sites in stream 1 showed a great variability over the monitoring period and was not influenced by rainfall (Figure 5.59). Colour showed a clear increase in spring, with maximum values during the summer, and subsequent decrease in winter (Figure 5.60).

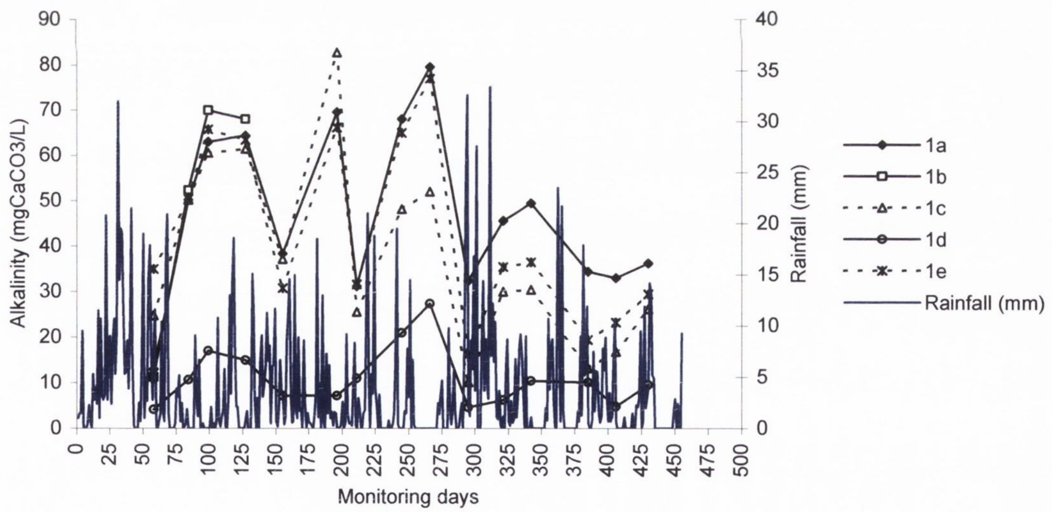

Figure 5.59: Seasonal variations in stream alkalinity (mg $CaCO_3$ l^{-1}) among the sites monitored in Stream 1 - February 2002 – March 2003. Daily variations in rainfall recorded in Ennistymon weather station are shown. On the X-Axis: Day 1=1st January 2002 and Day 366=1st January 2003.

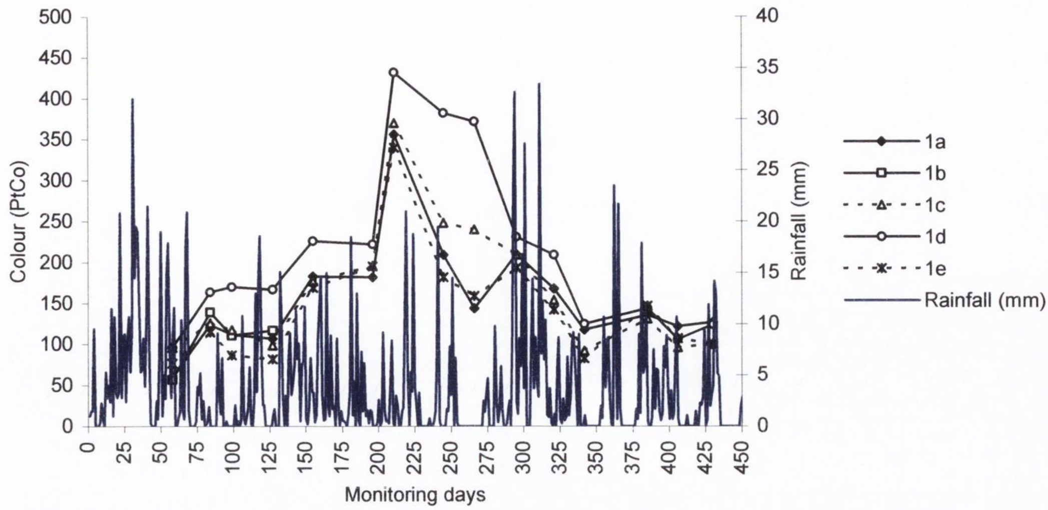

Figure 5.60: Seasonal variations in stream colour (PtCo) among the sites monitored in Stream 1 - February 2002 – March 2003. Daily variations in rainfall recorded in Ennistymon weather station are shown. On the X-Axis: Day 1=1st January 2002 and Day 366=1st January 2003.

Overall water chemistry of the monitored sites was found to be significantly different (M-ANOVA, $p \leq 0.05$, Appendix 5 – Table 8) among the ten stream basins between winter and summer and among sampling occasions. For each site, measured chemical variables (excluding TN and TDOC concentrations and pH and alkalinity levels) were found to be significantly different ($p \leq 0.05$) between winter and summer, with higher concentrations recorded generally during the summer.

Soil chemistry

- Overall soil chemistry

Soils in the Lickeen catchment (Table 5.20) were acidic, with recorded pH ranging from 3.93 (site 5f) to 6.32 (site 5j). Soils had moderate to high organic content, with %OM ranging from 12.8% (site 5j) to 88.9% (site 5f); %OM was significantly higher in soils classified as peats compared with gleys (Two sample t-test and Mann-Whitney U test, $p \leq 0.001$). Carbonate content in all soils was low, ranging from 2.1 % (site 5f) to 7 % (site 7a). Extractable iron levels were low to moderate, with a minimum of 5.5 mg Fe / g dry soil (site L13), a maximum of 24.5 (site 5q) and a mean of 12.1 mg Fe / g dry soil.

Table 5.20: Description of the soil general chemistry in October 2002 in the Lough Lickeen catchment, listing the soil types as observed in the field, pH (measured on dry soil), organic matter (%OM) and carbonates (% Carbonates) contents and also extractable Iron (mg Fe / g dry soil)

Sites	Soil Types	pH	% OM	% Carbonates	Extractable Fe (mg Fe/g dry soil)
1a	Gley	5.41	15.4	6.5	15.5
1b	Gley	5.20	25.3	5.7	16.8
1c	Gley	5.23	21.7	5.1	11.7
1d	Gley	5.32	17.7	5.2	14.4
1e	Gley	5.21	13.3	4.3	9.0
1f	Peat	4.96	75.4	4.9	12.6
2a	Gley	5.33	15.9	6.0	13.3
2b	Peaty Gley	5.41	33.9	4.0	12.3
3a	Gley	4.77	27.2	3.1	5.6
3b	Peat	4.51	71.9	2.8	5.5
4a	Gley	5.07	17.6	4.7	13.6
4b	Gley	5.14	16.6	4.0	10.2
5a	Gley	6.09	13.9	3.9	10.9
5b	Gley	5.42	13.0	4.1	10.0
5c	Gley	5.06	25.9	4.5	13.4
5d	Gley	5.24	13.9	3.7	10.9
5e	Gley	5.48	16.6	4.0	12.6
5f	Peat	3.93	88.9	2.1	7.5
5g	Gley	5.17	17.6	4.5	17.0
5h	Gley	4.37	14.9	4.1	8.8
5j	Gley	6.32	12.8	3.3	6.5
5k	Gley	5.40	18.3	5.1	13.9
5l	Gley	5.82	18.8	4.1	12.4
5m	Gley	4.81	32.5	4.2	13.1
5n	Peaty Gley	5.24	34.4	4.2	15.0
5o	Gley	5.09	21.4	5.4	23.1
5p	Gley	4.45	17.0	4.4	18.3
5q	Peat	4.87	67.0	5.8	24.5
5r	Gley	4.71	17.8	5.5	15.2
5s	Gley	5.34	18.0	5.7	12.6
5t	Gley	5.40	23.2	3.7	9.6
5u	Peaty Gley	5.46	34.8	5.0	9.1
6a	Peaty Gley	5.44	32.3	5.6	9.0
6b	Peaty Gley	5.43	34.2	5.0	8.1
7a	Gley	5.84	32.2	7.0	10.5
7b	Peat	5.03	76.0	3.1	8.4
X	Gley	5.16	19.3	5.4	17.4
Y	Peat	4.46	35.3	3.4	9.2
Z	Gley	5.12	17.5	4.2	6.8
L2	Gley	5.05	19.7	4.1	10.2
L10	Gley	5.44	15.2	4.9	14.3
L11	Gley	4.90	19.8	4.4	11.1
L12	Gley	5.25	17.5	6.6	13.4
L13	Gley	5.37	14.6	5.0	5.5
L14	Gley	4.81	17.1	6.1	14.6

Soils had low to moderate water extractable and Morgan P levels. Means of soil Morgan P for the three sampling occasions ranged from 1.6 mg PO_4-P $l^{-1}_{dry\ soil}$ (site L13) to 11.0 mg PO_4-P $l^{-1}_{dry\ soil}$ (site 7a). Total dissolved water extractable P (TDPw) ranged from 2.8 mg PO_4-P $l^{-1}_{dry\ soil}$ (site 1f) to 18.7 mg PO_4-P $l^{-1}_{dry\ soil}$ (site 5k), while soluble reactive water extractable P (SRPw) ranged from 1.2 mg PO_4-P $l^{-1}_{dry\ soil}$ (site 1f) to 10.9 mg PO_4-P $l^{-1}_{dry\ soil}$ (site 5k) (Table 5.21, Figure 5.61). Soil P level results were significantly different between sampling occasions for the same site (M-ANOVA, $p<0.01$, Appendix 5 – Table 9). Log(mean Soil Morgan P) was significantly correlated ($n=45$, $p\leq0.05$) with Log(mean SRPw) ($r_p=0.56$) and Log(mean TDPw) ($r_p=0.42$). Higher means of soil Morgan P concentrations were recorded for soil with greater organic matter content.

Table 5.21: Description of the soil P status in the Lough Lickeen catchment, giving mean concentrations and 95% confidence intervals (95% CI), of soluble reactive water extractable P (SRPw in mg PO_4-P $l^{-1}_{dry\ soil}$), total dissolved water extractable P (TDPw in mg PO_4-P $l^{-1}_{dry\ soil}$) and soil Morgan P (mg PO_4-P $l^{-1}_{dry\ soil}$) and total number of samples (n)

Sample	n	SRPw	95% CI	TDPw	95% CI	Morgan P	95% CI
1a	3	3.2	7.9	10.1	24.9	3.4	3.4
1b	3	1.6	1.5	5.4	5.4	3.3	3.3
1c	3	2.2	2.7	7.7	12.5	3.9	3.9
1d	3	4.9	5.9	12.8	16.4	5.7	5.7
1e	3	1.8	0.8	6.0	8.2	3.5	3.5
1f	3	1.2	1.0	2.8	4.0	3.1	3.1
2a	3	3.0	4.5	10.1	19.6	3.5	3.5
2b	3	5.0	12.1	16.0	46.5	4.2	4.2
3a	3	4.2	10.9	10.6	27.2	3.9	3.9
3b	3	5.0	12.3	6.1	6.2	4.9	4.9
4a	3	3.8	5.9	8.6	8.9	3.8	3.8
4b	3	5.4	13.9	13.5	32.6	4.3	4.3
5a	3	3.2	5.7	8.5	19.7	3.4	3.4
5b	3	2.6	6.6	8.0	23.6	3.2	3.2
5c	3	3.6	5.4	7.1	9.4	7.3	7.3
5d	3	4.1	8.8	9.4	21.6	3.2	3.2
5e	3	2.6	1.9	7.2	4.9	3.8	3.8
5f	3	4.7	4.4	7.7	9.3	4.0	4.0
5g	3	1.9	2.7	5.8	3.6	3.8	3.8
5h	3	2.8	6.0	7.9	18.1	3.0	3.0
5j	3	2.2	1.6	5.9	5.1	4.6	4.6
5k	3	10.9	28.8	18.7	51.4	6.0	6.0
5l	3	3.2	6.0	11.0	26.8	4.6	4.6
5m	3	6.1	16.2	14.7	41.4	4.0	4.0
5n	3	2.5	2.6	6.1	5.7	3.1	3.1
5o	3	2.7	2.6	7.3	6.3	4.1	4.1
5p	3	2.1	4.0	6.8	13.6	2.6	2.6
5q	3	4.0	5.2	6.9	9.7	6.4	6.4
5r	3	4.5	9.0	12.7	29.2	4.2	4.2
5s	3	4.0	7.2	8.8	22.0	3.1	3.1
5t	3	5.7	10.3	11.8	24.9	6.3	6.3
5u	3	2.5	3.0	5.9	8.2	4.2	4.2
6a	3	4.0	7.9	8.0	12.9	5.0	5.0
6b	3	3.5	4.9	10.6	23.9	4.3	4.3
7a	3	8.1	11.4	18.6	40.6	11.0	11.0
7b	3	4.0	3.5	9.5	19.4	7.3	7.3

Table 5.21 (continued)

Sample	n	SRPw	95% CI	TDPw	95% CI	Morgan P	95% CI
X	2	2.0	15.2	4.3	24.2	2.5	2.5
Y	2	2.8	6.4	4.5	1.9	2.8	2.8
Z	1	1.4		3.5		3.4	
L2	3	2.8	5.3	7.9	15.7	1.6	1.6
L10	3	5.8	10.2	12.0	25.2	4.3	4.3
L11	3	2.7	5.7	6.9	14.7	2.9	2.9
L12	3	2.5	5.1	6.3	14.1	1.6	1.6
L13	3	1.9	2.2	6.1	10.5	1.5	1.5
L14	3	4.1	9.4	13.6	36.2	2.3	2.3

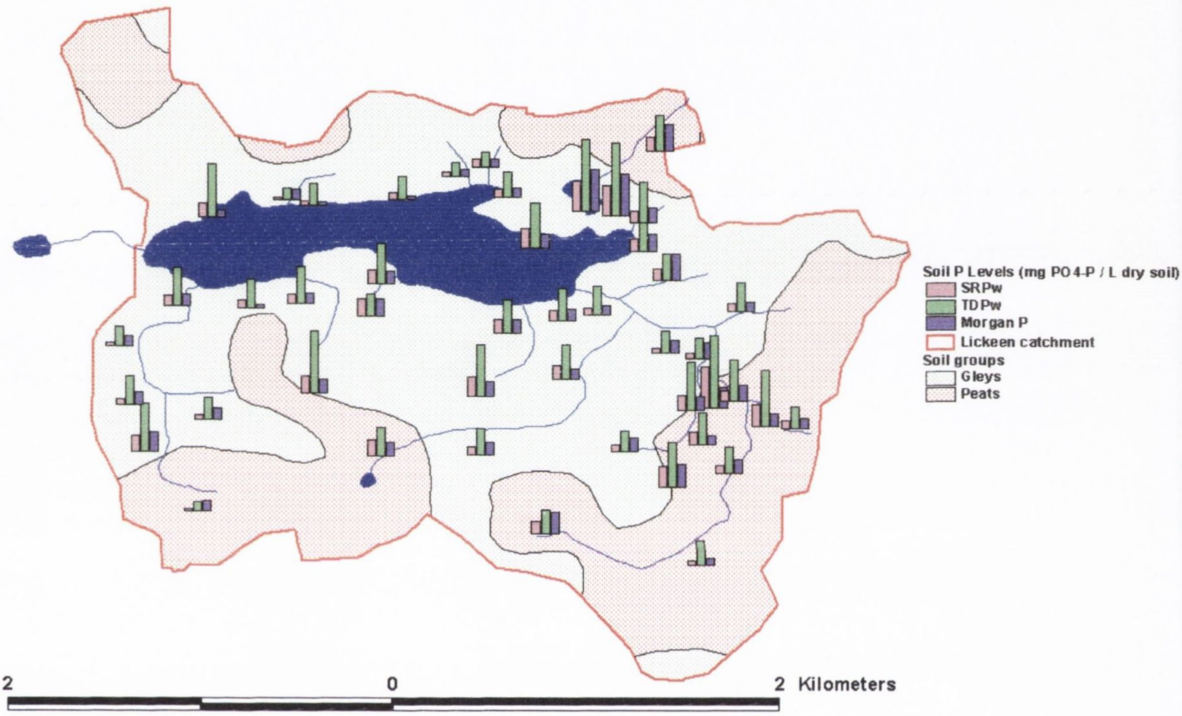

Figure 5.61: Spatial distribution of means of soil P Levels in Lough Lickeen catchment based on the soil monitoring 2002 – showing soluble reactive water extractable P (SRPw), total dissolved water extractable P (TDPw) and soil Morgan P, expressed in mg PO_4-P $l^{-1}{}_{dry\ soil}$. Soil group distribution in the catchment is shown.

- Temporal changes in soil P status

No clear temporal pattern of soil P status appeared among the monitored sites, although water extractable P (SRPw and TDPw) appeared to be greater in February, while for most sampling sites soil Morgan P levels were lower in July (Figures 5.62 to 5.64).

Overall catchment mean of SRPw and TDPw concentrations in February were significantly different (two sample t-tests and Mann-Whitney U tests, $p \leq 0.05$) from July and October. No significant differences were found between July and October. Soil Morgan P concentrations were significantly different (M-ANOVA, $p \leq 0.05$) between the three sampling occasions.

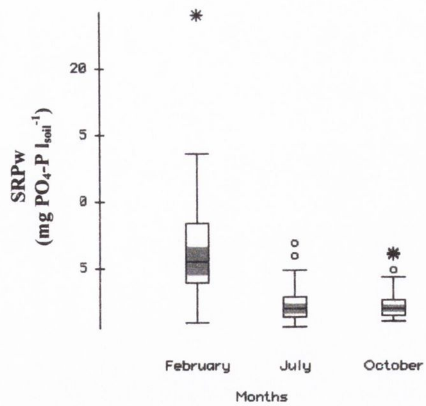

Figure 5.62: Distribution of soil SRPw concentrations (mg PO_4-P l_{soil}^{-1}) recorded in 2002 in Lough Lickeen catchment. (1)

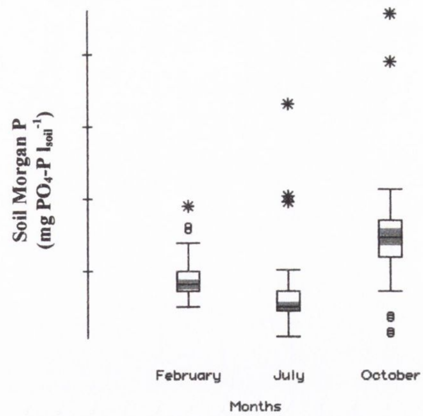

Figure 5.64: Distribution of soil Morgan P concentrations (mg PO_4-P l_{soil}^{-1}) recorded in 2002 in Lough Lickeen catchment. (1)

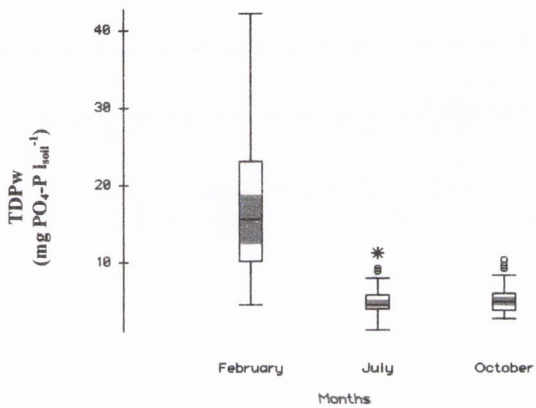

Figure 5.63: Distribution of soil TDPw concentrations (mg PO_4-P l_{soil}^{-1}) recorded in 2002 in Lough Lickeen catchment. (1)

Note (1):
The box depicts the central half of the data between the 25% and 75% points. The line across the box displays the median value. The whiskers extend from the top and the bottom of the box to depict the extent of the main body of the data. Extreme values are plotted with a circle. Very extreme data values are plotted with a starburst. The shaded area superimposed on each box is a 95% confidence interval around the median.

- Relationships with stream water chemistry

Stream sites with high mean turbidity levels were associated with organic soils (high %OM). Significant positive correlation ($n=38$, $p\leq0.05$) was found between Log(soil %OM) positively correlated with Log(mean stream turbidity) ($r_p=0.63$). Soil pH was also significantly positively correlated ($n=38$, $p\leq0.05$) with Log(mean stream alkalinity) ($r_p=0.34$) and Log(mean stream conductivity) ($r_p=0.35$).

No significant correlations were found between mean soil P concentrations and means of stream P concentrations. Agriculture in the catchment of Lough Lickeen is of low to moderate intensification and no obvious relationships between soil P levels and in-stream P concentrations were found in February and July 2002. High rainfall occurred in October 2002 (Figure 5.65) and significant positive correlations ($n=31$, $p\leq0.05$) were found between the log-transformed soil Morgan P levels and in-stream TP, TDP and SRP concentrations (respectively $r_p=0.44$, $r_p=0.46$, and $r_p=0.54$; Figure

5.66). Linear regression models of in-stream TP, TDP and SRP concentrations against soil Morgan P levels had low predictive power with, respectively, R^2=0.19, R^2=0.21, and R^2=0.30.

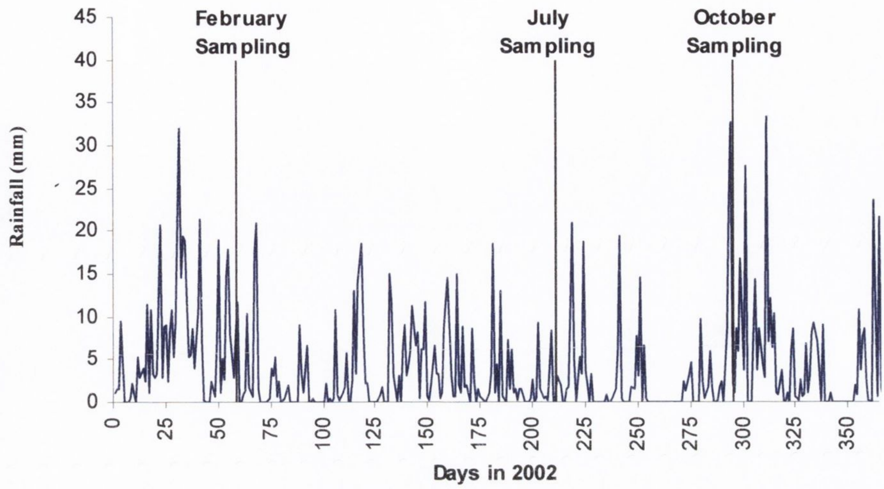

Figure 5.65: Daily rainfall (mm) recorded in Ennistymon weather station. Also showing the dates when soil sampling took place.

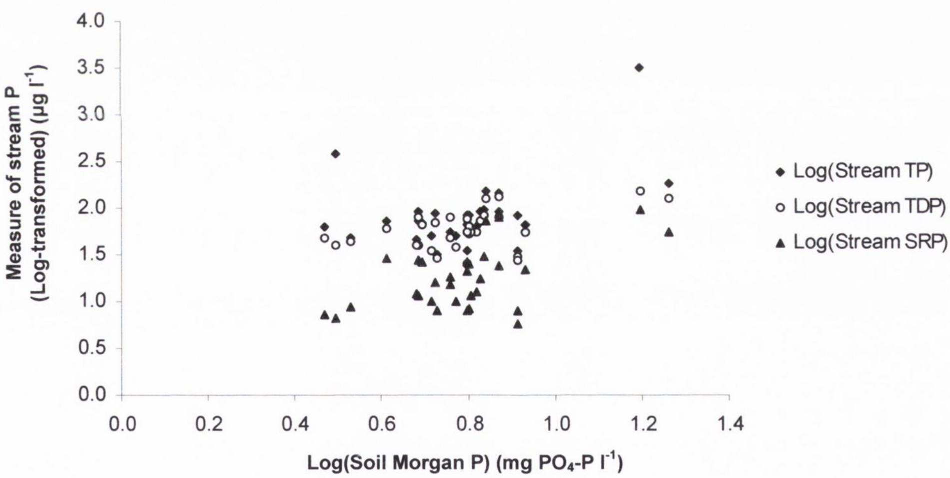

Figure 5.66: Log(stream TP), Log(Stream TDP) and Log(Stream SRP) (µg l^{-1}) compared with Log(Soil Morgan P) (mg PO_4-P l_{soil}^{-1}) in Lough Lickeen catchment – October 2002. Pearson's correlation and linear regression coefficients are, respectively, r_p=0.44, R^2=0.19; r_p=0.46, R^2=0.21; r_p=0.54, R^2=0.30 – n=31, $p \leq 0.05$)

No significant correlations were found between stream P and soil P concentrations for the peat soils in February, July or October 2002, while significant positive correlations (n=24, $p \leq 0.05$) were found for the gley soils between the log-transformed soil Morgan P levels and in-stream TP, TDP and SRP concentrations (respectively r_p=0.44, r_p=0.50, and r_p=0.63) in October 2002, and between the log-transformed soil Morgan P levels and in-stream SRP concentrations (r_p=0.43) in February 2002 (Figure 5.67).

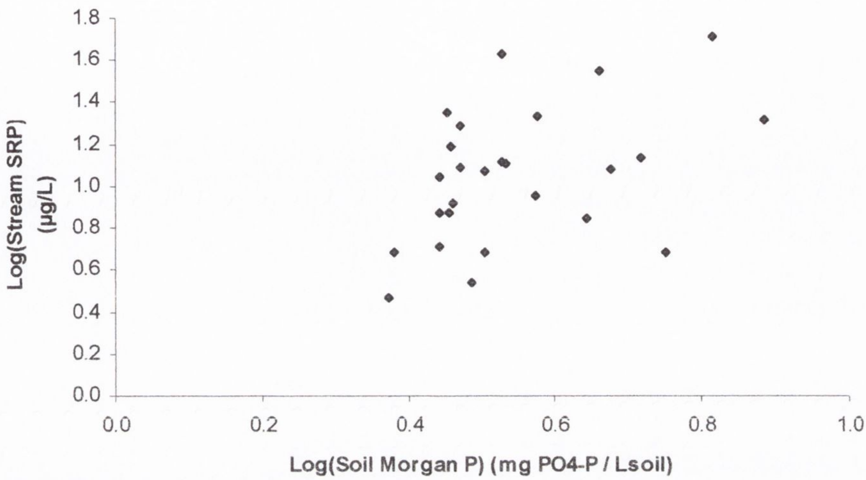

Figure 567: Log(Stream SRP) (μg l^{-1}) compared with Log(Soil Morgan P) (mg PO_4-P l_{soil}^{-1}) in Lough Lickeen catchment for the gley soils (n=26) in February 2002 (r_p=0.44, $p \leq 0.05$).

Relationships with sub-catchment descriptive variables

Spearman's Rank correlation coefficients between stream mean chemistry and sub-catchment descriptive variables are listed in Tables 5.22 to 5.23. High stream pH and alkalinity mean values were associated with gley soils and high soil P desorption index, while streams associated with peat soils and peatlands had more acidic water. Higher stream alkalinity was also associated with the coverage of total pasture in the sub-catchments, while lower values were associated with conifers. Lower stream NO_3-N and TN mean concentrations were associated with the coverage of peatlands, while higher mean concentrations were observed for sub-catchments with greater coverage of pasture. Higher stream TP, TDP and SRP were associated with the coverage of mixed grassland in the sub-catchments, while sub-catchments associated with peat soils had more coloured water and higher mean TDOC concentrations.

Sub-catchments were then grouped based on their soil type characteristics among mostly peats (>60%), mostly gleys (>60%) and mixed soils. No significant correlations (n=12) were observed between mean stream water chemistry and sub-catchment land use on gley soils. Among peat-dominated sub-catchments (n=11), higher stream mean TP concentrations were associated with greater soil %OM. In addition, higher stream mean TP, TDP and SRP concentrations were associated with mixed grasslands and total pasture, while lower values were observed for sub-catchments with conifers.

Table 5.22: Spearman's Rank correlation coefficients between sub-catchments variables and mean stream pH (X_1), Log(mean stream alkalinity) (X_2) and Log(mean stream conductivity) (X_3) among all the monitored sub-catchments (n=31) and differentiating peat-sub-catchments (n=11). Correlations significant at $p \leq 0.05$ are in bold and for $p \leq 0.01$ underlined.

	X_1-All	X_2-All	X_3-All	X_1-Peat	X_2-Peat	X_3-Peat
Log (Sub-catchment Area)	-0.01	-0.09	0.08	0.41	-0.01	-0.15
Min Elevation	**-0.39**	**-0.42**	**-0.45**	0.07	**-0.86**	**-0.97**
Maximum Elevation	0.03	-0.35	-0.27	0.12	-0.66	**-0.83**
Mean Elevation	-0.06	**-0.43**	**-0.41**	0.16	**-0.77**	**-0.90**
Maximum Slope	0.18	-0.13	-0.09	0.36	-0.33	-0.60
Mean Slope	**0.55**	0.36	0.16	0.47	-0.10	-0.47
% GI	0.16	**0.40**	**0.40**	-0.15	0.60	**0.85**
% CCG	-0.16	**-0.40**	**-0.40**	0.15	-0.60	**-0.85**
% Peats	**-0.63**	**-0.41**	-0.28			
% Gleys	**0.64**	**0.42**	0.29			
Soil P Desorption	**0.64**	**0.42**	0.29	0.30	-0.10	-0.06
Soil pH	0.11	0.27	0.26	-0.19	0.44	0.20
Soil % Carbonates	0.20	0.23	-0.19	0.16	0.24	0.10
Soil Extractable Fe	0.15	-0.01	-0.14	0.57	-0.03	-0.24
Log (soil %OM)	-0.20	-0.04	-0.25	-0.16	0.05	0.06
Log (Soil SRPw)	-0.35	-0.16	**0.46**	-0.58	-0.09	0.03
Log (Soil TDPw)	-0.21	-0.12	-0.02	-0.45	0.00	0.13
Log (Soil Morgan P)	**-0.44**	-0.02	**0.53**	-0.26	0.50	0.37
% Improved Grassland	0.33	**0.45**	0.36	0.00	0.37	0.37
% Unimproved Grassland	0.02	0.03	0.15	-0.48	0.41	0.37
% Mixed Grassland	0.04	**0.48**	0.25	-0.10	**0.83**	0.66
% Total Pasture	0.36	**0.68**	**0.44**	-0.17	**0.81**	**0.69**
% Total Peatlands	**-0.38**	**-0.39**	0.29	0.23	-0.31	-0.31
% Mixed Agriculture	0.01	0.15	0.22	0.02	0.06	0.37
% Conifers	-0.27	**-0.59**	-0.03	0.24	**-0.70**	-0.59
% Broadleafs	0.11	0.04	-0.18	0.59	0.32	0.03
Cattle	**0.47**	0.33	-0.15	-0.03	0.13	0.09
Horses	0.28	0.02	-0.05			
Humans	0.18	0.14	-0.11	0.03	0.36	0.38

Table 5.23: Spearman's Rank correlation coefficients between sub-catchment variables and Log(mean stream NO_3-N) (X_4), Log(mean stream TN) (X_5), Log(mean stream TP) (X_6), Log(mean stream TDP) (X_7), Log(mean stream SRP) (X_8), Log(mean stream TDOC) (X_9), Log(mean stream colour) (X_{10}) and Log(mean stream turbidity) (X_{11}) among all the monitored sub-catchments (n=31). Correlations significant at $p \leq 0.05$ are in bold and for $p \leq 0.01$ underlined.

	X_4-All	X_5-All	X_6-All	X_7-All	X_8-All	X_9-All	X_{10}-All	X_{11}-All
Log (Sub-catchment Area)	-0.11	**<u>-0.51</u>**	-0.23	0.00	0.20	-0.10	0.12	**<u>-0.60</u>**
Min Elevation	-0.37	-0.11	0.00	0.00	0.04	0.17	0.23	-0.05
Maximum Elevation	-0.21	**<u>-0.56</u>**	**-0.46**	-0.32	-0.15	**-0.37**	-0.07	**-0.47**
Mean Elevation	-0.34	**<u>-0.50</u>**	-0.35	-0.30	-0.18	-0.31	-0.06	-0.33
Maximum Slope	0.02	**-0.47**	**-0.41**	-0.21	-0.07	-0.32	-0.19	**<u>-0.53</u>**
Mean Slope	0.34	0.08	-0.09	-0.08	-0.10	**-0.38**	**<u>-0.68</u>**	0.03
% GI	0.28	**0.47**	0.29	0.27	0.15	0.25	-0.04	0.30
% CCG	-0.28	**-0.47**	-0.29	-0.27	-0.15	-0.25	0.04	-0.30
% Peats	-0.30	-0.05	0.11	0.21	0.35	**<u>0.53</u>**	**<u>0.80</u>**	-0.19
% Gleys	0.31	0.07	-0.11	-0.20	-0.35	**<u>-0.52</u>**	**<u>-0.79</u>**	0.20
Soil P Desorption	0.31	0.07	-0.11	-0.20	-0.34	**<u>-0.51</u>**	**<u>-0.79</u>**	0.21
Soil pH	**0.38**	0.07	-0.12	0.04	0.12	0.04	-0.02	-0.20
Soil % Carbonates	0.34	0.25	0.08	0.08	0.17	0.04	-0.06	0.14
Soil Extractable Fe	-0.13	-0.10	-0.04	-0.05	0.06	0.07	0.04	-0.18
Log (soil %OM)	-0.03	**0.44**	**0.43**	0.19	0.06	0.31	0.20	**<u>0.55</u>**
Log (Soil SRPw)	0.08	0.28	0.17	0.11	0.09	0.20	0.17	0.20
Log (Soil TDPw)	0.31	**0.39**	-0.01	0.12	0.22	0.23	0.24	-0.05
Log (Soil Morgan P)	0.28	0.32	0.16	0.11	0.16	0.28	0.23	0.23
Log(Channel length) (m)	0.17	-0.32	-0.17	0.10	0.25	-0.03	0.04	**<u>-0.57</u>**
Min. distance to Lickeen	-0.20	0.05	0.24	0.27	**0.37**	**0.39**	0.29	-0.08
Log (Max. distance to Lickeen)	-0.31	**-0.42**	-0.17	0.01	0.23	0.12	0.32	**<u>-0.54</u>**
Mean distance to Lickeen	**-0.42**	-0.33	-0.04	0.05	0.21	0.25	0.36	**-0.39**
% Improved Grassland	**0.41**	0.13	0.08	0.20	0.19	-0.01	-0.29	-0.22
% Umimproved Grassland	-0.05	-0.08	-0.20	-0.28	-0.34	-0.23	-0.16	0.06
% Mixed Grassland	**0.48**	**<u>0.54</u>**	**<u>0.60</u>**	**<u>0.65</u>**	**<u>0.67</u>**	**0.39**	0.17	0.26
% Total Pasture	**0.48**	**<u>0.61</u>**	**0.39**	0.24	0.11	0.09	-0.29	**<u>0.52</u>**
% Total Peatlands	**<u>-0.55</u>**	**-0.45**	-0.05	-0.02	-0.05	0.18	**0.37**	-0.28
% Mixed Agriculture	-0.02	-0.09	-0.02	0.13	0.17	0.21	0.05	-0.12

Table 5.23 (continued)

	X_4-All	X_5-All	X_6-All	X_7-All	X_8-All	X_9-All	X_{10}-All	X_{11}-All
% Conifers	-0.36	**-0.44**	-0.33	-0.16	0.00	-0.10	0.28	**-0.50**
% Broadleafs	0.02	-0.34	-0.23	-0.08	0.13	0.05	0.03	**-0.61**
Cattle	0.17	-0.21	-0.30	-0.28	-0.28	**-0.43**	**-0.49**	-0.24
Horses	0.07	**-0.46**	**-0.53**	**-0.47**	-0.35	**-0.47**	-0.34	-0.32
Humans	0.30	-0.27	-0.33	-0.15	-0.03	**-0.43**	-0.26	**-0.39**

Table 5.24: Spearman's Rank correlation coefficients between sub-catchment variables and Log(mean stream NO_3-N) (X_4), Log(mean stream TN) (X_5), Log(mean stream TP) (X_6), Log(mean stream TDP) (X_7), Log(mean stream SRP) (X_8), Log(mean stream TDOC) (X_9), Log(mean stream colour) (X_{10}) and Log(mean stream turbidity) (X_{11}) among the peat-sub-catchments (n=11). Correlations significant at $p \leq 0.05$ are in bold and for $p \leq 0.01$ underlined.

	X_4-Peats	X_5-Peats	X_6-Peats	X_7-Peats	X_8-Peats	X_9-Peats	X_{10}-Peats	X_{11}-Peats
Log (Sub-catchment Area)	0.06	-0.46	-0.57	-0.37	-0.37	-0.46	-0.64	**-0.72**
Min Elevation	**-0.75**	**-0.73**	-0.45	**-0.70**	-0.65	**-0.74**	-0.49	-0.47
Maximum Elevation	-0.49	**-0.91**	**-0.72**	**-0.90**	**-0.83**	**-0.92**	**-0.70**	-0.65
Mean Elevation	-0.58	**-0.82**	-0.59	**-0.82**	**-0.77**	**-0.83**	-0.61	-0.52
Maximum Slope	-0.16	**-0.77**	**-0.80**	**-0.74**	**-0.71**	**-0.81**	**-0.79**	**-0.81**
Mean Slope	0.03	-0.54	-0.51	-0.51	-0.41	-0.57	-0.67	**-0.71**
% GI	0.44	**0.83**	0.46	**0.74**	0.63	**0.88**	**0.74**	0.60
% CCG	-0.44	**-0.83**	-0.46	**-0.74**	-0.63	**-0.88**	**-0.74**	-0.60
% Peats								
% Gleys								
Soil P Desorption	0.06	0.30	**0.73**	0.39	0.48	0.18	0.31	0.63
Soil pH	0.41	0.32	-0.08	0.27	0.14	0.23	0.19	-0.05
Soil % Carbonates	0.04	0.08	-0.16	0.12	0.06	-0.10	-0.06	-0.37
Soil Extractable Fe	-0.01	0.34	0.37	0.23	0.18	0.40	0.56	0.68
Log (soil %OM)	0.06	0.49	0.38	0.35	0.26	0.53	0.68	**0.71**
Log (Soil SRPw)	0.63	0.27	0.35	0.25	0.32	0.29	0.13	0.50
Log (Soil TDPw)	0.47	-0.11	-0.26	-0.08	-0.06	-0.05	-0.29	-0.32
Log (Soil Morgan P)	0.54	-0.02	-0.17	0.10	0.14	-0.08	-0.40	-0.55
Log(Channel length)	0.06	0.35	0.00	0.30	0.26	0.39	0.21	-0.19

Table 5.24 (continued)

	X_4-Peats	X_5-Peats	X_6-Peats	X_7-Peats	X_8-Peats	X_9-Peats	X_{10}-Peats	X_{11}-Peats
Min. distance to Lickeen	-0.39	-0.15	-0.06	-0.15	-0.09	-0.15	-0.14	-0.31
Log (Max. distance to Lickeen)	-0.07	-0.29	-0.30	-0.19	-0.12	-0.30	-0.42	**-0.71**
Mean distance to Lickeen	-0.25	-0.15	-0.17	-0.15	-0.09	-0.16	-0.16	-0.46
% Improved Grassland	0.23	-0.22	-0.22	-0.15	-0.08	-0.15	-0.30	-0.37
% Umimproved Grassland	0.18	0.37	0.41	0.49	0.51	0.43	0.22	0.12
% Mixed Grassland	0.66	0.65	**0.77**	**0.76**	<u>**0.87**</u>	0.63	0.26	0.33
% Total Pasture	0.59	0.62	**0.72**	**0.75**	<u>**0.84**</u>	0.59	0.28	0.30
% Total Peatlands	-0.25	-0.38	-0.47	-0.26	-0.32	-0.37	-0.56	-0.55
% Mixed Agriculture	0.02	-0.09	-0.39	-0.18	-0.28	0.02	0.01	-0.06
% Conifers	-0.54	-0.60	**-0.69**	**-0.73**	**-0.80**	-0.60	-0.23	-0.31
% Broadleafs	0.30	0.00	-0.07	0.11	0.16	-0.07	-0.38	-0.54
Cattle	-0.01	-0.46	-0.41	-0.34	-0.27	-0.41	-0.53	-0.60
Horses								
Humans	0.22	-0.22	-0.22	-0.14	-0.07	-0.16	-0.28	-0.36

V-3.3 Phosphorus Export Modelling

Calculated annual average TP loadings and loading rates into streams

Using Equations 5.3 and 5.4, annual average TP loadings into the streams, expressed as kg P yr^{-1}, were estimated for the sampling sites most intensively monitored between February 2002 and March 2003 ($n \geq 8$ sampling occasions) (Table 5.25). TP loads were standardized to area-weighted loading rates (kg P ha^{-1} yr^{-1}), referred in the followings as calculated annual average TP loading rates. Higher loading rates were found for sub-catchments 7b, 6a and 7a (respectively 2.03, 1.86 and 1.12 kg P ha^{-1} yr^{-1}); while sub-catchment 4a had the lowest rate with 0.12 kg P ha^{-1} yr^{-1}. Stream basins 1 and 6 had higher loading rates near the stream inlet, while loading rates near the inlet of stream 5 were the lowest among the sub-catchments of stream basin 5.

Table 5.25: Calculated annual average TP loads (kg P yr^{-1}) and loading rates (kg P ha^{-1} yr^{-1}) for the sub-catchments monitored in 2002-03 in Lickeen catchment

Sub-catchments	Annual TP Loads (kg P yr^{-1})	TP Loading rates (kg P ha^{-1} yr^{-1})
1a	26.0	0.26
1c	11.9	0.19
1d	5.0	0.16
1e	4.5	0.25
2a	12.6	0.19
2b	1.5	0.18
3a	1.8	0.21
3b	0.2	0.20
4a	2.1	0.12
5a	70.2	0.19
5d	16.5	0.20
5e	7.4	0.19
5f	6.3	0.29
5g	53.7	0.23
5h	8.2	0.22
5j	39.9	0.22
5m	7.8	0.42
5o	25.5	0.23
5p	20.8	0.25
5q	2.8	0.24
5r	5.9	0.26
5s	4.8	0.27
5t	4.0	0.26
5u	2.5	0.28
6a	27.7	1.86
6b	1.5	0.20
7a	22.3	1.12
7b	23.4	2.03
X	3.4	0.29
Y	6.1	0.62
Z	2.6	0.13

Annual average TP exports from the whole Lickeen catchment calculated following Foy (1992) was estimated at 247.7 kg P yr^{-1}, which corresponded to a loading rate of 0.31 kg P ha^{-1} yr^{-1}. Annual TP loadings to the streams were also calculated for each stream basin (Table 5.26). As Stream 7 did not flow directly into the lake, total TP loads from the overall drainage area of inflowing streams were both calculated including and excluding exports from the catchment of Stream 7. Calculated total annual average TP loadings from the stream basins was estimated at 174.8 kg P yr^{-1} and at 152.5 kg P yr^{-1} if excluding the catchment of Stream 7.

Table 5.26: Calculated annual average TP loads (kg P yr^{-1}) and loading rates (kg P yr^{-1} ha^{-1}) into each stream basin, also expressed as % of annual total catchment export calculated using Foy (1992).

	Annual TP Loads (kg P yr^{-1})	**Loading Rates (kg P yr^{-1} ha^{-1})**	**% Annual Total Catchment export**
Stream 1	25.9	0.26	10
Stream 2	12.6	0.19	5
Stream 3	1.8	0.21	1
Stream 4	2.1	0.12	1
Stream 5	70.2	0.19	28
Stream 6	27.7	1.86	11
Stream 7	22.3	1.12	9
Stream X	3.4	0.29	1
Stream Y	6.1	0.62	2
Stream Z	2.6	0.13	1
Total incl. L9(7)	174.8		71
Total excl. L9(7)	152.5		62

Inflowing streams into Lough Lickeen drain over 80% of the catchment area. Calculated annual average TP exports from the drainage area of the inflowing streams contributed to 71% (62% if excluding stream 7) of the total annual average TP exports from the whole catchment calculated using Foy's equation (Foy, 1992). This assumes that no P losses occur between the monitoring sites near the stream inlets and the lake. Calculated annual average TP loadings were found to be significantly lower for the gley-dominated sub-catchments (n=31, $p \leq 0.01$). However, when comparing area-weighted loading rates, no significant difference was found.

Modelling TP loading rates – Statistical analyses

A first approach of phosphorus export modelling in the Lickeen catchment derived empirical relationships, based on calculated annual average TP loading rates (kg P ha^{-1} yr^{-1}) and sub-catchment descriptive variables, in order to predict variations in nutrient loading rates to surface waters in the catchment. Calculated Log(annual average TP loading rates) were significantly positively correlated (n=31) with Log(Soil % OM) ($r=0.42$, $p \leq 0.05$) and with % Mixed grassland in sub-catchments ($r=0.59$, $p<0.01$).

Stepwise multiple regression (Equation 5.8) predicted Log (annual average TP loading rates) (R^2=0.54, p≤0.01, df=29) (Appendix 4– Table 10), based on mean elevation, soil %OM, soil P desorption index and % Mixed grasslands in sub-catchments.

Predicted Log(annual average TP loading rates) (kg P ha^{-1} yr^{-1})=

-0.007 * Mean elevation (m) + 0.328 * Log(Soil % OM) – 0.292 * Soil P Desorption Index + 0.004 * % Mixed grasslands + 0.056

Equation 5.8

The predictive power of the multiple linear regression was moderate, with 54% of the variations in Log (annual average TP loading rates) explained by the model. Contributions to annual average TP loading rates into surface waters from other land uses, spatial variation in rainfall, livestock grazing and management practices, as well as influence of spatial location of the different sources of phosphorus in the catchment could affect the accuracy of the regression model.

Predicted Log (annual average TP loading rates) were significantly positively correlated (Pearson's Product-Moment correlation coefficient r_p=0.78, p≤0.01) with calculated Log (annual average TP loading rates) (Figure 5.68). Differentiating sub-catchments among peat, gley and mixed soils-dominated sub-catchments produced a stronger correlation coefficient between predicted and calculated Log (annual average TP loading rates) for peat-dominated sub-catchments, with r_p=0.94 (n=11, p≤0.01). No significant relationships were found for mixed soils or gley-dominated sub-catchments.

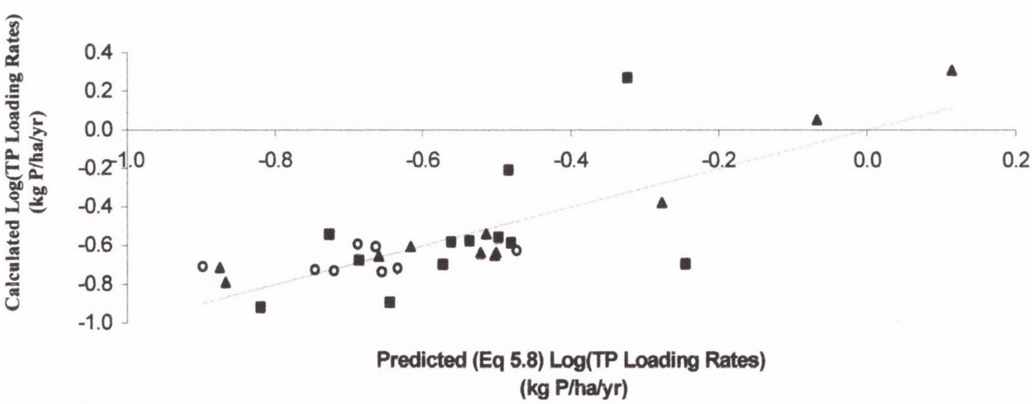

Figure 5.68: Calculated Log(annual average TP loading rates) (kg P ha^{-1} yr^{-1}) compared with predicted Log(annual average TP loading rates) (kg P ha^{-1} yr^{-1}) applying Equation 5.8, in all sub-catchments (r_p=0.78, p≤0.01, n=31), differentiating gley (■), mixed soils (○) and peat (▲) – dominated sub-catchments. The line 1:1 is shown in grey, and linear regression model between calculated and predicted Log(annual average TP loading rates) is featured in red: y = 0.9993 * x + 0.0003 (R^2=0.54, p≤0.01, df=29).

GIS-application of the statistical modelling

The derivation of a map of spatial variation of annual average TP loading rates within the Lickeen catchment, applying the results of the statistical analyses to the whole catchment, was not possible using the best regression model (Equation 5.8), because this was based on soil %OM data, applicable only near the sampling locations. Heterogeneity of soil characteristics prevented the interpolation of the monitoring results to the full area of the sub-catchments. It was, therefore, decided to use the second best linear regression model equation (Equation 5.9, R^2=0.48, df=27, $p<0.05$) predicting Log(Annual TP loading rates) (Appendix 4 – Table 11):

Predicted Log(annual average TP loading rates) (kg P ha^{-1} yr^{-1})=

-0.008 * Mean elevation (m) – 0.318 * Soil P Desorption Index + 0.004 * % Mixed grasslands + 0.608

Equation 5.9

A first grid-coverage of soil P desorption index was derived for the Lickeen catchment from the vector coverage of soil type distribution (Figure 5.8). After converting the shapefile into a grid-coverage, each 5*5 m^2-cell was given a soil P desorption index value of 1.0, if associated with peat soils and of 1.9, if associated with gley soils, as described by Daly (2000).A second grid-coverage of Mixed Grasslands was then derived from the vector coverage of land use (Figure 5.13). Converting the shapefile into a grid-coverage, each 5*5 m^2-cell was given a value of 1, if associated with mixed grasslands and of 0, if associated with other land use types.

Using the *Spatial Analyst*, a grid-coverage of modelled annual average TP loading rates into surface waters was produced (Figure 5.69) based on Equation 5.9, using the map calculation:

***TP loadings rates-Grid* =**

Exp_{10} (-0.008 * *Elevation-Grid* – 0.318 * *Soil P Desorption Index-Grid* + 0.004 * *% Mixed grasslands-Grid* + 0.608) **Equation 5.10**

The GIS-model based on Equation 5.9 indicated higher TP loading rates from the northeast and southeast of the catchment. Some modelled TP loading rate-class may not appear clearly on the map, as probably associated with single 5*5 m^2-cell, and, therefore, too small to be detected on the scale used in Figure 5.69

TP exports from sub-catchments, estimated from the GIS-model, were usually lower than the calculated values, with greater differences observed for sites 6a, 7a and 7b. Overall catchment annual average TP loadings predicted by the GIS-model was 172 kg P yr^{-1}, compared with 248 kg P yr^{-1} estimated from field measurements.

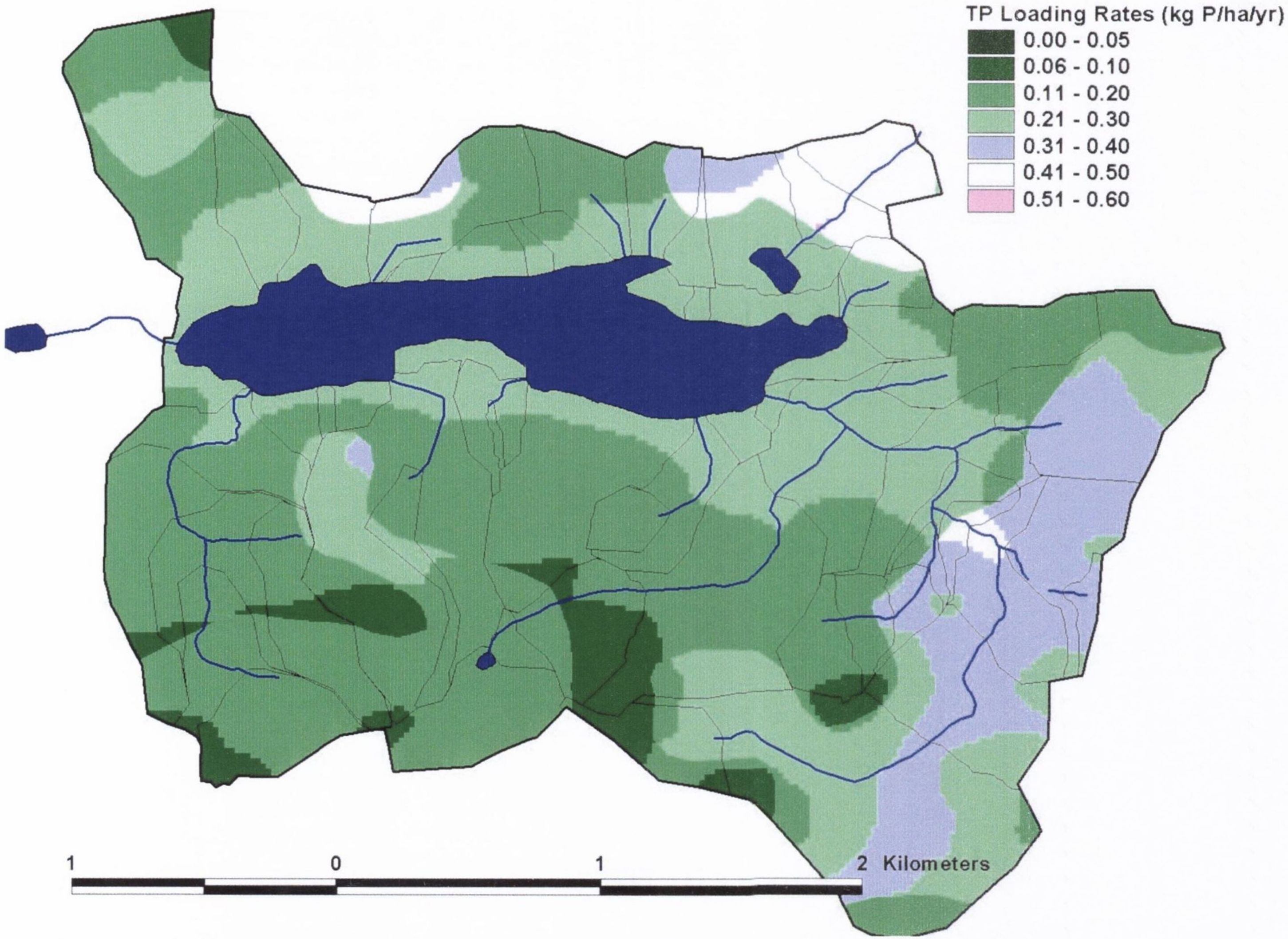

Figure 5.69: GIS-modelled TP loading rates in the Lough Lickeen catchment, produced based on Equation 5.9, by applying the following map calculation: *TP loadings rates-Grid* = Exp_{10} (-0.008 * *Elevation-Grid* – 0.318 * *Soil P Desorption Index-Grid* + 0.004 * *% Mixed grasslands-Grid* + 0.608)

Annual average TP exports (kg P yr^{-1}) from sub-catchments estimated from the monitoring 2002-03, "calculated annual average TP loadings", were compared with estimates based on the GIS-model, "GIS-modelled annual average TP loadings". GIS-modelled and calculated Log(annual average TP loadings) were significantly positively correlated (r_p=0.91, n=31, p≤0.01, Figure 5.70). The Nash-Sutcliffe measure was estimated at R^2_{NS}=0.81 (0.95 if excluding the sites 6a, 7a and 7b).

Annual average TP export rates (kg P ha^{-1} yr^{-1}) from sub-catchments estimated from the monitoring 2002-03, "calculated annual average TP loading rates", were then compared with estimates based on the GIS-model, "GIS-modelled annual average TP loading rates". A weaker but still significant positive correlation was found between GIS-modelled and calculated Log(annual average TP loading rates) with r_p=0.59 (n=31, p≤0.01, Figure 5.71).

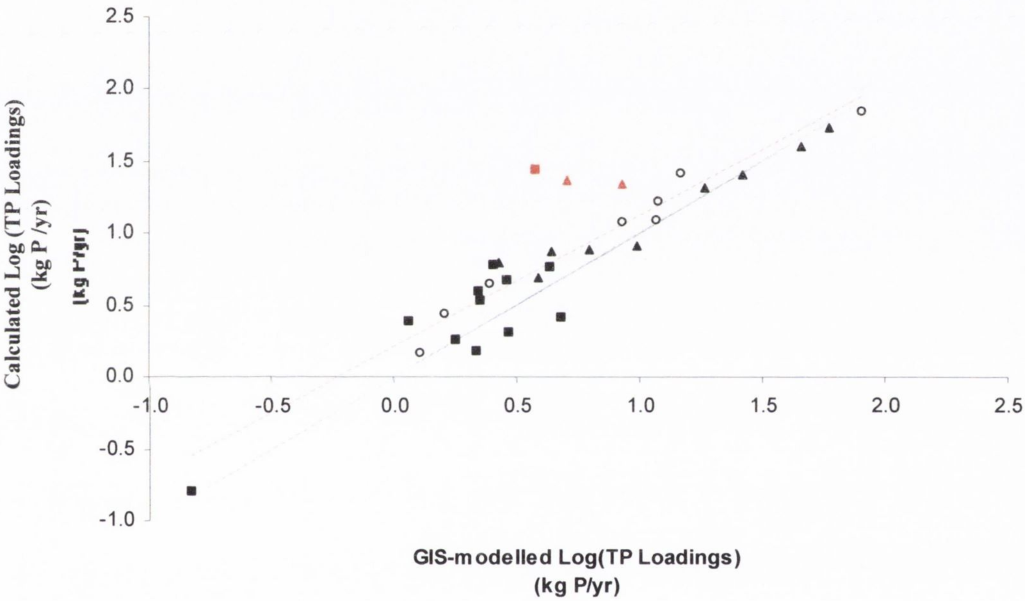

Figure 5.70 Comparison between Calculated and GIS-modelled Log(annual average TP Loadings) (kg P yr^{-1}) in the sub-catchments (n=31) monitored in 2002-03 in the Lickeen catchment, differentiating gley (■), mixed soils (○) and peat (▲) –dominated sub-catchments. Sites 6a (■), 7a and 7b (▲) are highlighted in red. The line 1:1 is also shown in grey. Pearson's correlation coefficient r_p= 0.91, n=31, p≤0.01; Nash-Sutcliffe Measure: R^2_{NS}=0.81; The linear regression model between GIS-modelled and calculated Log(annual average TP loadings) is shown in red: y = 0.91 * x + 0.21 (R^2=0.83, df=29, p≤0.0001).

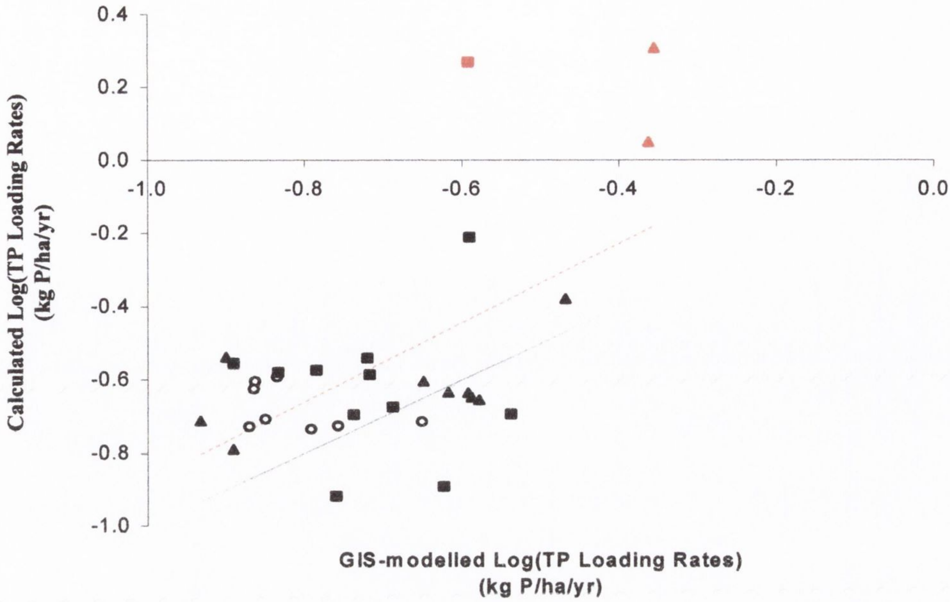

Figure 5.71: Comparison between Calculated and GIS-modelled Log(TP Loading rates) (kg P ha^{-1} yr^{-1}) in the sub-catchments (n=31) monitored in 2002-03 in the Lickeen Catchment, differentiating gley (■), mixed soils (○) and peat (▲) – sub-catchments. Sites 6a (■), 7a and 7b (▲) are highlighted in red. The line 1:1 is also shown in grey. Pearson's correlation coefficient r_p= 0.59, n=31, $p \leq 0.01$; Nash-Sutcliffe Measure: R^2_{NS}=0.12. The linear regression model between GIS-modelled and calculated Log(annual average TP loadings) is shown in red: y = 1.09 * x + 0.21 (R^2=0.33, df=29, $p \leq 0.001$).

Use of mathematical models

Two nutrient export coefficient models: Johnes *et al* (1996, 1998) and Jordan *et al* (2000), described in Chapter 4, were used to predict annual average TP exports from the entire catchment and each sub-catchment of Lough Lickeen. Additionally, estimates were derived using the model of Daly *et al* (2000), which predicts mean annual MRP concentration in streams (Equation5.5).

The "Jordan- model" (Jordan *et al*, 2000) was used by applying the export rate coefficients listed in Table 4.2. The "Johnes-model" (Johnes *et al*, 1996, 1998) was used applying two different sets of export coefficients (Table 5.27), derived from the Cober catchment (lowland catchment with steep slopes, mixed farming and impermeable bedrock) ("Johnes-Cober") and from the Waver catchment in England (flat lowland catchment with intensive dairy production, impermeable bedrock and poorly drained soils) ("Johnes-Waver"), which show similarities with the Lickeen catchment. Finally, SRP concentrations were estimated using the "Daly model" (Daly *et al*, 2000) for the wet soils, based on % Higrass, % Semi-natural areas, soil P levels and soil P desorption index (Equation 5.5).

Table 5.27: List of the TP export coefficients associated with the different land uses for the Cober and Waver catchments (England), as described in Johnes *et al* (1996, 1998).

Land Covers		Cober Catchment	Waver Catchment
Exports from Land Uses			
Permanent Grassland	kg ha^{-1}	0.40	0.10
Temporary Grassland	kg ha^{-1}	0.40	0.80
Cereals	kg ha^{-1}	0.60	0.60
Woodland	kg ha^{-1}	0.02	0.02
Rough Grazing	kg ha^{-1}	0.02	0.02
Exports from Peat Bogs			
Peat Bogs	%	100% throughput	100% throughput
Exports from Livestock			
Cattle (%)	%	2.90	2.60
Cattle input	kg P $head^{-1}$	7.65	7.65
Sheep (%)	%	3.00	3.00
Sheep input	kg P $head^{-1}$	1.5	1.5
Exports from unsewered population			
People	kg P $head^{-1}$	0.24	0.24
Export from rainfall			
Rain (%)	%	25.00	25.00
Rain input	kg P m^{-3}	$15\ 10^{-6}$	$15\ 10^{-6}$

Predicted annual average TP exports derived from the Jordan and the Johnes-Cober models (Table 5.28), were greater than the calculated values, except for three sites: 6a, 7a and 7b, which had the greatest calculated TP loadings and suspected point source of P loadings. The Johnes-Cober model predicted lower annual average TP exports than the calculated values for sites 1d, 5f and 5h. All three sites were surrounded by conifer plantations, which, in each case, covered more than 60% of their sub-catchment area. Predicted exports using the Johnes-Waver model gave lower exports (Table 5.28). Annual average MRP concentrations predicted using the Daly model for wet soils, also gave greater concentrations than the ones calculated during the monitoring, except for sites 6a, 7a, 7b and 5m.

Table 5.28: Predicted annual average TP exports (kg yr^{-1}) for the entire catchment and each sub-catchment of Lough Lickeen, using the models described by Jordan *et al* (2000); Johnes *et al* (1996, 1998) and Daly *et al* (2000). Calculated annual average TP loads (kg yr^{-1}) and annual average SRP concentrations (mg l^{-1}) from the monitoring 2002-03 are also provided for each sub-catchment. Drainage basins of the lake sites associated with stream inlet sub-catchments are given in brackets.

Sub-catchments	Calculated TP Loads	Jordan	Johnes Cober	Johnes Waver	Calculated Mean SRP (mg l^{-1})	Daly MRP (mg l^{-1})
1a (L1)	**25.95**	59.9	39.2	15.8	**0.023**	0.068
1b		49.7	30.7	12.7		0.063
1c	**11.94**	33.4	17.5	8.1	**0.013**	0.060
1d	**4.95**	12.8	2.6	1.6	**0.008**	0.053
1e	**4.48**	11.6	9.7	4.5	**0.017**	0.060

Table 5.28 (continued)

Sub-catchments	Calculated TP Loads	Jordan	Johnes Cober	Johnes Waver	Calculated Mean SRP ($mg\ l^{-1}$)	Daly MRP ($mg\ l^{-1}$)
1f		7.0	1.0	0.8		0.028
2a (L3)	**12.62**	40.4	31.8	11.9	**0.012**	0.065
2b	**1.48**	4.9	4.0	1.4	**0.011**	0.062
3a	**1.84**	4.8	3.8	1.5	**0.013**	0.099
3b	**0.16**	0.5	0.4	0.1	**0.007**	0.104
4a (L5)	**2.07**	9.8	8.6	3.0	**0.008**	0.101
4b		2.9	2.4	0.9		0.101
5a (L6)	**70.22**	197.6	131.8	50.6	**0.013**	0.053
5b		196.5	130.8	50.3		0.051
5c		11.0	7.0	2.1		0.109
5d	**16.54**	45.8	34.8	13.1	**0.011**	0.058
5e	**7.40**	15.5	10.9	5.1	**0.010**	0.026
5f	**6.25**	8.5	4.9	2.1	**0.017**	0.028
5g	**53.72**	121.4	74.6	30.9	**0.019**	0.044
5h	**8.23**	14.3	3.3	2.0	**0.017**	0.037
5j	**39.89**	98.4	66.8	27.1	**0.018**	0.044
5k		79.3	50.5	20.5		0.044
5l		77.3	48.3	19.5		0.036
5m	**7.79**	11.1	7.9	2.9	**0.040**	0.028
5n		1.8	1.5	0.6		0.013
5o	**25.51**	55.6	32.3	13.6	**0.023**	0.034
5p	**20.78**	41.1	22.3	9.4	**0.031**	0.032
5q	**2.78**	6.8	5.4	2.3	**0.008**	0.050
5r	**5.86**	16.8	13.8	4.9	**0.021**	0.092
5s	**4.76**	13.2	9.8	2.8	**0.022**	0.097
5t	**4.01**	11.4	8.4	2.4	**0.021**	0.122
5u	**2.50**	6.7	5.1	1.6	**0.024**	0.108
6a (L8)	**27.67**	11.0	8.7	2.8	**0.186**	0.109
6b	**1.52**	5.6	4.6	1.7	**0.010**	0.094
7a	**22.27**	13.9	11.6	4.0	**0.112**	0.074
7b	**23.43**	8.5	7.0	2.4	**0.129**	0.054
X	**3.42**	7.6	7.2	2.4	**0.010**	0.090
Y	**6.14**	6.2	5.6	2.0	**0.012**	0.064
Z	**2.59**	12.9	12.7	4.8	**0.007**	0.081
L2		0.7	0.7	0.2		
L7		9.6	4.7	2.0		
L9		21.1	18.2	7.9		
L10		0.5	0.5	0.2		
L11		1.0	0.7	0.7		
L12		1.3	1.1	0.4		
L13		0.9	0.8	0.3		
L14		8.7	9.8	4.9		
Lickeen	**247.7**	451.4	346.6	177.2		

Greater differences between predicted and calculated annual average TP exports were obtained for the mixed soils and peat-dominated sub-catchments. For the gley-dominated sub-catchments, predicted values were closer to calculated annual average TP exports, although greater differences were observed between predicted and calculated annual average TP loading rates using the Jordan and Johnes-Cober models. For the Daly model, predicted MRP annual average concentrations were closer to calculated concentrations for peat-sub-catchments.

No significant correlations were found between predicted MRP concentrations using the Daly model and calculated annual mean SRP in streams. Predicted annual average TP exports using the Jordan, Johnes-Cober and Johnes-Waver models were significantly correlated ($n=31$, $p\leq0.01$) with calculated annual average TP loads in the sub-catchments, as they were when differentiating them among main soil types (Table 5.29, Figures 5.72 to 5.74).

Table 5.29: Pearson's Product-Moment correlation coefficients between Calculated and Predicted Log(annual average TP exports). Coefficients are given for all sub-catchments (n-31) and differentiating gley, mixed soils and peat-dominated sub-catchments.

	All sub-catchments ($n=31$, $p\leq0.01$)	Gley-sub-catchments ($n=12$, $p\leq0.01$)	Mixed soils-sub-catchments ($n=8$, $p\leq0.01$)	Peat-sub-catchments ($n=11$, $p\leq0.01$)
Log(Jordan TP exports)	0.88	0.81	0.99	0.77
Log(Johnes-Cober TP exports)	0.84	0.80	0.99	0.87
Log(Johnes-Waver TP exports)	0.86	0.78	0.99	0.84

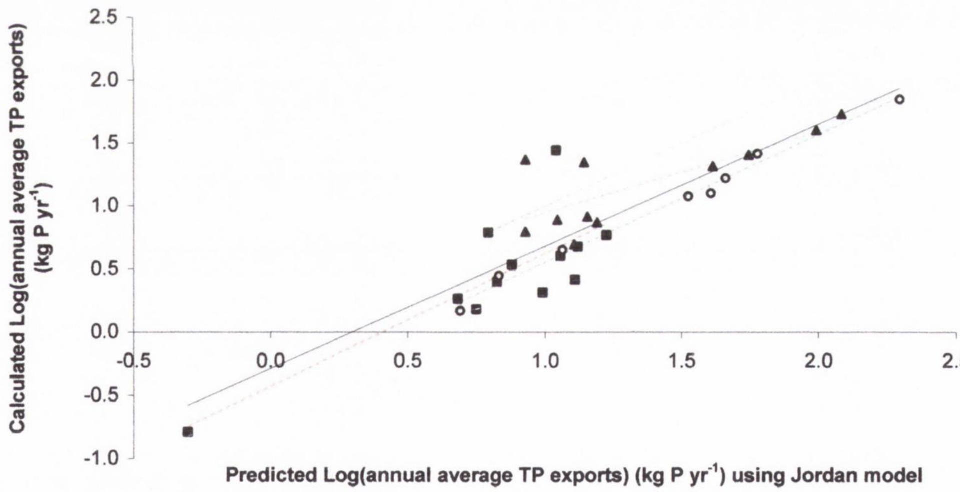

Figure 5.72: Comparison between Calculated and Predicted Log(TP Exports) (kg P yr^{-1}) using the Jordan model for each sub-catchment of Lough Lickeen ($r_p=0.88$, $n=31$, $p\leq0.01$), differentiating gley (■) ($r_p=0.81$, $n=12$, $p\leq0.01$), mixed soils (○) ($r_p=0.99$, $n=8$, $p\leq0.01$) and peat (▲) –dominated sub-catchments ($r_p=0.77$, $n=11$, $p\leq0.01$). The line 1:1 is also shown in grey. Linear regression models ($y = bx + a$) were derived for all datasets (black line: $b=0.97$, $R^2=0.77$, $df=29$, $p\leq0.0001$), gley (red-dotted line: $b=1.06$, $R^2=0.63$, $df=10$, $p\leq0.01$), mixed soils (green-dotted line: $b=1.01$, $R^2=0.99$, $df=6$, $p\leq0.0001$) and peat-dominated sub-catchments (blue-dotted line: $b=0.65$, $R^2=0.55$, $df=9$, $p\leq0.01$).

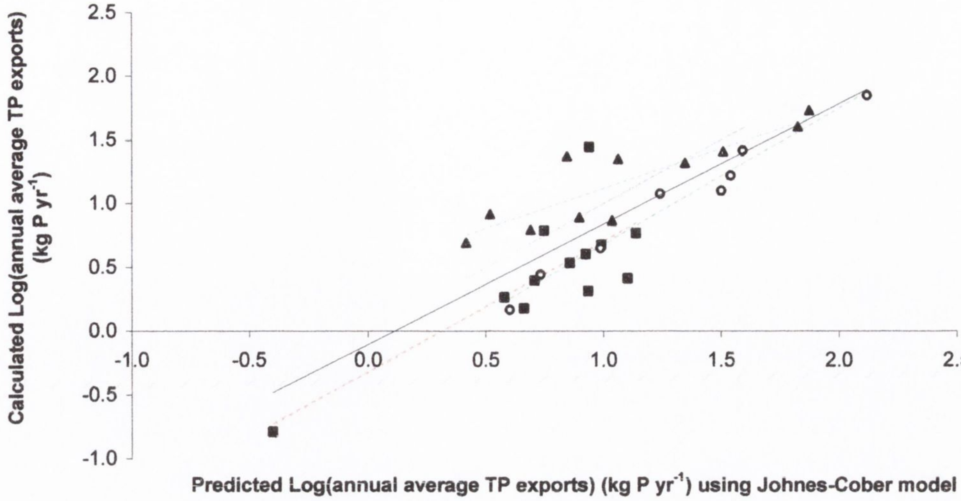

Figure 5.73: Comparison between Calculated and Predicted Log(TP Exports) (kg P yr^{-1}) using the Johnes-Cober model for each sub-catchment of Lough Lickeen (r_p=0.84, n=31, p≤0.01), differentiating gley (■) (r_p=0.80, n=12, p≤0.01), mixed soils (○) (r_p=0.99, n=8, p≤0.01) and peat (▲) –dominated sub-catchments (r_p=0.87, n=11, p≤0.01). The line 1:1 is also shown in grey. Linear regression models (y = bx + a) were derived for all datasets (black line: b=0.94, R^2=0.69, df=29, p≤0.0001), gley (red-dotted line: b=1.03, R^2=0.61, df=10, p≤0.01), mixed soils (green-dotted line: b=1.07, R^2=0.97, df=6, p≤0.0001) and peat-dominated sub-catchments (blue-dotted line: b=0.63, R^2=0.74, df=9, p≤0.01).

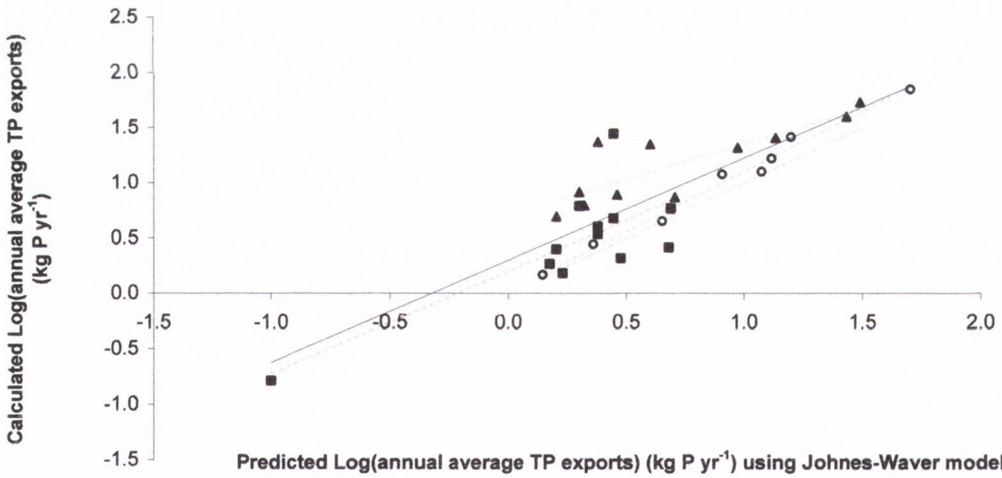

Figure 5.74: Comparison between Calculated and Predicted Log(TP Exports) (kg P yr^{-1}) using the Johnes-Waver model for each sub-catchment of Lough Lickeen (r_p=0.86, n=31, p≤0.01), differentiating gley (■) (r_p=0.76, n=12, p≤0.01), mixed soils (○) (r_p=0.99, n=8, p≤0.01) and peat (▲) –dominated sub-catchments (r_p=0.84, n=11, p≤0.01). The line 1:1 is also shown in grey. Linear regression models (y = bx + a) were derived for all datasets (black line: b=0.93, R^2=0.73, df=29, p≤0.0001), gley (red-dotted line: b=0.93, R^2=0.58, df=10, p≤0.01), mixed soils (green-dotted line: b=1.09, R^2=0.98, df=6, p≤0.0001) and peat-dominated sub-catchments (blue-dotted line: b=0.64, R^2=0.66, df=9, p≤0.01).

The validity of the models was tested using the area-weighted loading rates by comparing calculated and predicted annual average TP loading rates (kg P ha^{-1} yr^{-1}), as it was suspected that sub-catchment area was influencing the correlations. Predicted annual average TP loading rates (Table 5.30) were only significantly correlated with the calculated values (r_p=0.40, n=31, p $\leq$0.05) (Table 5.31) when using the Jordan model. This relationship (Figure 5.75) appeared highly influenced by the rates obtained for the sites 6a, 7a and 7b. No significant correlation was obtained when these sites were excluded (r_p=0.18, n=31, ns). Significant positive correlations between predicted and calculated Log(annual average TP loading rates) were observed (n=12, p$\leq$0.05) for the peat-dominated sub-catchments (Table 5.31) when using the Jordan, Johnes-Cober and Johnes-Waver models.

Table 5.30: Predicted annual average TP loading rates (kg ha^{-1} yr^{-1}) for each monitored sub-catchment, using the models described by Jordan *et al* (2000), Johnes (1996, 1998) and Daly *et al* (2000). Calculated annual average TP loading rates (kg ha^{-1} yr^{-1}) are also provided.

Sub-catchments	Soil	Calculated	Jordan model	Johnes-Cober model	Johnes-Waver model
1a	Mixed	**0.26**	0.59	0.39	0.16
1c	Mixed	**0.19**	0.52	0.27	0.13
1d	Peats	**0.16**	0.42	0.09	0.05
1e	Mixed	**0.25**	0.64	0.54	0.25
2a	Mixed	**0.19**	0.60	0.48	0.18
2b	Mixed	**0.18**	0.61	0.50	0.17
3a	Gleys	**0.21**	0.55	0.44	0.17
3b	Gleys	**0.20**	0.62	0.50	0.12
4a	Gleys	**0.12**	0.57	0.50	0.18
5a	Mixed	**0.19**	0.54	0.36	0.14
5d	Mixed	**0.20**	0.54	0.41	0.16
5e	Peats	**0.19**	0.41	0.29	0.13
5f	Peats	**0.29**	0.39	0.23	0.10
5g	Peats	**0.23**	0.52	0.32	0.13
5h	Peats	**0.22**	0.39	0.09	0.05
5j	Peats	**0.22**	0.55	0.38	0.15
5m	Peats	**0.42**	0.60	0.42	0.16
5o	Peats	**0.23**	0.51	0.29	0.12
5p	Peats	**0.25**	0.49	0.27	0.11
5q	Mixed	**0.24**	0.58	0.46	0.20
5r	Gleys	**0.26**	0.74	0.61	0.22
5s	Gleys	**0.27**	0.74	0.55	0.16
5t	Gleys	**0.26**	0.75	0.55	0.16
5u	Gleys	**0.28**	0.75	0.57	0.18
6a	Gleys	**1.86**	0.74	0.58	0.19
6b	Gleys	**0.20**	0.75	0.61	0.23
7a	Peats	**1.12**	0.70	0.59	0.20
7b	Peats	**2.03**	0.74	0.61	0.21
X	Gleys	**0.29**	0.64	0.61	0.20
Y	Gleys	**0.62**	0.62	0.56	0.20
Z	Gleys	**0.13**	0.64	0.63	0.24

Table 5.31: Pearson's Product-Moment correlation coefficients between Calculated and Predicted Log(annual average TP export rates). Coefficients are given for all sub-catchments (n-31) and differentiating gley, mixed soils and peat-dominated sub-catchments. Coefficients significant at $p \leq 0.05$ are in bold, and at $p \leq 0.01$ are underlined.

	All sub-catchments (n=31)	Gley-sub-catchments (n=12)	Mixed soils-sub-catchments (n=8)	Peat-sub-catchments (n=11)
Log(Jordan TP export rates)	**0.40**	0.35	0.47	**<u>0.83</u>**
Log(Johnes-Cober TP export rates)	0.30	0.19	0.31	**0.69**
Log(Johnes-Waver TP export rates)	0.26	0.02	0.55	**0.68**

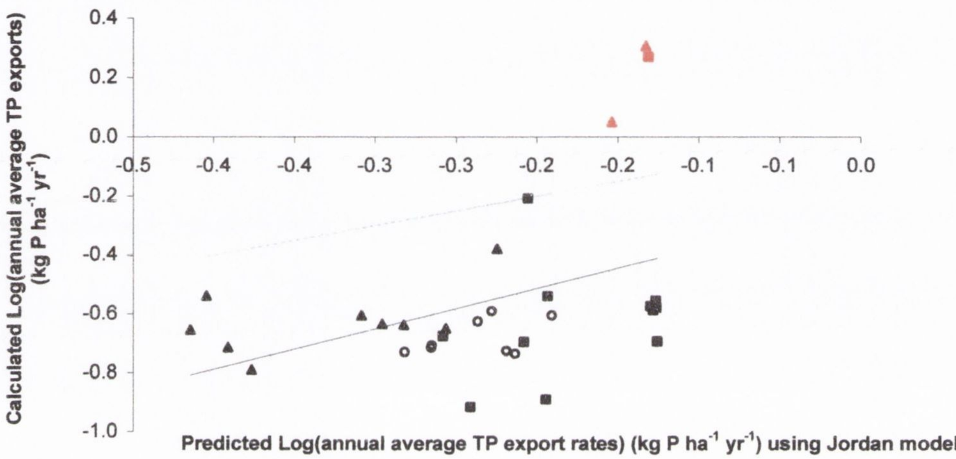

Figure 5.75: Comparison between Calculated and Predicted Log(TP Export rates) (kg P ha^{-1} yr^{-1}) using the Jordan model for each sub-catchment of Lough Lickeen (r_p=0.40, n=31, $p \leq 0.05$), differentiating gley (■) (r_p=0.35, n=12, ns), mixed soils (○) (r_p=0.47, n=8, ns) and peat (▲) –dominated sub-catchments (r_p=0.83, n=11, $p \leq 0.01$). The line 1:1 is also shown in grey. Linear regression models (y = bx + a) was derived (black line: b=1.38, R^2=0.13, df=29, $p \leq 0.05$). Sites 6a (■), 7a and 7b (▲) are highlighted in red.

<u>Deriving land cover export coefficients specific to the Lickeen catchment:</u>

Based on calculated annual average TP loading rates for each sub-catchment and their land cover types, specific export coefficients were derived for each land cover class in the Lickeen catchment (Table 5.32) from:

$$[\textbf{Annual average TP loading rates (kg P ha}^{-1}\textbf{ yr}^{-1}\textbf{)}]_i = [\Sigma A_{k,i} * E_{k,i}] / A_i$$

Equation 5.11

$$E_k = \text{Mean}(E_{k,i})$$

Equation 5.12

Where
i, relates to sub-catchment i
$A_{k,i}$: Area covered by land use k (ha) in sub-catchment i
E_k: average export coefficient associated with land use k in the Lickeen catchment (kg P ha^{-1} yr^{-1})
$E_{k,i}$: export coefficient associated with land use k (kg P ha^{-1} yr^{-1}) in sub-catchment i
A_i: Area of sub-catchment i (ha)

A first step was to derive an export coefficient for "Pasture", without differentiating improved, mixed and unimproved grasslands (Modelling A). Based on annual average TP loading rates calculated for sub-catchments comprising 100% pasture, export coefficients for "Pasture" were derived for each sub-catchment. The average export coefficient for "Pasture" in the entire Lickeen catchment was obtained by calculating the mean of the export coefficients obtained in the subset of sub-catchments. Applying the same approach, export coefficients for "Conifers" and "Peatlands" were then derived from sub-catchments comprising pasture and conifers or pasture and peatlands. Finally, export coefficients for "Mixed Agriculture" and "Broadleafs" were derived from the remaining sub-catchments.

The second step (Modelling B) was to differentiate the different classes of grasslands, using the average export coefficients derived from Modelling A for the other types of land covers, i.e $E_{peatlands}$, $E_{conifers}$, $E_{broadleafs}$ and $E_{mixed\ agric.}$. Following the method used in Modelling A, export coefficients for improved, mixed and unimproved grasslands were derived from annual average loading rates calculated for the different sub-catchments and average export coefficients for the entire Lickeen catchment obtained by calculating the means.

Table 5.32: Description of the export coefficients (kg P ha^{-1} yr^{-1}) derived for the Lough Lickeen catchment, derived from the estimated TP loading rates in the monitored sub-catchments between February 2002 and March 2003, with A: undifferentiating the types of grasslands and B: differentiating the types of grasslands.

	Coefficients A	Coefficients B
Unimproved Grassland	0.26	0.18
Mixed Grassland	0.26	0.31
Improved Grassland	0.26	0.38
Peatlands	0.20	0.20
Conifers	0.18	0.18
Broadleafs	0.03	0.03
Mixed Agriculture	0.36	0.36

Modelling spatial variation of loading rates within the Lickeen catchment using GIS

In the following sections, the new set of export coefficients derived for the Lickeen catchment was applied using GIS to spatially model variations in annual TP loading rates within the catchment. The influence of catchment physical characteristics (e.g. elevation, slope, soil P desorption and soil types) were assessed using linear multiple regressions. In order to test the validity and predictive power of the models, GIS-modelled annual TP loading rates were compared with the calculated values from the monitoring during 2002-03.

As site 6a was almost certainly impacted by point sources from a nearby farmyard (Figure 5.12) and TP, SRP and TDP concentrations recorded for this site were significantly greater than those recorded for site 6b (Paired t-test, α=0.05, n=15, p<0.05), it was excluded from the datasets in the modelling approach. Sites 7a and 7b were also suspected to be impacted by point sources of P. No obvious potential point sources of P could be identified, especially for site 7b. TP loading rates calculated for site 7a might have been influenced by a nearby farmyard, for which, however, potential run-offs were modelled to flow directly into Lake 9, without reaching the stream (Figure 5.12). In addition, no significant differences were found between TP concentrations recorded for sites 7a and 7b, while both TDP and SRP concentrations recorded for site 7b were significantly greater than those recorded for site 7a (Paired t-test, α=0.05, n=15, p<0.05). Both sites also recorded the greatest Soil Morgan P levels in the catchment with, respectively, 11.0 and 7.3 mg PO_4-P l^{-1}. As no clear explanation could be made regarding why loading rates recording at sites 7a and 7b were much greater than for the other sites (respectively 1.12 and 2.03 kg P ha^{-1} yr^{-1}), they were kept within the datasets for the following modelling.

- GIS-Model 1: Export coefficients derived for the Lickeen catchment

A grid coverage of the spatial distribution in the TP loading rates in the catchment (*GIS-Modelled-Grid*) was produced using GIS (Figure 5.76 – Appendix 4/Modelling/GIS-Model 1) by indexing each land use type by the associated average export coefficient (Modelling B). GIS-modelled TP loadings and loading rates were derived for each sub-catchment and the entire catchment for Lough Lickeen and compared with the calculated values from the monitoring 2002-03.

Overall TP loadings from the Lickeen catchment predicted by the GIS-model were 195 kg P yr^{-1} and significant positive correlations were found between calculated and GIS-modelled Log(TP loadings). For annual average loading rates (kg P ha^{-1} yr^{-1}), the relationship between calculated and GIS-modelled Log(TP loading rates) had a weaker but still significant (n=30, p<0.05) correlation coefficient (Table 5.33, Figure 5.77). When grouping sub-catchments based on their predominant soil types, significant correlations were found for peat-dominated (r_p=0.90, p≤0.01, n=11) and mixed soils sub-catchments (r_p=0.88, p≤0.01, n=8), while no correlation was found for gley-dominated sub-catchments (r_p=0.30, ns, n=11).

Table 5.33: Pearson's Product-Moment correlation coefficients (r_p) between calculated and GIS-Modelled Log(TP Loadings) and Log(TP Loading Rates) (n=30). Coefficients of determination, R^2 and Nash-Sutcliffe measure, R^2_{NS}, are also given. r_p significant at p≤0.05 are in bold and at p≤0.01 underlined.

	r_p	R^2	R^2_{NS}
Log(TP Loadings)	**<u>0.89</u>**	0.79	0.78
Log(TP Loading Rates)	**0.47**	0.22	0.02

Sites 7a and 7b impacted the relationships and when excluding the two sites from the datasets, no correlation was found between GIS-modelled and calculated Log(annual TP loading rates) (r_p=0.20, ns, n=28).

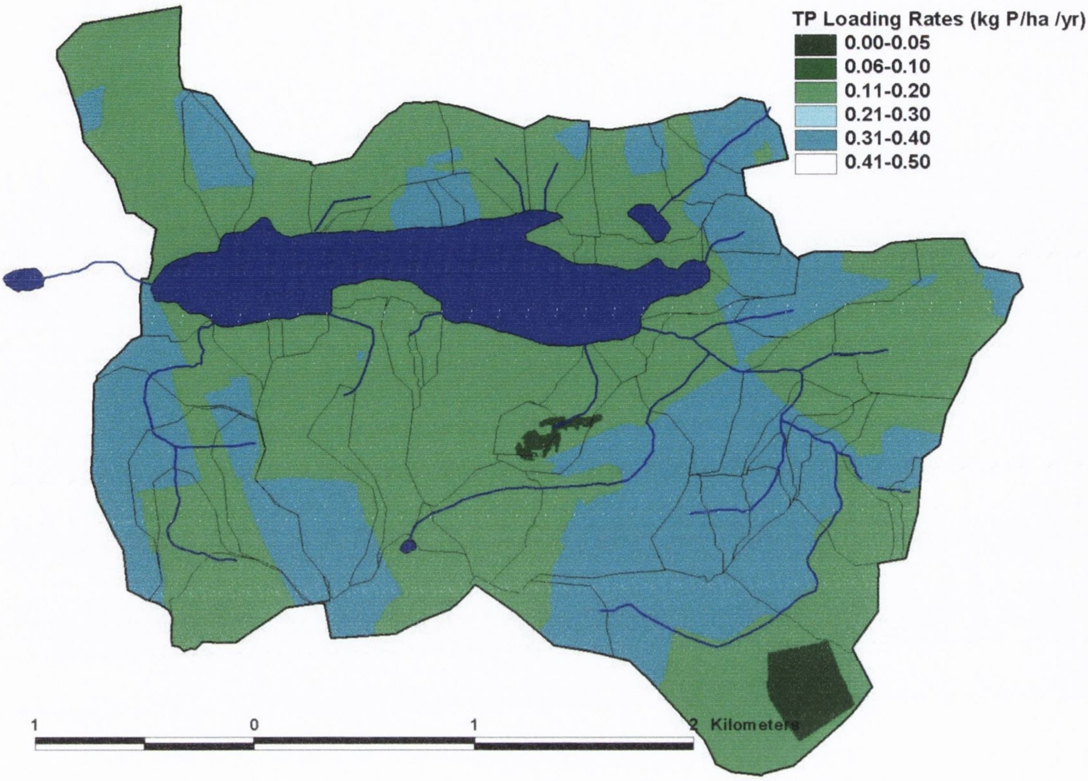

Figure 5.76: GIS-Modelled TP loading rates (kg P ha^{-1} yr^{-1}) in the Lough Lickeen catchment, produced by indexing the land cover-grid coverage with the associated export coefficients (Table 5.32), differentiating the grassland types (Modelling B).

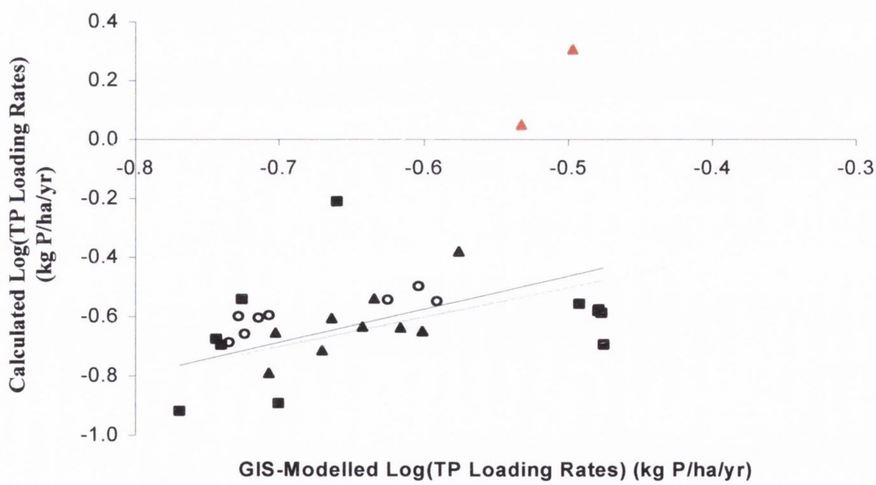

Figure 5.77: Comparison between Calculated and GIS-Modelled Log(TP Export rates) (kg P ha^{-1} yr^{-1}) using the new export coefficients (Table 5.32) for the sub-catchments in the Lough Lickeen catchment (r_p=0.47, n=30, p≤0.05), differentiating gley (■), mixed soils (○) and peat (▲) –sub-catchments. The line 1:1 is also shown in grey. Linear regression model is shown by the black line: y = 1.17 * x + 0.23 (R^2=0.22, df=28). Sites 7a and 7b (▲) are highlighted in red.

To improve the predictive power and accuracy of the GIS model and account for the influence of sub-catchment physical characteristics (topography, slope and soil types) on annual average TP loading rates into surface waters, a stepwise multiple regression (Equation 5.14 – Appendix 4, Table 12) predicted the variations of Log(Calculated annual average TP loading rates) (R^2=0.50, df=26, $p \leq 0.05$) as:

Log(Calculated annual average TP Loading Rates)= 0.98 * Log(GIS-Modelled annual average TP Loading Rates) – 0.007 * Mean Elevation – 0.39 * Soil P Desorption Index + 1.35

Equation 5.14

- GIS-Model 2: Application of Equation 5.14

In order to illustrate the spatial variations in annual average TP loading rates within the Lickeen catchment as predicted by Equation 5.14 and to assess the accuracy of the new model at the entire catchment-scale (i.e. total annual export from Lickeen), a new GIS coverage (Figure 5.78 - Appendix 4/Modelling/GIS-Model 2) was produced from Equation 5.14, based on the *Elevation-Grid, Soil P Desorption index-Grid* and *GIS-Modelled-Grid,* using the following map calculation:

GIS-Model TP loadings rates-Grid =

Exp_{10} (0.98 * Log(*GIS-Modelled TP Loading Rates-Grid*) – 0.007 * *Elevation-Grid* – 0.39 * *Soil P Desorption Index-Grid* + 1.35)

Equation 5.15

The introduction of Equations 5.14 and 5.15 in the modelling approach improved the accuracy of the predictions at the entire-catchment-scale, with overall TP loadings from the catchment predicted at 215 kg P yr^{-1}. Stronger significant correlations were found between calculated and GIS-modelled Log (annual average TP loading rates) (r_p=0.75, $p \leq 0.01$, n=30). The model also gave more accurate (R^2_{NS}=0.50) predicted TP loading rates at the sub-catchment scale (Figure 5.79).

When grouping the sub-catchments based on their predominant soil type, a significant correlation was found between calculated and GIS-modelled Log(TP loading rates) among the peat-dominated sub-catchments (r_p=0.88, n=11, $p \leq 0.01$), while no significant correlations were found for gley-dominated and mixed soils sub-catchments. If excluding sites 7a and 7b from the datasets, a significant correlation (n=28, $p \leq 0.05$) was still found between calculated and GIS-modelled Log(TP loading rates) (r_p=0.44).

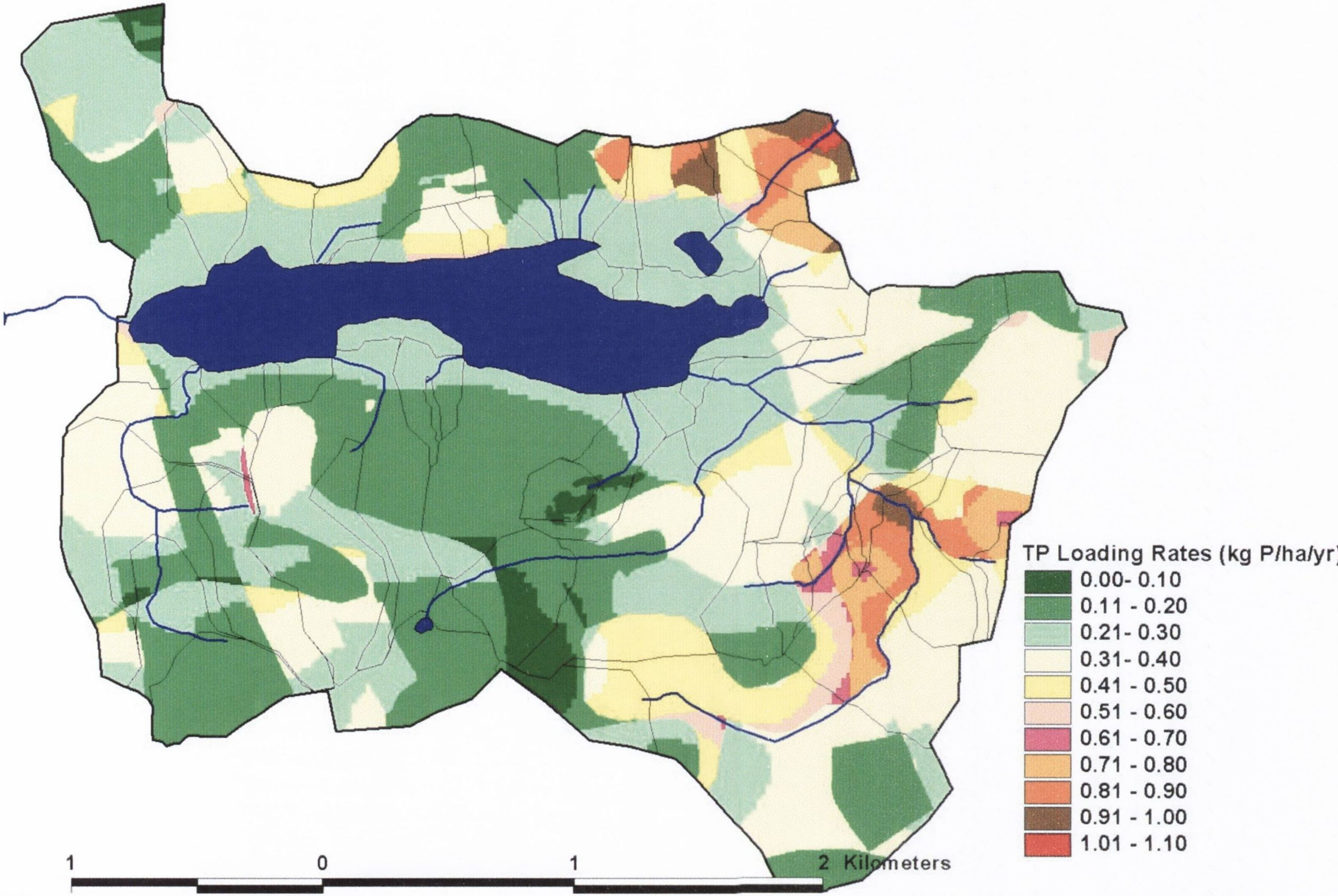

Figure 5.78: GIS-Modelled TP loading rates (kg P ha^{-1} yr^{-1}) in the Lough Lickeen catchment, produced based on Equation 5.14, applying the following Map Calculation: *GIS-Modelled2-TP loadings rates-Grid* = Exp$_{10}$ (0.98 * Log(*GIS-Modelled TP Loading Rates-Grid*) – 0.007 * *Elevation-Grid* – 0.39 * *Soil P Desorption Index-Grid* + 1.35)

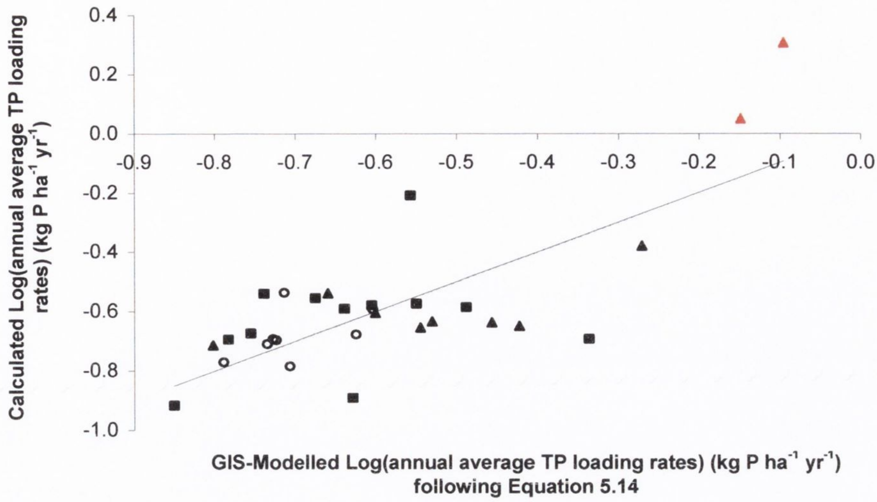

Figure 5.79: Comparison between Estimated and GIS-Modelled (Equation 5.14) Log(TP Export rates) (kg P ha^{-1} yr^{-1}) for the sub-catchments in the Lough Lickeen catchment (r_p=0.72, n=30, p≤0.01), differentiating gley (■), mixed soils (○) and peat (▲) –sub-catchments. The line 1:1 is also shown in grey. Linear regression model is shown by the black line (slope=1, R^2=0.56, df=28). Sites 7a and 7b (▲) are highlighted in red.

- GIS-Model 3: Introduction of a distance-coefficient

In order to assess the impact of distance from streams and lake on TP loadings and area-weighted loading rates, a coefficient was introduced to differentiate zones within 50 m from stream and/or lake from the remaining of the drainage area. This new approach aimed at improving the accuracy of the predictions at the sub-catchment-scale, but was subjective in the delineation of the riparian zone (i.e. 50 m from surface waters) and in its choice of indices attributed to the riparian zone and zone away from streams and lakes.

Grid-coverages of distance from stream and from lake were derived and combined into a distance coefficient-Grid. Each cell located within 50m of the lake and/or stream was arbitrary indexed 1.25, while the remaining cells were attributed the value 1.0. These indices gave the best results among the different combinations of indices used: 1.0 / 0.8; 1.0 / 0.9; 1.11 / 1.0 and 1.25 / 1.0 for, respectively, the riparian zone and remaining of the catchment. A final grid coverage of modelled TP loading rates in the Lickeen catchment (Figure 5.80 – Appendix 4/Modelling/GIS-Model 3) was produced, applying the following map calculation:

GIS-Modelled P loadings rates-Grid =

Distance Coefficient-Grid * GIS-Modelled-TP loading rates (Eq. 5.15)-Grid

Equation 5.16

The accuracy of the new model was higher at the entire catchment-scale with overall TP loadings from the catchment, predicted at 253 kg P yr^{-1}, but also at the sub-catchment-scale with R^2_{NS}=0.55.

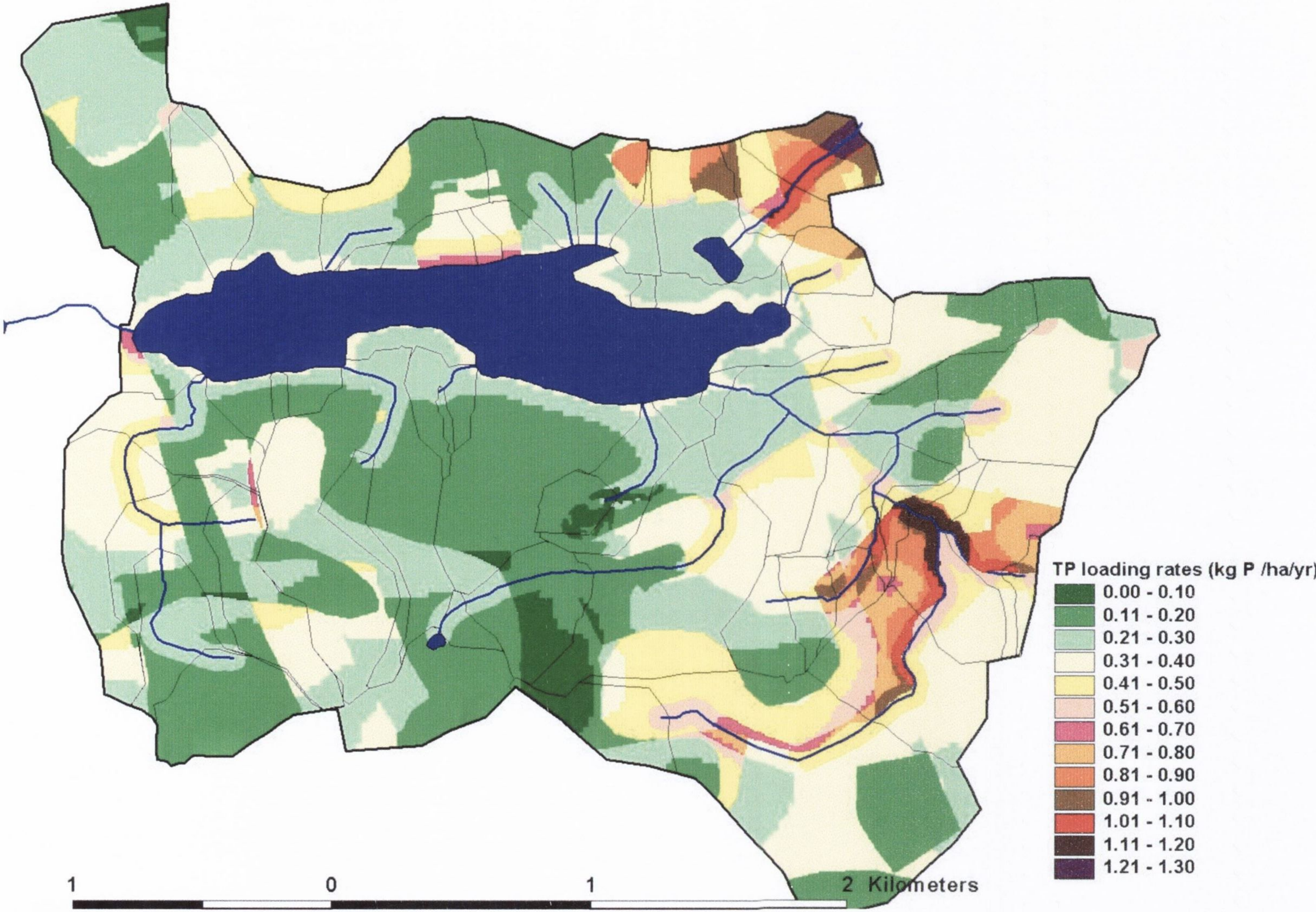

Figure 5.80: GIS-Modelled TP loading rates (kg P ha^{-1} yr^{-1}) in the Lough Lickeen catchment, introducing a distance coefficient, applying the following Map Calculation: *GIS-Modelled3-TP loadings rates-Grid* = Distance Coefficient-Grid * *GIS-Modelled (Eq 5.15)-TP loadings rates-Grid*

Significant positive correlations were found between estimated and GIS-modelled Log (TP loading rates) (r_p=0.74, p≤0.01, n=30 - Figure 5.81). When grouping the sub-catchments based on their predominant soil type, a significant correlation was found between calculated and GIS-modelled Log (TP loading rates) among the peat-dominated sub-catchments (r_p=0.84, n=10, p≤0.01), while no significant correlations were found for gley-dominated and mixed soils sub-catchments. If excluding sites 7a and 7b from the datasets, a significant correlation (n=28, p≤0.05) was still found between calculated and GIS-modelled Log (TP loading rates) (r_p=0.45).

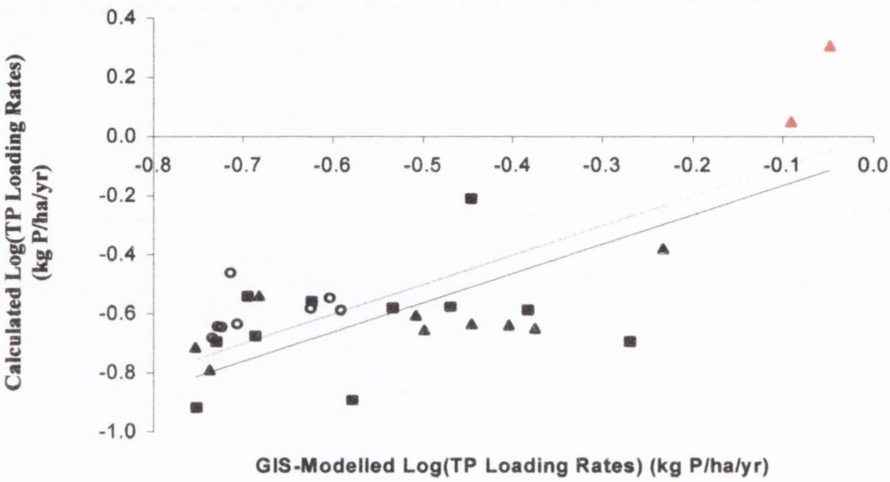

Figure 5.81: Comparison between Calculated and GIS-Modelled (distance coefficient) Log(TP Export rates) (kg P ha^{-1} yr^{-1}) for the sub-catchments in the Lough Lickeen Catchment (r_p=0.74, n=30, p≤0.01), differentiating gley (■), mixed soils (○) and peat (▲) –sub-catchments. The line 1:1 is also shown in grey. Linear regression model is shown by the black line: y = 1.00 * x – 0.06 (R^2=0.55, df=28). 7a and 7b (▲) are highlighted in red.

Summary of the different modelling approaches

Table 5.34 summarises the results obtained using the different modelling approaches. Equation 5.14 had the greatest but, nevertheless, modest power of prediction (R^2=0.56). The distance-corrected model gave similar results at the sub-catchment scale and closer estimates of the overall exports from the whole catchment, estimated at 248 kg P yr^{-1}. This approach is subjective and requires further modelling work.

Table 5.34: Summary of the results obtained when comparing Calculated and GIS-modelled Log(TP loading rates) (kg P ha^{-1} yr^{-1}) for the different modelling approaches applied to the sub-catchments (n=30) of the Lough Lickeen catchment. Pearson's Product-Moment coefficients (r_p) and coefficient of determination (R^2) are provided. Predicted annual average TP exports from the whole catchment (kg P yr^{-1}) are also given.

Modelling approaches:	**r_p (n=31)**	**R^2 (df=29)**	**Predicted Lickeen TP exports (kg P yr^{-1})**
Equation 5.9	0.59 ($p \leq 0.05$)	0.33 ($p \leq 0.0001$)	172
Jordan's	0.40 ($p \leq 0.05$)	0.13 ($p \leq 0.05$)	451
Johnes-Cober	0.30 (ns)		347
Johnes-Waver	0.26 (ns)		177
Land covers indexed by export coefficients	0.47 ($p \leq 0.05$)	0.22 ($p \leq 0.05$)	195
Equation 5.14	0.75 ($p \leq 0.01$)	0.56 ($p \leq 0.0001$)	215
Equation 5.14 distance-corrected	0.74 ($p \leq 0.01$)	0.55 ($p \leq 0.0001$)	253

When grouping the sub-catchments based on their predominant soil types, significant correlations were usually found between calculated and predicted TP loading rates among peat-dominated sub-catchments, while no significant correlations were found among mixed soils and gley-dominated sub-catchments, when using the different models described in this chapter. Loading rates calculated at sites 7a and 7b, which were suspected to be impacted by point source of P, influenced the relationships between calculated and modelled TP loading rates. When excluding these data, significant correlations were still found for the different models described in this section.

Validation with other acidic catchments in County Clare

In Chapter 4, existing mathematical models were applied to the 31 catchments from County Clare included in the medium and high frequency monitoring 2000-01. Empirical relationships predicting annual average TP loading rates to surface waters were derived based on catchment descriptive variables. In this chapter, models were derived for one specific catchment, Lough Lickeen, based on the calculated annual average TP loading rates into surface waters within the catchment. This section deals with the applicability of the different models to other catchments presenting similar bedrock geology.

Using GIS, the different GIS models developed in the previous sections, i.e. Equations 5.9, 5.14 and Equation 5.14 corrected by the distance-coefficient, were applied to eleven acidic catchments, included in the monitoring 2000-01 (Table 5.35). Based on soil and land cover coverages of County Clare, grid coverages of soil P index and indexed land uses were derived. Three grid coverages of spatial variation in TP loading rates were produced based on Equation 5.9 (Figure 5.82), Equation 5.14 (Figure 5.83) and Equation 5.14 further corrected by the distance-coefficient.

The greatest differences between GIS-modelled and calculated annual average TP loading rates were obtained for Loughs Acrow and Keagh catchments for which modelled rates were more than 10 times lower than the calculated values estimated from the monitoring 2000-01 (respectively n=4 and 13 sampling occasions). Both were upland peatland catchments, with elevation higher than 180 m and mean elevation of 203 m for Lough Acrow and of 190 m for Lough Keagh, which is higher than for Lough Lickeen (67 m -162 m). They were covered principally by peatlands and some conifers for Lough Acrow. Modelled TP loading rates were, in contrast, three to four times higher than the calculated value for Lough Moanmore which has a flat lowland catchment (mean elevation: 13.9m) principally covered by peatlands.

Comparing GIS-modelled annual average TP loading rates with calculated values, no significant correlations were found. Excluding Loughs Acrow and Keagh from the datasets, significant positive correlations (n=9, $p \leq 0.05$, Table 5.36) were obtained for the models based on Equation 5.9 (Figure 5.84), Equation 5.14 (Figure 5.85) and Equation 5.14-distance corrected. Models had modest predictive power ($R^2 \leq 0.63$). Equation 5.14 gave the stronger correlation and predictive power.

Table 5.35: Comparison between Calculated and GIS-modelled TP loading rates (kg P ha^{-1} yr^{-1}) obtained for eleven acidic catchments in County Clare, using Equation 5.9, Equation 5.14 and Equation 5.14 further corrected by the distance to lake-index. Calculated rates are based on the monitoring results 2000-01.

Catchment	Calculated from monitoring 00-01	Equation 5.9	Equation 5.14	Equation 5.14 dist-corrected
Acrow	0.46	0.04	0.04	0.04
Ballyleann	0.27	0.38	0.85	0.68
Cloonmackan	0.32	0.31	0.37	0.21
Cloonsnaghta	0.25	0.30	0.44	0.35
Doolough	0.22	0.14	0.19	0.14
Gortglass	0.29	0.27	0.37	0.30
Keagh	0.89	0.05	0.06	0.05
Knockalough	0.23	0.31	0.75	0.43
Lisnahan	0.41	0.25	0.63	0.49
Moanmore	0.38	1.44	1.88	1.50
Naminna	0.13	0.06	0.07	0.05

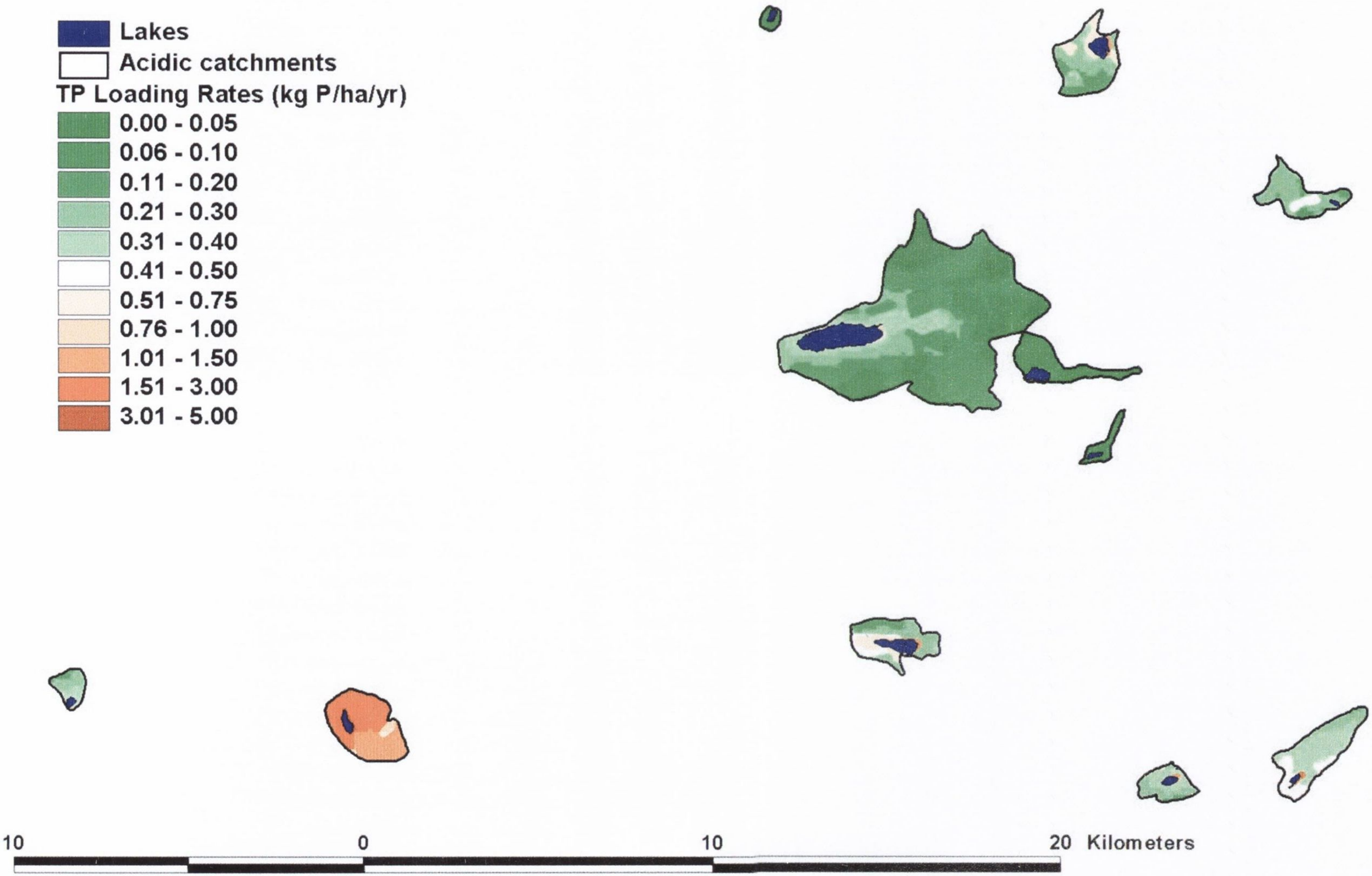

Figure 5.82: GIS-modelled TP loading rates in eleven acidic catchments in County Clare, produced based on Equation 5.9, by applying the following map calculation: *TP loadings rates-Grid* = Exp_{10} (-0.008 * *Elevation-Grid* – 0.318 * *Soil P Desorption Index-Grid* + 0.004 * *% Mixed grasslands-Grid* + 0.608)

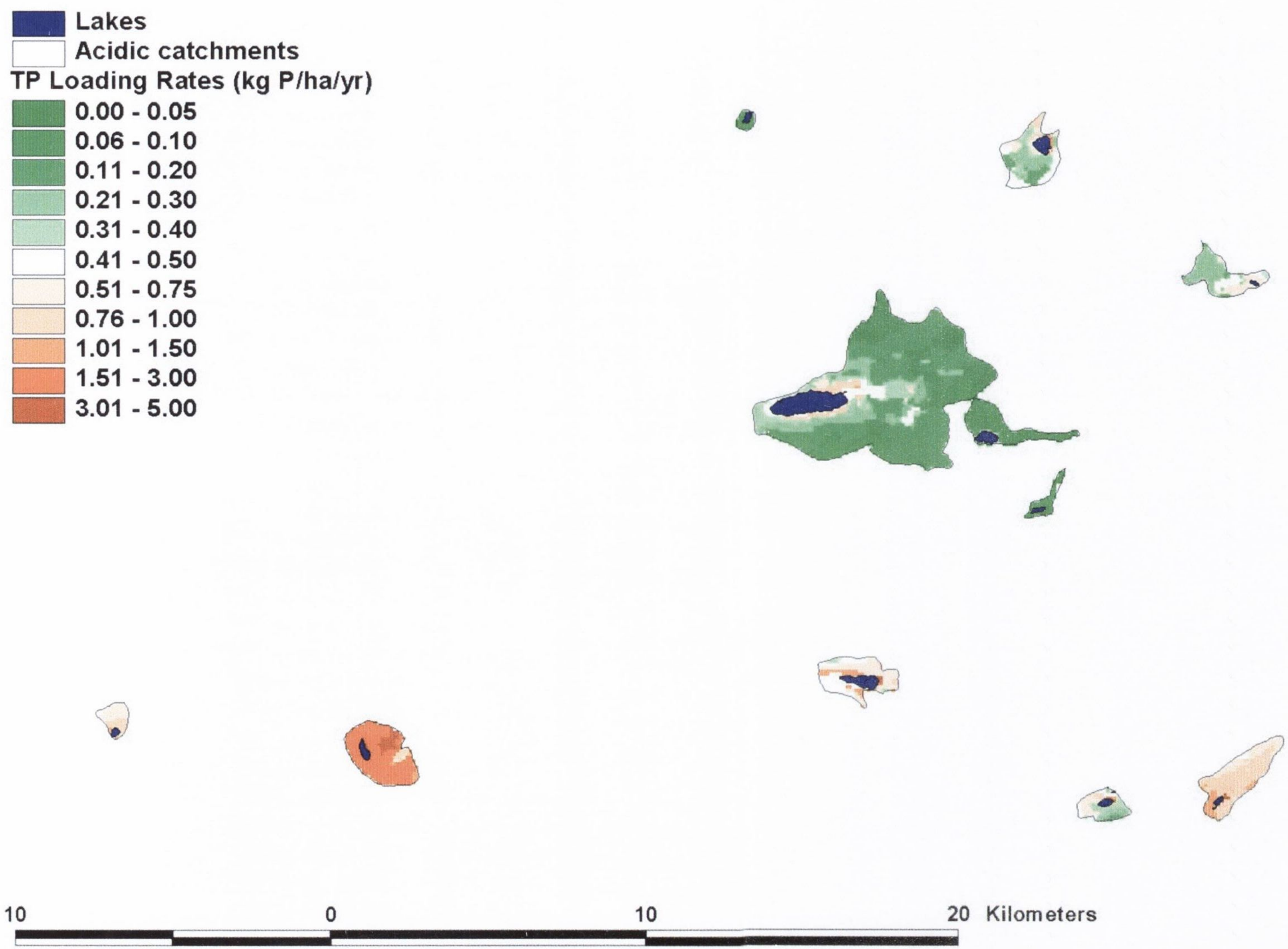

Figure 5.83: GIS-Modelled TP loading rates (kg P ha^{-1} yr^{-1}) in eleven acidic catchments in County Clare, produced based on Equation 5.14, applying the following Map Calculation: *GIS-Modelled2-TP loadings rates-Grid* = Exp_{10} (0.98 * Log(*GIS-Modelled TP Loading Rates-Grid*) – 0.007 * *Elevation-Grid* – 0.39 * *Soil P Desorption Index-Grid* + 1.35)

Table 5.36: Summary of the results obtained when comparing Calculated with GIS-modelled Log(TP loading rates) (kg P ha^{-1} yr^{-1}) for the different modelling approaches applied to nine acidic catchments from County Clare. Pearson's Product-Moment coefficients (r_p) and coefficient of determination (R^2) are provided

Modelling approaches:	r_p (n=9)	R^2 (df=7)
Equation 5.9	0.77 ($p \leq 0.05$)	0.54 ($p \leq 0.0001$)
Equation 5.14	0.79 ($p \leq 0.01$)	0.63 ($p \leq 0.0001$)
Equation 5.14 distance-corrected	0.79 ($p \leq 0.01$)	0.63 ($p \leq 0.0001$)

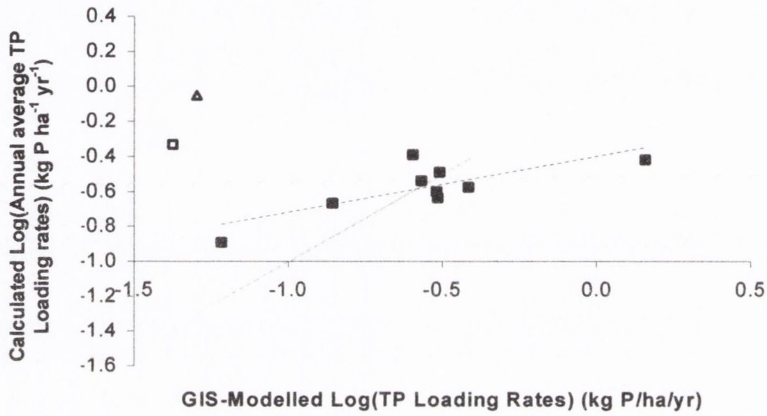

Figure 5.84: Comparison between Calculated and GIS-Modelled (Equation 5.9) Log(TP Loading Rates) (kg P ha^{-1} yr^{-1}) obtained for nine acidic catchments (■) in County Clare (r_p=0.77, n=9, $p \leq 0.05$). The linear regression model is illustrated by the black line (df=7, R^2=0.54, $p \leq 0.01$) and the line 1:1 is in grey. Estimated and Modelled loading rates for Loughs Acrow (□) and Keagh (Δ) are also shown.

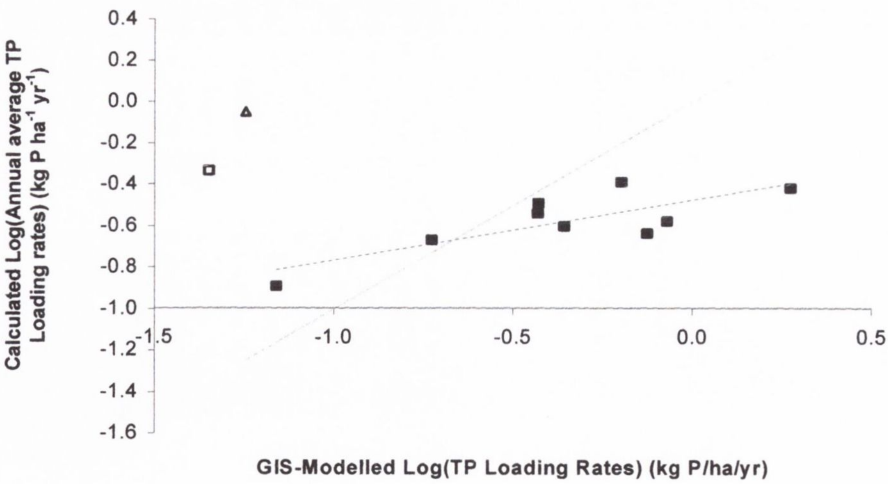

Figure 5.85: Comparison between Calculated and GIS-Modelled (Equation 5.14) Log(TP Loading Rates) (kg P ha^{-1} yr^{-1}) obtained for nine acidic catchments (■) in County Clare (r_p=0.79, n=9, $p \leq 0.05$). The linear regression model is illustrated by the black line (df=7, R^2=0.63, $p \leq 0.01$) and the line 1:1 is in grey. Estimated and Modelled loading rates for Loughs Acrow (□) and Keagh (Δ) are also shown.

V-4 DISCUSSION

A catchment-based analysis of nutrient loading dynamics within the Lickeen catchment (County Clare) was carried out based on intensive monitoring of the lakes, streams and soils in 2002-03 and on catchment descriptive variables. The aims of this chapter were to apply a similar modelling approach to the one used in Chapter 4 but at a smaller scale, and to derive empirical relationships predicting annual average TP loading rates to surface waters in the Lickeen catchment. The validation of relationships between pressures from catchment activities with impacts on water ecological quality is an important step in the implementation of the Water Framework Directive (2000/60/EEC).

Lough Lickeen: Source of water supply for the Northwest of Clare

Lough Lickeen is used as the main water supply for the northwest of the county, with an annual volume of 1.61 10^6 m^3 abstracted by the water treatment plant. On an annual average basis, over 40% of the water received by the lake through run-off is abstracted. This has a significant impact on the lake hydrological regime. Average monthly discharge rates recorded at the outflow ranged between 0.1 and 1.8 m^3 s^{-1} during the monitoring. In periods of extended dry weather, the outflow dries up (Jim Penny, EPA, Pers. Com.). The first collection of samples in February 2002 coincided with flooding conditions, with the outflow recording the greatest discharge rate since, at least, 1986.

The lake flushing rate and retention time varied between winter and summer, with flushing rates greater than 2 yr^{-1} during the winter 2001/02 and winter 2002/03, while during the summer 2002, estimated catchment run-offs were lower than the volume abstracted for water supply. Lower precipitation and greater PET during the summer result in greater retention time, which is favourable to the development of algal blooms.

The lakes in the catchment showed impaired water quality and were classified as eutrophic based on their maximum chlorophyll-*a* concentrations (OECD, 1982). The impact of eutrophication on drinking water supply could reduce its final quality. During the monitoring period, a problem of taste and colour of the water supply (Mary Burke, Clare Co. Council, Pers. com.) was associated with algal blooms and high chlorophyll-*a* concentrations in the lake. In 1981, investigation into a serious taste and odour problem of the water abstracted from Lough Lickeen found a close relationship between intensity and persistency of the odour problem and the periodicity of the *Anabaena* spp. population in the lake (Bowman, 1981). Eutrophication can also result in rapid clogging of filters by diatoms and other algae, disturbance of flocculation by organic substances, change of colour or other disturbances and risk of increased bacterial growth in drinking water (OECD, 1982).

Increasing use of the Lickeen catchment for conifer plantations

Lough Lickeen showed a moderate buffering capacity against acidification. However, concerns may be raised that a lowering of pH in run-off waters may result from increasing use of the catchment for conifer plantations. Based on the CORINE coverage of 1989/90, no conifer plantations were detected in the catchment. In 1998, 13 % of the catchment was covered by conifers (FIPS, 1998) and in 2003, the field survey recorded 22 % of the catchment area covered by conifers. Some of the coniferous plantations were located close to the lake. If this trend continues, it could constitute a risk of lake acidification. Lough Lickeen has an amenity value for angling. If the lake buffering capacity was to be exceeded, this would result in decrease in fish stock and ultimately fish kills. The monitoring 2002-03 showed that lower pH and alkalinity levels were usually associated with streams draining conifer plantations and more acidic soils. However, no major changes in the lake alkalinity levels were observed since 1981 (20 and 39 mg $CaCO_3$ l^{-1} (Bowman, 1981)). In 1996/97, alkalinity levels ranged between 17 and 23 mg $CaCO_3$ l^{-1} (Irvine *et al*, 2001) and in 2002/03, the mean alkalinity was 24.6 mg $CaCO_3$ l^{-1}. The upstream lake, Lough Ballard, draining peatlands and conifers was, however, poorly buffered against acidification.

Temporal trend in eutrophication of Lough Lickeen

Lough Lickeen has shown a decline in water quality since 1986, with increasing maximum chlorophyll-*a* concentrations. Maximum chlorophyll-*a* concentrations recorded in the lake was 45 µg l^{-1} in 1981 (Bowman, 1981.) and 61 µg l^{-1} in 2002/03. TP concentrations decreased between 1981 (10-65 µg l^{-1}) (Bowman, 1981) and 1996/97 (10-25 µg l^{-1}) (Irvine *et al*, 2001), but have increased since, with a mean concentration of 36 µg l^{-1} recorded in 2002/03. Between 1986 and 2003, there have been increased conifer plantations, increased coverage by mixed and improved grasslands and decreased area of peatlands and unimproved grasslands (CORINE, 1989/90, FIPS, 1998 and farm survey, 2003). A slight decrease in cattle density was observed between 1991 and 2000 (Agricultural Census of 1991 and 2000, CSO). Between 1996 and 2002, no changes in human population were observed (Human population Census of 1996 and 2002, CSO). Decrease in the water quality could have been caused by increased fertiliser applications, especially fertiliser inputs at the planting of new conifers, and increasing abstraction for water supply. However, no data on fertiliser applications are available.

Based on Foy (1992) and Vollenweider (1968) equations, a mesotrophic state for Lough Lickeen (based on annual mean in-lake TP concentration) would require exports from the catchment lower than 243 kg P yr^{-1}. This represents a marginal reduction of at least 2% of the actual exports. However, to ensure an oligotrophic state, exports should be lower than 58 kg P yr^{-1}, which represents a reduction of at least 77% of the exports calculated for 2002-03.

As observed for some of the lakes monitored in 2000-01 (Chapter 3), no obvious seasonal trends were observed in TP and TN concentrations in the lakes, while NO_3-N concentrations showed a decline during the spring with minimum summer concentrations, which could be explained by biological uptake in the lake and reduced inputs from the drainage area. Lake colour showed a steady but slight decline during the spring. For the lakes in the catchment, chlorophyll-*a* concentrations were maximum during the summer. Limitation of algal growth by nitrogen is thought to be occurring if the ratio (NH_4 + NO_3)/MRP is lower than 10 (Horne and Goldman, 1994; Irvine *et al*, 2001). All lakes showed signs of potential seasonal nitrogen limitation, especially during the summer and usually associated with high algal biomass, high SRP and low NO_3-N concentrations.

Impact on the downstream lake: Lough Cloonmara

Seasonal variations in lake water chemistry were more pronounced for the downstream lake, Lough Cloonmara. However, the lower number of samples taken for Cloonmara (n=9) could have influenced the results of the statistical analyses carried out on the water chemistry of the four lakes. The outflow from Lough Lickeen joins Lough Cloonmara after about 0.6 km. At about 0.1 km from Lough Cloonmara, it is joined by a secondary stream, draining mainly peatlands and conifer plantations. Other areas drained by the Cloonmara catchment comprised mixed and unimproved grasslands and were covered principally by gley and peat soils. Lough Cloonmara had slightly greater average nutrient and chlorophyll-*a* concentrations, colour and conductivity levels than Lough Lickeen. However, highest maximum chlorophyll-*a* concentrations were recorded for Lickeen.

Observation of outflow discharge rates since 1991 for Lough Lickeen indicated that rates recorded in 2002 were much greater than previous years. The annual average discharge volume of the outflow, based on data recorded between 1991 and 2001, was estimated at 6.8 10^6 m^3 yr^{-1}, compared with the annual average outflow discharge rate of 14.5 10^6 m^3 yr^{-1} during the monitoring period. Additional monitoring of the lake water quality in Lough Cloonmara could assess if the eutrophic conditions recorded in 2002-03 were caused by increased nutrient inputs from the Lickeen outflow. Additional monitoring of its outflow, the Ballymacravan River, would also indicate if the lake is acting as a sink for nutrients exported from Lickeen.

Spatial heterogeneity in the water chemistry of Lough Lickeen

The assumption that the water quality near the lake outlet was representative of the overall lake chemistry was confirmed by the lake monitoring 2002-03, which supports the monitoring approach carried out in 2000/01. It required the number of samples taken during the year to be large enough to account for seasonal and spatial variation in chemistry. Ten sampling occasions were used to make the comparison between the water chemistry observed for the whole lake and the site lake Middle B. However, maximum chlorophyll-*a* concentrations recorded between the two datasets differed greatly with 61 μg l^{-1} for the overall lake sites and 17 μg l^{-1} at lake middle B. This suggests that several monitoring stations may be required to produce accurate estimates of water chemistry of lakes, as wind action and the shape of the lake may reduce lake mixing.

Results from Lough Lickeen raise questions regarding the reliability of lakeshore samples in lake monitoring. Significant differences were observed between lakeshore and overall water chemistry from the middle of the lake. This could be explained by different mixing regimes, influence of inflowing stream chemistry, and shape of the lake shoreline and wind action. However, no significant differences in TP and chlorophyll-*a* mean concentrations were observed but greater maximum chlorophyll-*a* concentrations were usually recorded among lakeshore samples. Lakeshore sites may have been more sheltered from wind than open water area, favouring algae development. Differences observed in the water chemistry recorded among the lakeshore samples ("stream inlet" and "no stream") may be explained by the impact of the inflowing streams. However, lakeshore samples were collated from a boat a few metres away from the stream inlets and no significant difference were observed between the overall water chemistry of "stream inlet" and "no stream" lakeshore samples, despite more variability observed for "stream-inlet" samples.

Spatial modelling of eutrophication conditions

An advantage in sampling the lake at different locations was to develop a GIS spatial model of trophic status of Lough Lickeen, based on factors generally used to classify lakes into trophic classes (mean TN and TP concentrations, mean and maximum chlorophyll-*a* concentrations). It allowed comparison of different indicators.

Single variable trophic state criteria represent subjective judgments and may be limited spatially (Therriault and Platt, 1978; Reckhow and Chapra, 1983, Powel *et al*, 1989, Danilov and Ekelund, 1999). The use of descriptive classifications for lake trophic states such as oligotrophic, mesotrophic, eutrophic create difficulties for describing continuous changes in lake trophic status (Shannon and Brezonik, 1972; Carlson, 1977; Yoshimi, 1987). Trophic state criteria or indices using multivariate approaches have been proposed by a number of researchers (Shannon, 1970; Shannon and Brezonik, 1972; Carlson, 1977; Walker, 1979; Porcella *et al*, 1980; Ritter, 1981; Swanson, 1998). Trophic status indices (TSI) based on several biological, chemical and physical indicators offer the most suitable and acceptable method for evaluating lake eutrophication. Xu *et al* (2001) based their TSI on TP, TN, chemical oxygen demand, Secchi disc depth, chlorophyll-*a* and phytoplankton biomass. For Lough Lickeen, TSI based on maximum chlorophyll-*a*, which is the criteria the most widely used in lake classification, gave a similar index to the overall TSI used in this study but showed much more spatial variability within the lake than other indicators.

Based on the TSI spatial distribution, mesotrophic conditions were most common in Lough Lickeen, while eutrophic conditions were associated principally with the inlets of streams 3, 4 and 5. Hypertrophic conditions were found at the inlet of stream 3. Streams 1 and 5 showed moderate concentrations of nutrients (respectively 53 and 40 $\mu g\ l^{-1}$ for TP and 1.1 and 0.9 $mg\ l^{-1}$ for TN) at the stream inlets and greatest discharge rates, especially for stream 5. They were likely to have an impact on the overall lake chemical status, while streams 3 and 6, recording moderate to high nutrient concentrations (respectively 44 and 381 $\mu g\ l^{-1}$ for TP and 1.3 and 2.0 $mg\ l^{-1}$ for TN), but very low discharge rates, were most likely to have only a localised effect on the overall trophic state of the lake. Sub-catchment 5a recorded one of the highest annual average TP loadings into the lake (70 $kg\ P\ yr^{-1}$) but had moderate annual TP area-weighted loading rate (0.19 $kg\ P\ ha^{-1}\ yr^{-1}$).

Stream 4 had low to moderate TP and TN concentrations during the monitoring period (25 $\mu g\ l^{-1}$ for TP and 0.7 $mg\ l^{-1}$ for TN) and had the lowest estimated annual TP area-weighted loading rate (0.12 $kg\ P\ ha^{-1}\ yr^{-1}$). Its small sub-catchment comprised principally unimproved grasslands and broadleaved trees. No particular livestock grazing activities were noticed near the stream inlet and no fertilisers (organic or chemical) were known to be applied in the fields within its sub-catchment. However, TN and chlorophyll-*a* concentrations recorded at the associated lakeshore site (L5) (0.9 $mg\ l^{-1}$ for TN and 13 $\mu g\ l^{-1}$ for chlorophyll-*a*) were among the highest recorded in Lough Lickeen. Eutrophic conditions recorded in the surroundings of the inlet of stream 4 could be explained partly by loadings from stream 5, located less than 300m from the stream 4 inlet, lake flow direction, mixing regime and shape of the shoreline. Also, overall clearer water at its inlet could be favourable to algae development.

Stream 3 recorded high NO_3-N and TN concentrations (respectively 0.4 and 1.3 $mg\ l^{-1}$) with moderate TP concentrations (44 $\mu g\ l^{-1}$) and had moderate annual TP area-weighted loading rates (0.21 $kg\ P\ ha^{-1}\ yr^{-1}$ for 3a and 0.20 $kg\ P\ ha^{-1}\ yr^{-1}$ for 3b). The associated lake site (L4) had the greatest nutrient and chlorophyll-*a* concentrations (1.1 $mg\ l^{-1}$ for TN and 50 $\mu g\ l^{-1}$ for TP and 15 $\mu g\ l^{-1}$ for chlorophyll-*a*), as well as the highest turbidity levels (6.4 NTU). The maximum chlorophyll-*a* concentration obtained for Lough Lickeen during the monitoring period was recorded at this site (61 $ug\ l^{-1}$). Its sub-catchment drains conifers and unimproved grasslands. No fertilisers were applied on the grasslands and only limited grazing activities were observed. Fields located both sides of the stream inlet had a steep slope and were planted with young conifer plantations, for which no data on fertiliser application were collated. The lakeshore at the inlet of stream 3 is curved and this might favour the accumulation of nutrient flowing from streams 5 and 6.

Stream 6 did not appear to have an important localised effect on the lake. Sub-catchment 6a recorded the greatest annual average TP area-weighted loading rate with 1.86 kg P ha^{-1} yr^{-1} and a very limited discharge during the monitoring. An important difference was observed between area-weighted loading rates calculated for 6a and 6b (0.20 kg P ha^{-1} yr^{-1}), which cannot be explained by the application of organic and chemical fertilisers on the mixed grasslands, as it would affect also the site 6b. Some livestock grazing activity was observed in the surroundings of stream 6, but the significant increase in nutrient loadings observed between the two sites was more likely to have been caused by run-off from a nearby farmyard.

P losses from soils to surface waters

No significant correlations were found between overall soil P status and stream P fraction concentrations. However, significant correlations were found between stream SRP and soil Morgan P levels among gley sub-catchments in February and October 2002, when rainfall is maximal. Associated R^2 values ($R^2 \leq 0.30$, n=31, $p \leq 0.05$) were low owing to the interactions of other factors influencing in-stream P concentrations.

Soils in the Lickeen catchment were water-saturated during the monitoring period. Between February 2002 and March 2003, the number of days with more than 1 mm of rain (wet days) was 221 days, including 49 days with heavy rainfall (> 10 mm). Peat and gley soils have a low capacity for storing P and usually generate overland flow because of poor infiltration. If located near a stream or river, their contribution to overland flow into water surface network can be significant (Daly *et al*, 2000). Artificial drainage in the catchment was limited, usually associated with peat soils and conifer plantations, but provided a direct link between field systems and the catchment drainage network. It is likely that the main sources of P losses from soils to water occurred via subsurface flow but also as surface runoff. The hydrological, biological and chemical processes controlling P loss to water are complex and vary both temporally and spatially. Therefore, all fields or areas within a field do not contribute equally to P loss to water in a catchment. .Much of the total annual P export may come from a relatively small proportion (most hydrologically active source areas) of the catchment during a relatively small number of heavy rainfall events (Tunney *et al*, 2000); the extent of the P losses from soils during heavy rainfall event can be underestimated by discrete sampling methods (Grant *et al*, 1997; Wiggers, 1997).

In the Lickeen catchment, organic soils and mixed grasslands were associated with greater TP loading rates. Daly (2000) identified soils vulnerable to P losses by desorption as those having elevated soil P status and lower P sorption capacities. Organic soils are associated with low sorption/desorption capacities and have high risk of P loss to water following fertiliser inputs. Mineral soils have greater sorption capacity and will retain more P. However, at high P levels, they are more likely to lose P to waters owing to greater P desorption capacity. In this study, field observations showed that peat soil-areas were more intensively managed than gley soils. They were usually associated with conifer forests, peatlands, mixed grasslands and mixed agriculture. Both organic and chemical fertilisers were applied on the peat soils, resulting in probable high P losses to waters. Mineral soils (gleys) had more variable but usually lower soil Morgan P levels than peat soils. Peat soils in the catchment appear, therefore, to have greatest risk of losing P to surface waters.

In the modelling approach carried out in Chapter 4, soil characteristics and catchment topography were important factors in controlling P losses from soils to surface waters. Based on the linear model equation predicting TP loading rates to surface waters derived from the monitoring data (Equation 5.8), it appeared that annual average TP loading rates decreased with increasing elevation, % mineral soils, high soil P desorption index, while increased with % mixed grasslands. Catchment topography influences both the magnitude of the phosphorus load and the pathways utilised. Slope length and angle increase phosphorus in runoff. Ahuja *et al* (1982) attributed an increase in concentration with slope length to an increase in the amount of phosphorus sorbed per unit area, while Heathwaite and Dils (2000) reported significant downslope increases in the mean concentration of all phosphorus fractions in grassland surface runoff.

Nutrient export modelling

Two existing nutrient export coefficients models, Jordan *et al* (2000) (referred as Jordan model) and Johnes *et al* (1994, 1998) (referred as Johnes model) were applied to the sub-catchments. The model of Jordan *et al* (2000) tended to overestimate the amount of P exported. Free (2002) found that when applying the model to 31 lakes in Ireland, the residuals from the linear regression predicted/calculated exports were significantly correlated with the number of people (ha^{-1}) in the catchments.

In Chapter 4, when applied to the lakes monitored in Clare, both models also tended to overestimate the calculated export rates and no significant correlations were observed between predicted and calculated TP export rates (kg P ha^{-1} yr^{-1}). For the Lickeen catchment, significant correlations were observed only among peat-dominated sub-catchments. It was previously suggested (Chapter 4) that the difference observed between predicted and calculated TP exports could be explained by the models been derived among catchments with different intensity of agricultural activities and greater soil P levels. In this chapter, the Johnes model, using export coefficients derived from the Cober catchment, also overestimated the calculated TP exports, while usually the exports were underestimated when using coefficients derived from the Waver catchment. The major difference between the two sets of coefficients relies on the coefficients used for permanent grasslands (Cober: 0.40 kg P ha^{-1} yr^{-1}; Waver: 0.10 kg P ha^{-1} yr^{-1}) and for cattle (Cober: 2.85%, Waver: 2.75%). The Lickeen catchment has low to moderate soil Morgan P status ($\leq$11 mg PO_4-P l^{-1}), and low-intensity agricultural activity, while the Waver catchment has dairy farming activities on flat lowlands; and the Cober catchment has mixed arable and dairy farming activities on lowland with steep slopes (Johnes *et al*, 1994, 1996).

The Daly model (Daly *et al*, 2000) developed for wet soils overestimated stream MRP concentrations and no correlations were observed between predicted and calculated MRP concentrations. The model predicted stream MRP concentrations based on the land use classes: higrass, peatlands and semi-natural areas. They covered less than 13% of the entire Lickeen catchment area and, therefore, the impact of other land use types on the TP loading dynamics were not accounted for by the model. Another possible explanation of the lack of correlations could be that the model was developed based on flow-weighted P concentrations (normalised by flow) using MRP concentrations and flow data for the period 1991-94 for 35 catchments in Ireland. Annual flow-weighted MRP concentrations used to derive the model ranged from 9.1 to 261.6 µg l^{-1}, while, if excluding sites 6a, 7a and 7b, in-stream SRP concentrations ranged from 4 to 40 µg l^{-1} in the Lickeen catchment.

For all models, three sites (6a, 7a and 7b) showed greater calculated annual average TP exports than the predicted values. In addition, predicted values for site Y using Johnes and Jordan models were very close to the calculated exports from the monitoring. The four sites recorded the greatest TP area-weighted loading rates in the catchment. Potential run-off effluents from nearby farmyards may partly explain greater loading rates for the sub-catchment 6a; while source of TP loadings in sub-catchments 7a, 7b and Y were not obvious. However, more detailed observations are needed to determine clearly the sources of P in these sub-catchments.

Drainage areas influenced greatly the correlations between calculated and predicted loadings using the Jordan and Johnes models. When looking at annual average area-weighted loading rates (kg P ha^{-1} yr^{-1}) instead of TP loadings (kg P ha^{-1}), no significant correlations were obtained between calculated and predicted, except for peat sub-catchments, which appeared to be more responsive to changes in land use in terms of TP loadings to surface waters. This was also observed in the following modelling approach, where, when grouping sub-catchments based on their main soil types, significant correlations between GIS-modelled and calculated TP area-weighted loading rates usually were only found among peat-dominated sub-catchments. A possible explanation could reside in greater soil P levels and intensity of agricultural management among these sub-catchments. The lack or low accuracy of the correlations may be explained by the use of average cattle density for each field used as grazing pasture. In addition, spatial variation in rainfall among sub-catchments was not accounted for and no accurate flow data were available. In a multiple regression of flow and time on MRP load, Foy and Bailey-Watts (1998) found that flow accounted for 44% of the variations in the river Ballinderry (Northern Ireland) between 1974 and 1994. Also, further refinement could have been achieved by differentiating land use in riparian zone and allocating them higher export coefficients (Johnes, 1996; Johnes and Heathwaite, 1997).

When deriving export coefficients for Lickeen, low coefficients were obtained for broadleaf and conifer forests with, respectively, 0.03 and 0.18 kg TP ha^{-1} yr^{-1}. These fall within the range given by Johnes *et al* (1996) for undifferentiated forests with 0.02-2.00 kg TP ha^{-1} yr^{-1} and is lower than exports used by Jordan *et al* (2000) with, respectively, 0.23 and 0.39 kg TP ha^{-1} yr^{-1}. In the Lickeen catchment, most conifer plantations are young and phosphorus exports can increase markedly during establishment and deforestation and following fertiliser additions (Hobbie and Likens, 1973; Allott *et al*, 1998; Nisbet, 2001). While no significant correlations were observed between % conifers in the sub-catchments and TP loading rates to surface waters, it is likely that coniferous plantations close to the inlet of stream 3 contribute to increased TP loadings from the sub-catchment 3a and hypertrophic conditions of the lake in the proximity of the inlet and directly on the lakeshore. These plantations are lying on waterlogged gley soils with steep slopes. Applications of fertilisers followed by rainfall would result in increased P losses to the lake. In addition, the monitoring 2002-03 showed that greater nutrient concentrations were recorded among acidic streams and that increasing stream acidity was usually associated with increasing coverage by conifer plantations. Export coefficients derived for peatlands (0.20 kg TP ha^{-1} yr^{-1}) were greater than that used by Johnes *et al* (1996) (0.15 kg TP ha^{-1} yr^{-1}) and lower than that used by Jordan *et al* (2000) (0.23 kg TP ha^{-1} yr^{-1}). Greatest export coefficients were recorded in grasslands. These ranged between 0.18 kg TP ha^{-1} yr^{-1} (unimproved grasslands) and 0.36 kg TP ha^{-1} yr^{-1} (improved grasslands), which are much lower than export coefficients used by Jordan *et al* (2000): 0.64-0.84 kg TP ha^{-1} yr^{-1}. The major diffuse phosphorus loss to surface waters in Ireland is from grasslands. Tunney *et al* (1997) reported losses of 0.1 kg TP ha^{-1} yr^{-1} in surface run-off from grassland with low soil P test levels in Wexford, which probably represent conditions in Ireland before widespread use of chemical fertilisers. Phosphorus export from intensively managed grassland can be closer to 4 kg TP ha^{-1} yr^{-1} (Lee-STRIDE, 1995; Tunney *et al*, 1997; Kurz, 2000).

The use of nutrient export coefficients to predict nutrient runoff does not account for internal catchment processes, such as dynamics of phosphorus transport through soil and effect of landscape heterogeneity (Irvine *et al*, 2001). In addition, in some models there is an unresolved interaction between coefficients applied to grasslands and those calculated from cattle. In this study, coefficients derived for the different types of grasslands accounted for the average stocking density in the catchment but did not distinguish spatial variation in nutrient runoff from pasture because of variation in stocking density.

The approach applied in the Lickeen catchment was to combine statistical and spatial analyses in a stepwise process in order to improve both accuracy at the sub-catchment and entire catchment-scale. However, there is a risk of losing sight of the overall aim of nutrient modelling, which resides on its widespread usefulness for lake monitoring and its applicability to other catchments presenting similar characteristics.

Introducing a distance – decay concept did not improve the accuracy of the estimates at the sub-catchment scale, but gave a closer estimate of the overall TP exports from the Lickeen catchment. The modelling approach entailed subjective delineation of the riparian zone (i.e. within 50 m of streams and lakes) and in the choice of indices attributed to the riparian land and remaining area. More work is required to validate this approach, such as deriving coefficients for each land use class, differentiating the riparian zone and lands away from stream and lake (i.e. two sets of export coefficients for each land use class) and assessing the effect of varying the width of the riparian zone on the modelled loading rates. The actual area of land that contributes to storm run-off, and thus sediment transport, can be relatively small and dynamic (Hibbert and Troaendle, 1988; Eshleman *et al*, 1993). The "variable source area concept" has been applied at the event scale for relatively small sub-catchments. The attenuation of sediment and nutrients by runoff is influenced not only by distance to water, but also by topography, riparian land use, disturbance and the presence of impervious surfaces. Some studies have found that including the riparian factor does not improve regressions of water chemistry parameters against land use indices. Others have found that regressions improved when riparian land was considered or weighted more heavily than other lands (Johnes and Heathwaite, 1997; Jennings *et al*, 2002). Field studies have shown that riparian vegetation can reduce nutrient flow to surface waters. Soranno *et al* (1996) showed that the area of the sub-catchment that contributes most to the loading is much less than the total sub-catchment area, dynamic in width and strongly dependant on precipitation. Only spatially confined areas of a sub-catchment contribute to surface runoff and P mobilisation does not occur unless such areas coincide with land of high P potential (Gburek *et al*, 1996, 2000; Pionke *et al*, 1997; Pote *et al*, 1996). The spatially and temporally dynamic variable source areas controlling P loss reflect the coincidence of source and transport factors. For example, Pionke *et al* (1997) showed that up to 90% of annual P loss comes from less than 10% of the land area in hill-land sub-catchments. Schoumans and Breeuwsma (1997) found that soils with high P saturation contributed only to 40 % of TP load, while a further 40% came from areas where the soils have only a moderate P saturation but high hydraulic connectivity with the drainage network.

Phosphorus loading rates from the Lickeen catchment

Annual average TP loading rates calculated in the Lickeen catchment from the discrete sampling carried out in 2002-03 ranged between 0.22 (site 4a) kg P ha^{-1} yr^{-1} and 0.42 kg P ha^{-1} yr^{-1} (site 5m), which is within the range of loading rates calculated among the 13 acidic catchments monitored seasonally in the county in 2000-01 (0.07 kg P ha^{-1} yr^{-1} for Lough Keagh and 0.40 kg P ha^{-1} yr^{-1} for Lough Cloonmackan). Sites Y, 6a, 7a and 7b had greater loading rates with, respectively, 0.62, 1.86, 1.12 and 2.03 kg P ha^{-1} yr^{-1}, but were also suspected to be impacted by point sources of P. Equation 5.14, based on mean elevation (-), soil P desorption (-) and exports from land uses, gave the best predictions in variations in annual average TP loading rates for the sub-catchments and the entire catchment of Lough Lickeen (r_p=0.75, p≤0.01, n=30), and also when applied to similar catchments in Co. Clare (r_p=0.79, p≤0.01, n=9). However, the model greatly underestimated calculated TP loading rates when applied to Loughs Acrow and Keagh catchments, which are two upland peaty catchments. This is likely explained because of high exports from peatlands and presence of conifer plantations within these two catchments.

Linear regressions between modelled and calculated annual export loading rates only gave moderate R^2 values (R^2≤0.56), which would indicate that the models developed in this chapter only have a limited use in quantifying exports, as opposed to recognising trends of in-lake phosphorus concentrations. While the model developed for Lickeen could have been improved further by adjusting the export coefficients and accounting for the riparian zone, this could also have induced a loss of general applicability. Overall total annual TP exports predicted by the model (215 kg TP yr^{-1}) accounted for 87% of the calculated value obtained from discrete sampling in 2002/03 (248 kg TP yr^{-1}).

Spatial variations in annual average TP loading rates to surface waters within Lough Lickeen were produced based on Equation 5.14 and using GIS, as illustrated by Figure 5.78. Based on the monitoring and modelling approach, it appears that areas most sensitive to P losses in Lough Lickeen catchment were associated with peat soils, which usually are away from the lakeshore but nearby inflowing streams. Areas of greater risk of diffuse TP losses to surface waters (TP loading rates ≥ 0.5 kg TP ha^{-1} yr^{-1}) are summarised in Figure 5.86.

Areas F and D (Figure 5.86), located, respectively, around streams 5 and 7, were associated with low to moderate slope, but were close to the surface drainage network. Along the northern shore, Area B is in the immediate surroundings of the lake and has steep slope. Even if predicted potential TP loading rates were lower than for the other sensitive areas, its location and topography make this an area of importance in terms of potential risk of P losses to surface waters; a view supported by the observation that eutrophic conditions were associated with that part of the lake. In the northwest of the catchment, Area A is located away from the lake and inflowing streams. Eutrophic conditions were associated with the near-shore samples where modelling indicated that runoff from this area drained. Eutrophic conditions could, however, also have been caused by overland runoff from the farmyards.

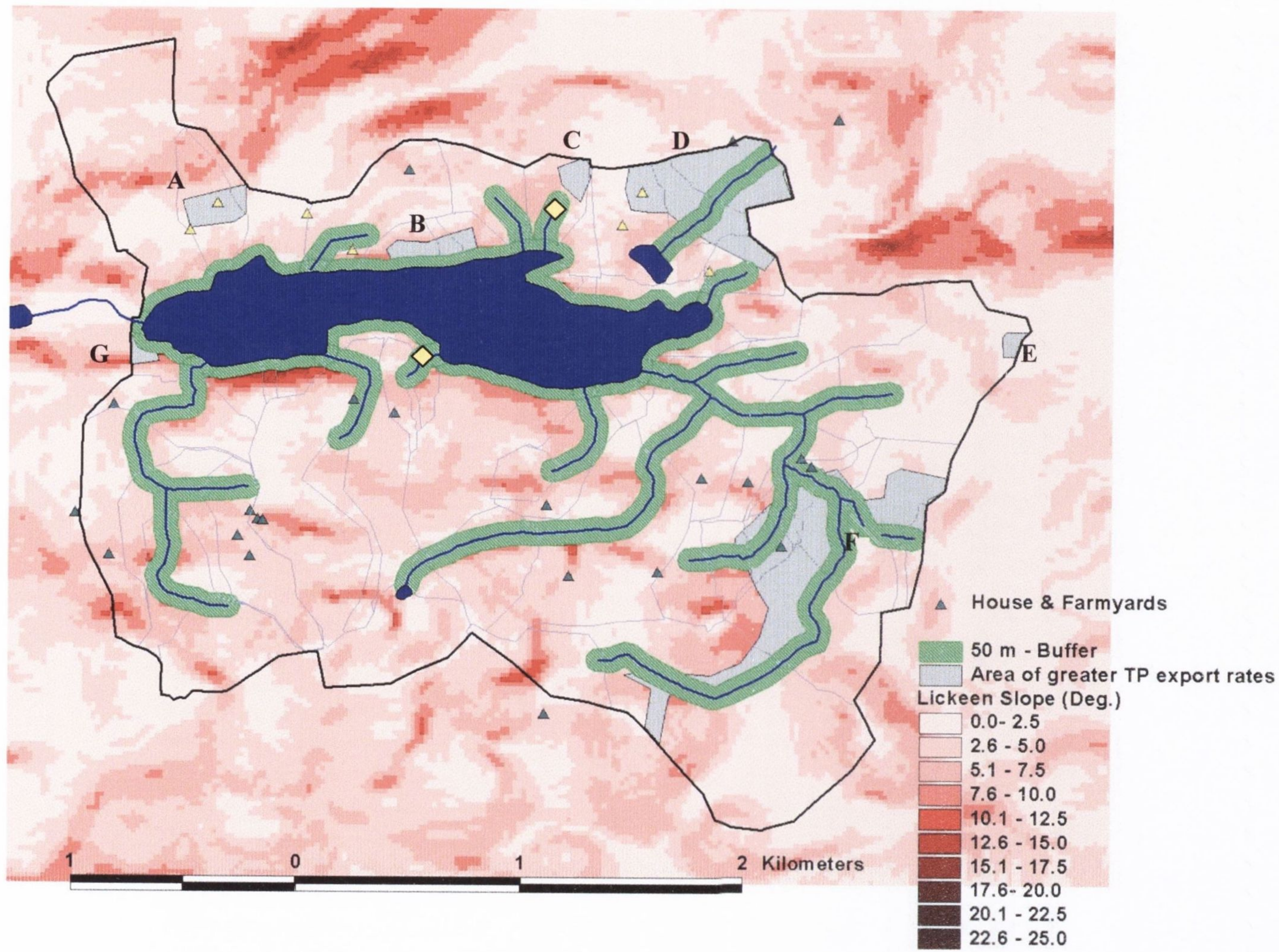

Figure 5.86: Areas (A to G) presenting the greater risk in terms of TP loadings to surface waters (annual average TP loading rates ≥ 0.5 kg TP ha^{-1} yr^{-1}) from diffuse sources within the Lough Lickeen catchment, also giving spatial variation in slope and 50m-zone from streams and lakes. House and farmyards (▲), potential point sources of TP from farmyards identified by the monitoring and modelling approach (△), as well as other potential sources to be investigated (◇) are also shown.

Areas C and E were associated with greater potential TP area-weighted loadings rates (0.6 kg TP ha^{-1} yr^{-1} for E and > 1 kg TP ha-^{1} yr^{-1} for C). However, they were located away from the lake and drainage network and should only have a limited impact on the overall TP loadings to the lake. Area G (0.5-0.7 kg TP ha^{-1} yr^{-1}) is located near the inlet of stream 1, but no apparent localised impact on the lake eutrophication conditions were observed. However, this area is located near the intake of the water supply and should, therefore, be managed carefully.

Careful management of these areas in terms of fertiliser and manure/slurry application and livestock grazing and farmyard practices, especially for areas associated with steeper slope and high connectivity to the surface drainage network, should be considered. Similar recommendations could apply to the immediate surroundings of the lake to reduce direct P losses into the lake. Planning of plantation of new conifers should also take note of the proximity to the drainage network and lakeshore, the soil type and steepness of the slope. More data are required to identify the impacts of the management of coniferous plantations around the inlet of stream 3 and their association with hypertrophic conditions observed in the lake. Potential point sources of TP, most probably associated with farmyard practices, were identified in the northeast of the catchment around streams 6, 7 and Y, and should be further investigated. Based on coefficients used by Johnes *et al* (1994, 1996, 1998), annual TP exports from livestock accounted for at least 35% of the overall TP export calculated in the whole catchment from the monitoring 2002-03, while exports from the unsewered population accounted for 5%. However, this figure is likely to increase during the angling season, as a few B&Bs are present in the catchment.

Conclusions

In the previous and, in particular, this chapter, GIS constituted an important tool for compiling, spatially analysing and modelling data. Combined with monitoring and statistical analyses, it allowed identification of an empirical relationship predicting annual average TP loadings to surface waters. The model was useful in predicting trends in TP loadings in other catchments with similar physical characteristics to the Lickeen catchment. The spatial application of the model at the sub-catchment scale in other catchments would have to be verified by intensive monitoring of surface water chemistry. A map of spatial variation in diffuse TP loading rates produced for the Lickeen catchment identified areas highly sensitive to P losses, as required by Article 5 of the Water Framework Directive (2000/60/EEC).

VI-1 Summary of main findings

This study included sixty-nine catchments located in County Clare, Ireland. They covered 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 use were collated and analysed spatially using Geographic Information System (G.I.S.). 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).

In 2002-03, a catchment-based analysis of nutrient loading dynamics within the Lickeen catchment (County Clare) was carried out based on intensive monitoring of the lakes, streams and soils and catchment descriptive variables. Lough Lickeen has a small lowland acidic catchment covered by poorly drained soils such as gleys and peats. It has diverse uses as source of water supply for the northwest of the county, amenity for angling, has low-intensity agricultural activities, comprising mainly pasture and extensive livestock-rearing activities, and is, increasingly, used for conifer plantations.

Identification of catchment types in County Clare

Two main types of landscape were identified among the catchments (Chapter 2). 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. These catchments usually had greater drainage areas and were associated with lakes of greater surface areas, volumes and shorelines. Some catchments were underlain by underlying karstified aquifers and were part of the Fergus catchment. In such areas, groundwater inputs and outputs should be taken into consideration owing to the close linkages between surface water and groundwater (Coxon and Drew, 2000; Kilroy, 2001). Acidic catchments, with impermeable bedrock composed of shales and similar rock types, were usually associated with higher elevations and poorly/imperfectly-drained soils such as gleys and peats. These catchments had smaller drainage areas with lower lake surface areas, volumes and shorelines. 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 associated with carboniferous limestone catchments. Such catchments present a natural buffering capacity making the risk of acidification negligible. The low alkalinity lakes, associated with shale catchments, are more vulnerable to acidification either through deposition from the atmosphere or as a consequence of intensification of coniferous forestry. Calcareous catchments had lower mean colour levels and TDOC concentrations than acidic catchments. Compared with softer lakes, hard-water lakes were usually associated with higher NO_3-N mean concentrations, TN/TP and NO_3-N/TN ratios, 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 no significant correlation found for high-colour lakes or acidic catchments. A key distinction between acidic and calcareous catchments was that ratios of 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 rates from groundwater inputs may limit the phytoplankton growth in such lakes. Phosphorus may also be bound in organic phosphates and cellular constituents and into organic colloids (Lucey *et al*, 1999; Cole, 1975; Wetzel & Lickens, 1991; Daly, 2000) rather than in the form of orthophosphate (PO_4^{3-}), which will reduce bioavailability of phosphorus. High flushing from groundwater together with chemical precipitation of phosphorus with carbonate complexes may, therefore, provide an effective buffering against nutrient enrichment among the calcareous lakes.

Seasonal variations, assessed in twelve lakes between March 2000 and October 2001, showed that in-lake TP concentrations, alkalinity, conductivity and colour were significantly influenced by the nature of the underlying bedrock geology. Different patterns of variation in alkalinity and pH were observed between hard and softer-water lakes. Lakes lying on carboniferous limestone bedrock had greater alkalinity and showed during the summer an increase in pH, likely driven by increased photosynthetic algal activity, and a decrease in alkalinity owing to precipitation of calcium carbonates. Lakes influenced by groundwater had a greater range of variation in alkalinity. Colour showed a general decrease during 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 had overall lower colour. 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 occured from winter to summer. Gradual decline of in-lake TN concentrations from winter to summer was observed for Loughs Castle, Cullaunyheeda, Dromore and Gortglass, and could be explained by sedimentation after incorporation into phytoplankton in lakes with low summer flushing, 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.

Lake classification schemes

Among the thirty lakes monitored seasonally ($n \geq 4$ sampling occasions) between March 2000 and October 2001 and based on maximum chlorophyll-*a* concentrations (Lucey *et al*, 1999), two lakes were found to be oligotrophic, nineteen mesotrophic, eight eutrophic and one hypertrophic. Based on one-off summer measurement(s) (n=1-2) of chlorophyll-*a* concentrations, four lakes were found to be ultra-oligotrophic, twelve oligotrophic, fifteen mesotrophic, seven eutrophic and one hypertrophic.

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. The OECD (1982) scheme and its modified version (Lucey *et al*, 1999) relies exclusively on boundary limit values and places too much emphasis on small differences across boundary limit values. In addition, it does not really identify impairment in water quality in lakes of the same trophic category. 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 established in the 1970s are unlikely to represent baseline reference conditions (undisturbed status) as required in the new European Water Framework Directive (2000/60/EC).

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 should not suffer any biological damage owing to acidity (H^+). Based on the alkalinity averages, five lakes had 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, a relationship observed between pH and alkalinity clearly identified three groups of lakes based on their alkalinity. Acidic catchments were associated with poor (alkalinity <10 mg $CaCO_3$ l^{-1}) to moderate (10-100 mg $CaCO_3$ l^{-1}) buffering capacity against acidification, while calcareous catchments all had good buffering capacity (>100 mg $CaCO_3$ l^{-1}).

Lake monitoring

<u>Seasonal spread of monitoring</u>

A three-tier sampling frequency was applied to monitor the sixty-nine catchments in Clare. More accurate means were observed when samples were evenly distributed over the monitoring period. Difficulties related to the spread and frequency of seasonal monitoring are common in sampling programmes and variability in the accuracy of the monitoring means 2000-01 is to be expected. In order to simplify the processing and statistical analyses of the data, high and medium frequency monitoring datasets were processed together. Nevertheless, a 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.

Spatial heterogeneity of lake water chemistry

In this study, one sample was collected per lake on each sampling occasion and most samples were taken from the lakeshore near the outflow. Sampling the centre of a lake avoids localised littoral edge effects, but involves a boat. The water near the outflow should, however, be representative of the mixed layers of the lake. Near-outflow or outflow samples, provided they are not taken some way down stream, are generally indistinguishable from those taken in the centre of the lakes (Johnes *et al*, 1998b). In Lickeen the water quality near the lake outlet was representative of the overall lake chemistry. Ten sampling occasions were used to make the comparison between the water chemistry observed for the whole lake and at the site lake Middle B. However, maximum chlorophyll-*a* concentrations recorded between the two datasets differed greatly with 61 $\mu g\ l^{-1}$ for the overall lake sites, but only 17 $\mu g\ l^{-1}$ for lake middle B. This suggests that several monitoring stations may be required to produce accurate estimates of water chemistry of lakes, as wind action and the shape of the lake may lead to a lack of homogeneity. Significant differences observed between lakeshore and overall water chemistry from the middle of the lake was supported by the development of a GIS spatial model of the trophic state of Lough Lickeen. This showed that mesotrophic conditions were most common in Lough Lickeen, while eutrophic conditions were principally associated with the inlets of streams located on the southern and eastern shore.

Results from the monitoring carried out in Lough Lickeen raise questions regarding the validity of shore-samples in lake monitoring. However, no significant differences in TP and chlorophyll-*a* concentrations were observed between lakeshore and middle lake samples, but greater maximum chlorophyll-*a* concentrations were usually recorded among lakeshore samples. Lakeshore sites may have been more sheltered from wind than open water area, favouring development of algae.

Use of mathematical models predicting TP loading exports to surface waters

Predicted annual TP export rates using two mathematical models, described by Jordan *et al* (2000) and Johnes *et al* (1994, 1996, 1998), were compared with calculated values from the monitoring at the catchment-scale among the thirty catchments monitored seasonally between March 2000 and October2001, but also at the sub-catchment-scale among Lickeen sub-catchments monitored in 2002-03. Both models tended to overestimate calculated export rates. No significant correlations were found between predicted and calculated export rates, even when differentiating catchment types. One possible explanation of the low accuracy of these models could be that the models were derived for catchments with different agricultural intensities and different soil characteristics, such as soil Morgan P levels.

At the catchment-scale, a significant multiple linear regression model between calculated and predicted export rates using the Jordan model was based on mean elevation (negative coefficient), mean slope (positive coefficient) and rainfall (positive coefficient), suggesting that the export coefficient approach should take into account catchment hydromorphology. Among the sub-catchments of Lough Lickeen, it was observed that when differentiating sub-catchments based on their main soil types (peat, gley or mixed soils), significant correlations ($r_p \geq 0.68$, n=11, $p \leq 0.05$) were observed for the peat-dominated catchments between calculated and predicted export rates using the Johnes and Jordan models.

The equation predicting annual mean MRP concentrations in streams derived for wet soils by Daly *et al* (2000) applied for the Lickeen sub-catchments also found no correlations between predicted and calculated concentrations in streams. Flow-weighted MRP concentrations and the greater range of concentrations and different agricultural activities among the catchments used to derive the model could partly explain the lack of relationship.

The use of the export coefficient models described by Johnes *et al* (1994, 1996 and 1998) and Jordan *et al* (2000), allowed, however, the identification of sites potentially affected by point sources of P within the Lickeen catchment. For these sites, predicted loading rates by the models were always lower than the calculated rates from the monitoring 2002-03.

Relationships between water chemistry and catchment characteristics

Relationships between catchment land use and water chemistry were assessed among catchments (n=30) and among sub-catchments in Lough Lickeen (n=31). Similar relationships with pH, alkalinity and colour of waters were observed both at the catchment and sub-catchment scale, while relationships between nutrient concentrations and land use were only observed at the sub-catchment scale. Among the thirty catchments monitored seasonally in Clare in 2000-01, measures of lake acidity status, such as pH and alkalinity, were correlated with the occurrence of peatlands and conifers in the catchments and lake colour was positively associated with peatlands. Within Lough Lickeen, high stream pH and alkalinity mean values were associated with gley soils and high soil P desorption indices, while streams associated with peat soils and peatlands had more acidic water. Higher stream alkalinity was also associated with the coverage of total pasture in the sub-catchments, while lower values were associated with conifers. Lower stream NO_3-N and TN mean concentrations were associated with peatlands, while higher mean concentrations were observed for sub-catchments with greater coverage of pasture. Higher stream TP, TDP and SRP were associated with the coverage of mixed grasslands in the sub-catchments, while sub-catchments associated with peat soils had more coloured water and higher mean TDOC concentrations.

Annual average TP export rates were estimated based on the monitoring 2002-03, using Foy (1992) and Vollenweider (1968) equations. No significant differences were found between area-weighted loading rates calculated in calcareous and acidic catchments, or between catchments with well, moderately and poorly drained soils. TP export rates from non-peaty catchments were, however, significantly greater than those from peaty catchments. In this study, areas covered with broadleaf forests and mixed grasslands for calcareous catchments and unimproved grasslands for acidic catchments were associated with greater annual average TP export rates. Within Lough Lickeen, organic soils and mixed grasslands were associated with greater TP loading rates. At both scales, no relationships were observed with average cattle density. Data on livestock derived from agricultural census data or farm survey may not be reliable, especially considering the low and small range of cattle densities encountered among the catchments.

Modelling TP loading rates based on catchment characteristics

This study has outlined that general modelling of TP loading rates should take into account differences in catchment types. Soil hydrology, P content and desorption properties, and the impact of varying physical environments were shown to be important in controlling the dynamics of P losses to surface waters. Within Lough Lickeen catchment, no significant correlations were found between the overall soil P status and stream P fraction concentrations. However, significant correlations were found between stream SRP and soil Morgan P levels among gley sub-catchments in February and October 2002, which corresponded to greater rainfall conditions. Associated R^2 values ($R^2 \leq 0.30$, n=31, $p \leq 0.05$) were low owing to the interactions of other factors influencing in-stream P concentrations. Soils in the Lickeen catchment were water-saturated during the monitoring period and the main source of phosphorus transport would have been by overland flow. The hydrological, biological and chemical processes controlling P loss to water are complex and vary both temporally and spatially. Therefore, all fields or areas within a field do not contribute equally to P loss to water in a catchment. As much of the total annual P export may come from a relatively small proportion of the catchment during a relatively small number of heavy rainfall events during the year (Tunney *et al*, 2000), the extent of the P losses from soils during heavy rainfall event can, therefore, be underestimated by discrete sampling methods (Grant *et al*, 1997; Wiggers, 1997).

Empirical relationships predicting annual average TP export rates to surface waters were derived from the monitoring in 2000-01 but also within the Lickeen catchment, based on the monitoring 2002-03. Overall, the accuracy and predictive power of the derived models at the catchment-scale were good, with $R^2 \geq 0.67$ and $R^2_{NS} \geq 0.67$ and increased when grouping the catchments among different types based on predominant bedrock types (acidic/calcareous), soil properties (peaty/non-peaty) and drainage characteristics (well/moderately/poorly-drained soils). For all six models, the predominant factors influencing annual average TP export rates were the catchment slope (positive coefficient), soil P levels (positive coefficient) and desorption index (negative coefficient).

The modelling approach applied in the Lickeen catchment was to combine statistical and spatial analyses in a stepwise process. Soil characteristics and catchment topography appear important in controlling P losses from soils to surface waters among the sub-catchments of Lough Lickeen. A first step was to derive a linear equation based on the monitoring 2002-03 and sub-catchment characteristics. This showed that annual average TP loading rates decreased with increasing elevation, mineral soils, high soil P desorption index, while they increased with % mixed grasslands (r_p=0.78, $p \leq 0.01$, n=31). A second step was to derive specific export coefficients for each land use class in the sub-catchments (r_p=0.47, $p \leq 0.05$, n=30). This approach was further improved by looking at the impacts of sub-catchment characteristics, such as soil characteristics, elevation and slope (r_p=0.75, $p \leq 0.01$, n=30). The distance-decay concept (riparian zone) was introduced but did not improve the accuracy of the predictions (r_p=0.74, $p \leq 0.01$, n=30). The best prediction of annual average TP loading rates for the sub-catchments and the entire catchment of Lough Lickeen (r_p=0.75, $p \leq 0.01$, n=30) was based on mean elevation (-), soil P desorption (-) and exports from land use. The model gave relatively good estimates (r_p=0.79, $p \leq 0.01$, n=9), when applied to nine other acidic catchments in Clare.

The modelling approach in this study was derived from measures of the catchment land use. While the CORINE land cover and Census of Agriculture datasets both provide data on catchment land use, they are not directly comparable. CORINE datasets describe the biophysical land occupation in the whole catchment, but specific land usages are not distinguished. The Census data summarises actual land usage but is not location specific. The CORINE datasets categorise grassland into high productivity, mixed and low productivity grasslands, which are more difficult to relate to actual agricultural farming practices in Ireland. In addition, such sub-divisions may be less meaningful in terms of nutrient losses from agriculture than the ones used in the Census data, which divides grasslands into silage, permanent hay, rough grazing and sum of rotation under 5 years.

The models derived in this study were developed for a limited range of catchment characteristics and may require further validation for areas with physical and hydrological parameters outside this range, especially in terms of slope and soil Morgan P levels. The need for further testing particularly applied to the modelling of TP loadings to surface waters in the North and East of the county associated with steeper slopes and greater soil Morgan P levels.

The use of export coefficient modelling allows estimation of nutrient loads into a lake based on catchment geology, topography and land use, and could be an alternative to long-term and continuous measurement of nutrient and hydraulic transport. Such a modelling approach, however, does not take into account catchment physical processes such as soil-phosphorus kinetics. It can also provide a good comparison in terms of risk assessment of P losses to water of the potential sources in a catchment. Simple empirical relationships derived from catchment characteristics and lake nutrient status could also be an effective method for the prediction of phosphorus load in the catchment and further reduce the requirements for data collection.

Identification of risk areas within Lough Lickeen catchment

The intensive monitoring of soil, streams and lakes in the Lickeen catchment combined with the modelling approach allowed visualisation of the spatial variation in TP loading rates to surface waters within the catchment using GIS and, therefore, the identification of the areas that constitute high risk to water quality from nutrient enrichment. Areas most sensitive to P losses in Lough Lickeen catchment were associated with peat soils, which are usually away from the lakeshore but nearby inflowing streams. Potential point sources of P, most probably associated with farmyard practices, were identified in the northeast of the catchment around streams 6, 7 and Y. It was also suggested that conifer plantations close to the lakeshore may be associated with the occurrence of hypertrophic conditions in the lake near the inlet of stream 3.

Lough Lickeen is used as the main water supply for the northwest of the county. Water abstraction impacts on the lake hydrological regime, especially during the summer. Lough Lickeen showed a moderate buffering capacity against acidification. However, a lowering of pH in run-off waters may result from increasing use of the catchment for conifer plantations. Based on the spatial modelling of trophic state within Lough Lickeen, mesotrophic conditions prevailed at the intake of water supply. Risk assessment of P losses to surface waters in the catchment showed that a sensitive area (0.5-0.7 kg P ha^{-1} yr^{-1}) was associated with the inlet of Stream 1 (Area G) and close to the intake of the water supply. This area requires careful management to prevent impact on the quality of the drinking water supply.

Use of GIS in the modelling process

GIS is an important tool in modelling and management, allowing spatial analysis, extrapolating models to other and wider geographical areas and producing final maps of risk assessment from P losses to surface waters. It supports catchment management and decision making processes. In this research, GIS allowed the production of interpolated surfaces of rainfall for County Clare, the creation of bathymetric maps based on the bathymetric surveys carried out in October 2001, and the visualisation of spatial variation in trophic state within Lough Lickeen. Collating characteristics for the sixty-nine catchments in Clare and for the sub-catchments of Lough Lickeen would have been more difficult, probably, less accurate and more time consuming without GIS. Spatial analyses, such as overlay, intersection and interpolation of several coverages, as well as deriving surfaces of modelled TP loading rates based on statistical equations could not have been carried out without GIS.

VI-2 Key contributions

This study contributes to a better understanding of the lake water chemistry in County Clare and the relationships between catchment land use and water quality, with an emphasis on TP loading rates to surface waters. It is particularly relevant to the implementation of the Water Framework Directive (2000/60/EEC), especially to Article 5, which requires the characterisation of impacts of potential pressures from anthropogenic sources to water quality and to consider water bodies based on catchment typology; but also, to Article 8, which requires that a comprehensive and coherent overview of the water ecological status be established within each RBD. However, this study only dealt with lakes, which are only one type of water bodies defined in the Directive (Article 1) and only considered the chemical status.

The key contributions from this work are:

- Compilation of a comprehensive database on catchment characteristics (Chapter 2 and p293):
    - Collation and spatial analysis of relevant existing digital coverages for County Clare,
    - Delineation of catchment boundaries for sixty-nine lakes,
    - Update of the lake coverage for County Clare,
    - Detailed stream network for the Lickeen catchment was digitised,
    - Detailed bathymetric survey carried out for fifteen lakes,
    - Identification of a linear regression model allowing the estimation of lake volume based on lake area,
    - Detailed land use and soil chemistry within the Lickeen catchment.

- Comprehensive water quality assessment of the County (Chapter 3 and pp293-297):
    - Comprehensive sampling programme in the county, covering 20% of the total number of lakes in the county, estimated at 358 (Kennelly, 1997),
    - Risk of acidification for the lakes lying on acidic bedrock,
    - Risk of eutrophication is the most common threat among the monitored lakes,
    - Potential buffering capacity against nutrient enrichment for the lakes lying on carboniferous limestone and karstic aquifers.

- Classification of lakes (Chapter 3 and p294):

The Directive (2000/60/EEC) refers to the ecological status of surface waters, which is linked to the chemical, hydrological and biological status and are defined based on their deviation from reference conditions ("undisturbed ecological status"). It classifies water bodies with high, good, moderate and poor ecological status. The EPA is to develop a classification system for water bodies by June 2006. The study suggested that the current method of lake classification (OECD, 1982; Lucey *et al*, 1999), based on fixed-boundary schemes should be used carefully, unless the number of samples taken is large enough to be representative of the overall seasonal variations of the lake chemistry.

- Lake monitoring protocol (Chapter 3 and pp295-296):

The Water Framework Directive provides both requirements and guidelines for monitoring. While the aims of monitoring are well defined, spatial and temporal scales of sampling, and sampling and analysis protocols are to be decided by the Member States. In Ireland, the EPA is to develop a programme of monitoring of water bodies by June 2006. The intensive monitoring of Lough Lickeen in 2002-03 suggested that monitoring should account for the spatial heterogeneity of water chemistry across the lake, but also that near-outflow sample was representative of the overall lake quality. The three-tier sampling frequency used in the monitoring 2000-01 also suggested that more accurate means were obtained for samples evenly taken throughout the year.

- Modelling TP loading rates to surface waters (Chapter 4 and pp297-301):
    - General modelling should account for difference in catchment types,
    - The assumption that variations in catchment land use impacted on lake water chemistry was validated by the small-scale study,
    - Important factors controlling the dynamics of P losses to surface waters were identified as soil hydrology, P content and desorption properties and impact of varying physical environments,
    - Statistical models predicting annual TP loading rates to surface waters at the catchment-scale were derived accounting for the influence of predominant bedrock and soil types among the catchments,

- Maps of spatial variation in annual TP loading rates were produced for the whole county,
- Statistical models predicting annual TP loading rates to surface waters within the Lickeen catchment were derived and risk areas were identified in terms of increased nutrient loadings,
- Specific sets of export coefficients were derived for each land use class found in the Lickeen catchment,
- Maps of spatial variation in annual TP loading rates were produced within the Lickeen catchment.

VI-3 Evaluation of research approach and future research

The research contained in this thesis aimed to establish a protocol for monitoring lake ecological quality through risk assessment based on catchment characteristics (physical, hydrological, land use and human activities), as required by the Water Framework Directive (2000/60/EC). In this study, the modelling approach relied mostly on estimates of area-weighted TP loading rates (referred as calculated TP loading rates). They were estimated based on Foy (1992) and Vollenweider (1968) equations, which relied on estimates of annual concentrations of nutrients, rainfall and flushing rates. A more accurate but costly method to quantify exports from a catchment would have been to automatically measure discharge and monitor water chemistry at the lake inflows and outflows.

The study relied on topographic divides for the calcareous catchments. However, some catchments were influenced by groundwater and the topographic divides may not correspond to the phreatic divides. Miscalculations of catchment and drainage areas may have incurred when using topographic divides and lead to errors when estimating hydrological parameters, such as flushing rate and retention time. However, it was not feasible in the scope of this research, to use chemical tracers to accurately define the boundaries of such catchments. Estimates of TP exports were expressed as annual area-weighted TP loading rates (kg P ha^{-1} yr^{-1}), which will reduce errors incurred by inaccurate catchment areas.

Rainfall estimates were limited by the available data from the different weather stations located throughout the County. However, the use of spatial interpolation with GIS allowed the interpolation of surfaces of rainfall across the county. Such a method 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 made. However, it was not possible to draw a precipitation contour map using isohyetal lines, taking into account the influence of the topography (Fetter, 2001), as this method is not only time consuming, but needs to be applied separately for each catchment.

Estimates of lake flushing rates and retention time also relied on estimates of lake volumes. However, fifteen lakes were surveyed in October 2001 to produce bathymetric maps and a significant linear regression model was derived to predict lake volumes based on lake areas (r_p=0.86, n=25, p<0.01).

Annual concentrations of nutrients were based on 4-16 sampling occasions, combining medium and high frequency monitoring and were assumed to be representative of the overall annual lake water quality. It was shown that more accurate means were calculated when samples were taken evenly over the monitoring period and more variability in the accuracy of the means using the medium frequency monitoring was observed. However, in order to simplify the processing and statistical analyses of the data, high and medium frequency monitoring datasets were processed together. Difficulties related to spread and frequency of seasonal monitoring are common in sampling programmes and variability in the accuracy of the monitoring means 2000-01 is to be expected.

For the small-scale study in Lickeen, use of continuous rainfall and flow measurement integrated with continuous water monitoring could have helped identifying daily variations in stream nutrient concentrations, quantifying nutrient loadings to the stream and assessing the influence of high rainfall events on nutrient losses by run-off. In addition, assessment of seasonal stratification and sediment sampling would provide a detailed picture of nutrient loading process and its impacts on the lake water quality.

The modelling approach relied mostly on correlations and regression analyses combined with spatial analysis using GIS. The use of statistical and spatial analyses to identify relationships between catchment descriptive variables and lake chemistry did not account for the complexities of physical and chemical processes in the environment. However, a process-based approach was not possible because of the variability of the characteristics of the catchments included in this study.

The question of riparian zones was only briefly dealt with. The modelling approach, however, was subjective in the delineation of the riparian zone (i.e. within 50 m of streams and lakes) and in the choice of indices attributed to the riparian land and remaining area. Further research is required to validate this approach and could aim at deriving coefficients for each land use class, differentiating the riparian zone and lands away from stream and lake (i.e. two sets of export coefficients for each land use class), but also assessing the effect of varying the width of the riparian zone on the modelled loading rates. Such research would be particularly relevant for farm nutrient management plans and catchment management strategies.

While the lack of accuracy of the soil P data (Soil Morgan P levels) and farm land use data derived from the agricultural census was mentioned several times during the thesis, the modelling approach in the Lickeen catchment relied on detailed soil sampling (45 sites within a catchment of 9 km^2). A farm survey carried out in March 2003, and showed that soil P characteristics was a significant factor in controlling P losses to surface waters. This supported the findings of the modelling carried out at the catchment-scale and suggested that detailed soil P data, most probably on field-by-field basis, are essential to proper farm nutrient management and accurate modelling of P losses to surface waters.

The study mainly concentrated on risk of P losses to surface waters. A similar approach could have been applied to other nutrients, such as nitrogen and silicate-silicon. In particular, it would have been interesting to assess the spatial variability in sources of P and N and their relative impacts on the lake water quality, among the catchments and within the Lickeen catchment, as any management plan should account for the two nutrients.

Concluding remarks:

Overall, the work carried out in this thesis successfully fulfilled its main objectives, outlined in Chapter 1. The research in the Lickeen catchment allowed the validation of the assumption that changes in land uses impacted on lake water quality and supported the findings of the modelling approach carried out among the sixty-nine catchments in Clare and allowed the modelling of spatial variation in trophic state within the lake. The study combined extensive and intensive lake water chemistry monitoring among a large number of lakes within a geographically restricted area (County Clare), and at the sub-catchment scale in Lough Lickeen. The GIS constituted a valuable tool in this work by allowing better data management and analysis, design of monitoring protocol and spatial modelling. Finally, this research highlighted important considerations for the characterisation of catchments and the implementation of the Water Framework Directive (2000/60/EEC).

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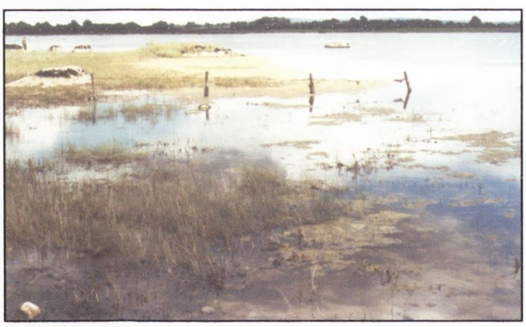
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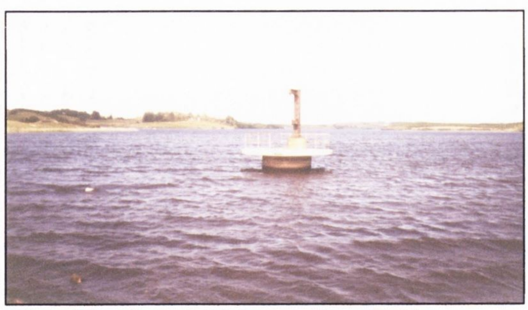
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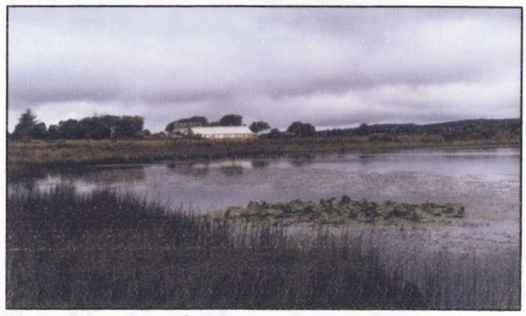
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__Note:__ No pictures were taken at Loughs Bridget, Bunny, Drumcullaun, Finn, O'Briens and Rushaun.

APPENDIX 1: Bathymetric survey – October 2001

Table 1: Summary GPS Survey results (October 2001). GIS estimates of lake area (m^2), shoreline (m), minimum (Min.), maximum (Max.) and mean depth (m), as well as lake volume (10^6 m^3) are listed.

Lake	Area (m^2)	Shoreline (m)	Min Depth (m)	Max Depth (m)	Mean Depth (m)	Volume (10^6 m^3)
Atedaun	379921	3155	0.5	8.1	1.4	0.548
Ballybeg	197332	3446	0.9	5.7	2.7	0.532
Ballyallia	326061	3361	1.1	13.0	6.4	2.073
Burke	103305	1825	2.4	10.3	6.1	0.635
Cloonmackan	234497	2118	0.7	15.0	2.9	0.891
Cullaunyheeda	1528024	7230	1.1	25.0	7.8	11.238
Cloonsnaghta	85632	1187	2.3	7.6	4.1	0.355
Doon North	484380	3362	1.2	15.1	6.7	3.235
Gortglass	291635	3310	0.8	14.1	4.9	1.427
Inchichronan	1166982	11957	0.8	18.1	6.5	7.548
Killone	190723	1992	2.7	16	9.6	1.820
Knockalough	339083	3199	1.5	9.5	2.9	0.983
Knockerra	74106	1446	0.9	2.0	1.5	0.116
Muckanagh	960957	6277	0.7	15.0	2.9	2.794
Naminna	199871	2016	2.2	10.9	4.4	0.872

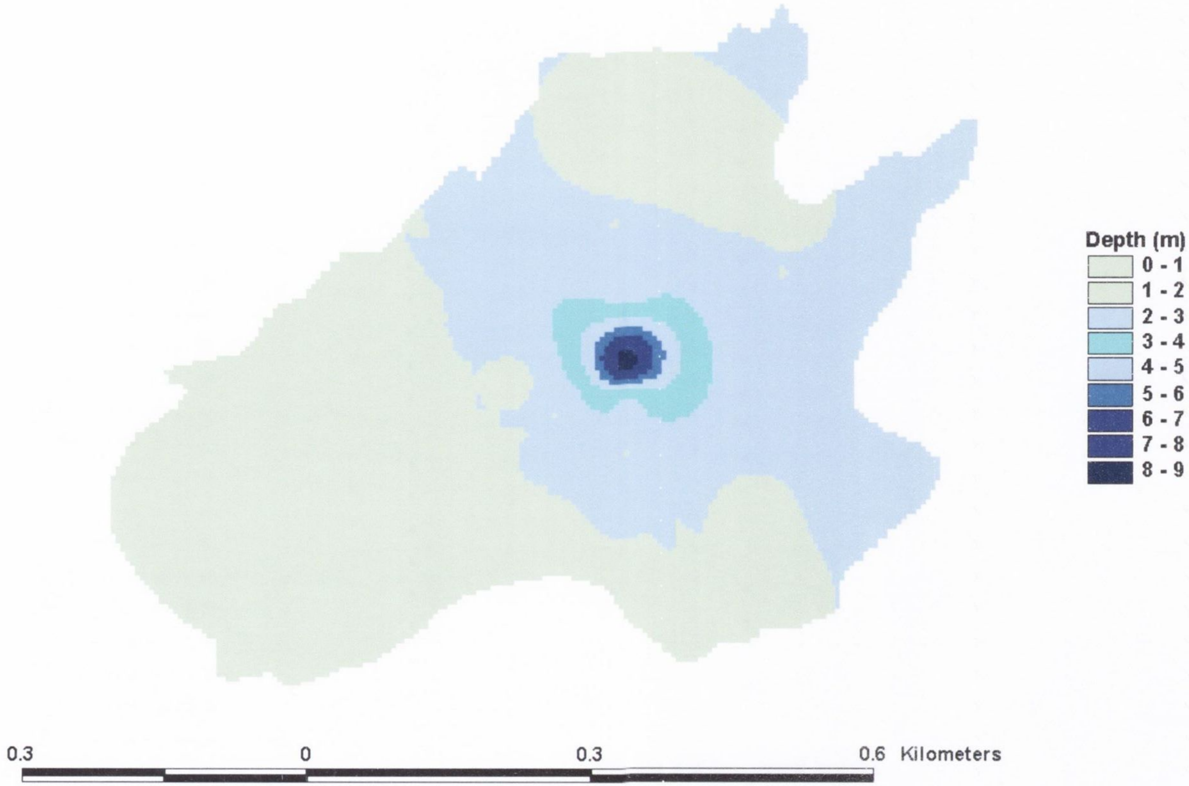
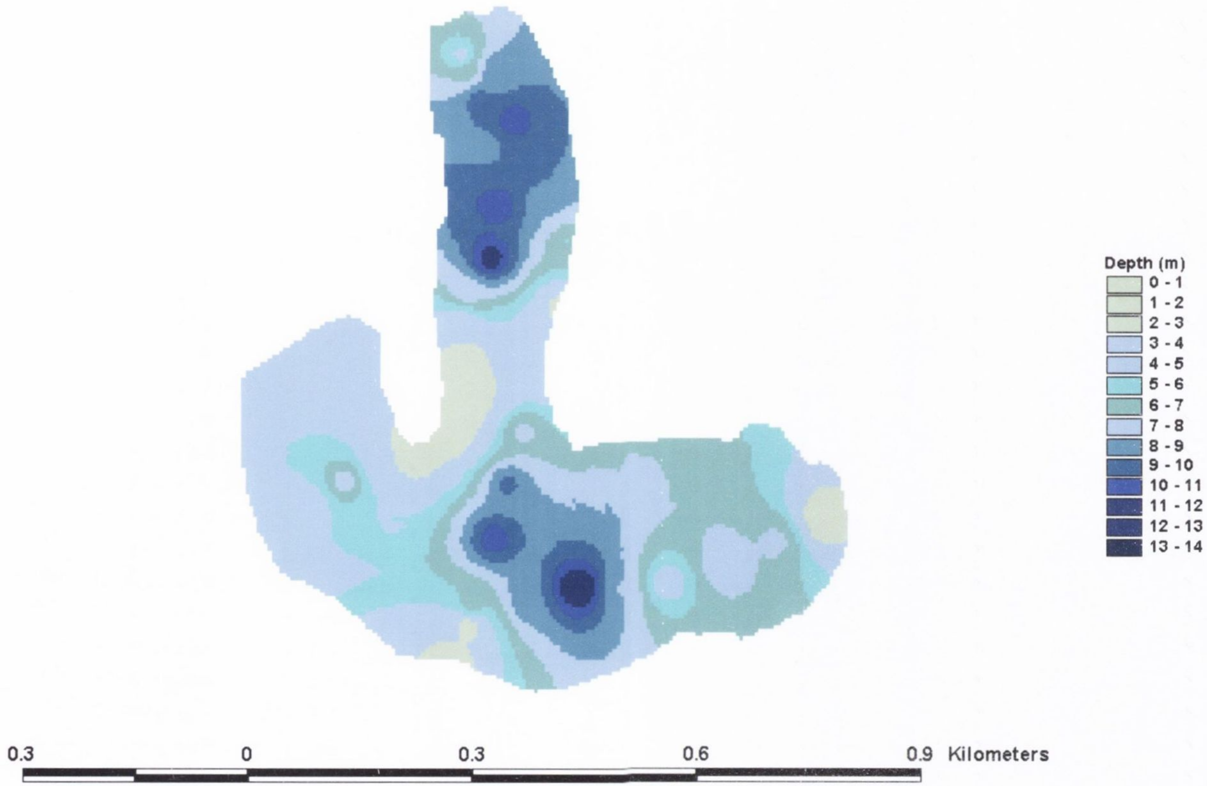


Figure 1: Lough Atedaun – Bathymetric map



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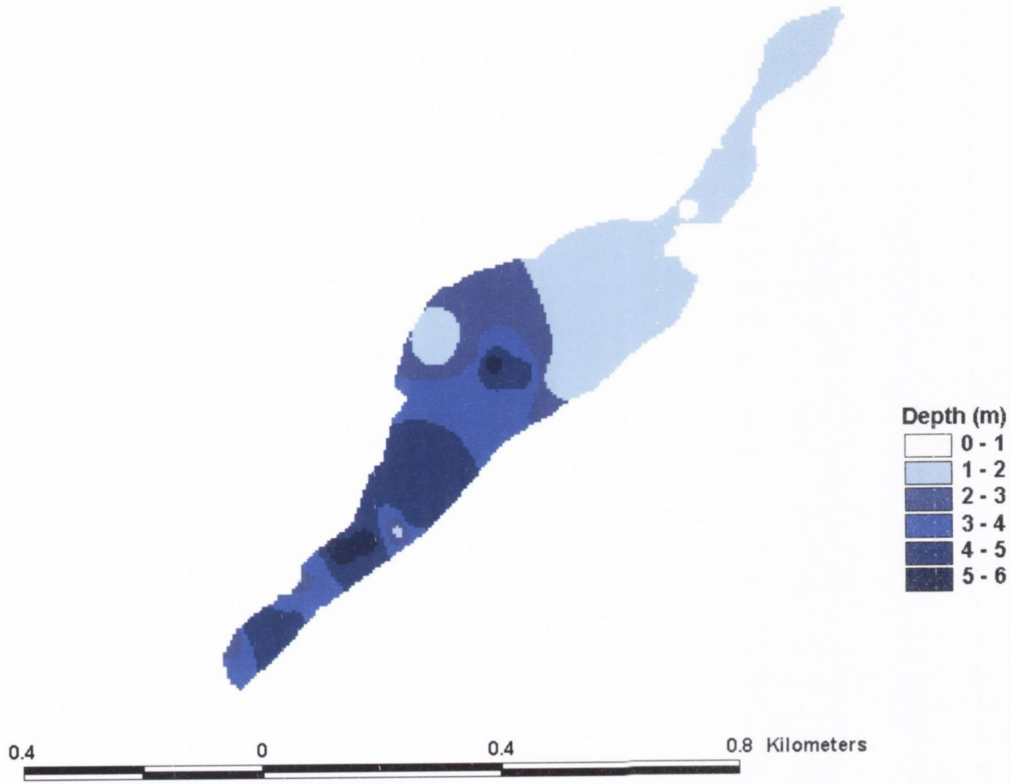

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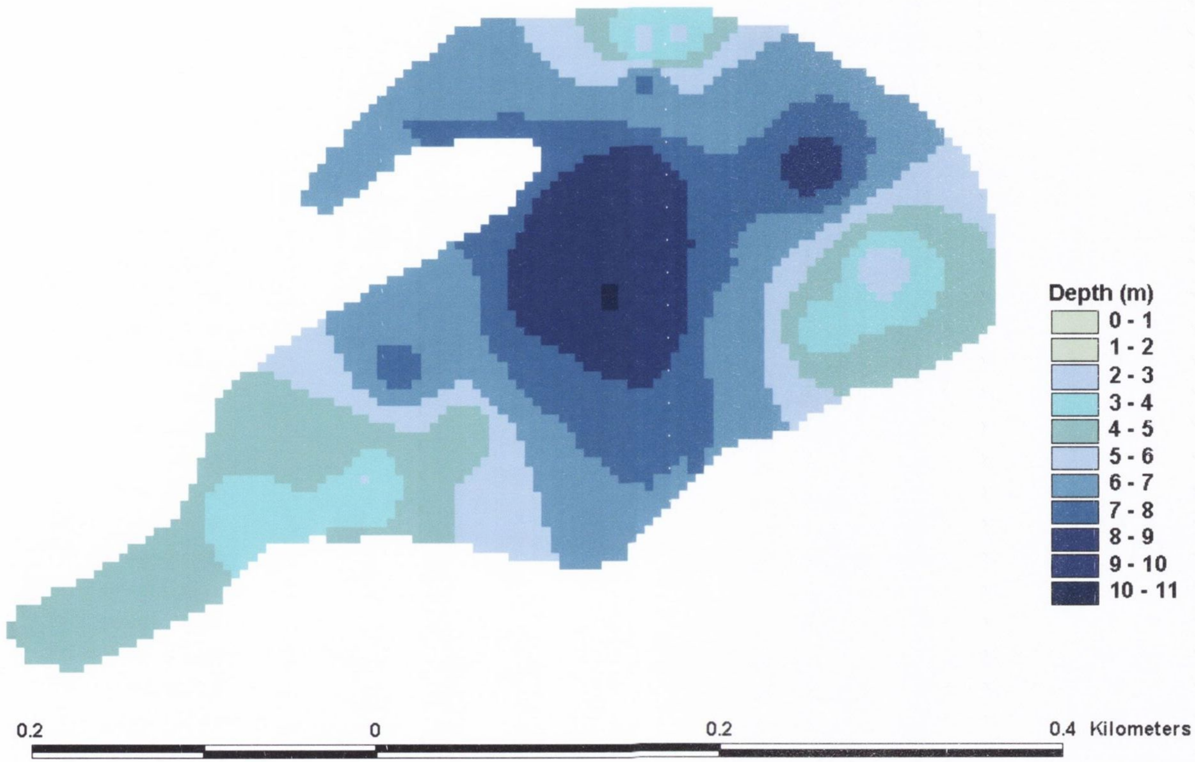


Figure 4: Lough Burke – Bathymetric map

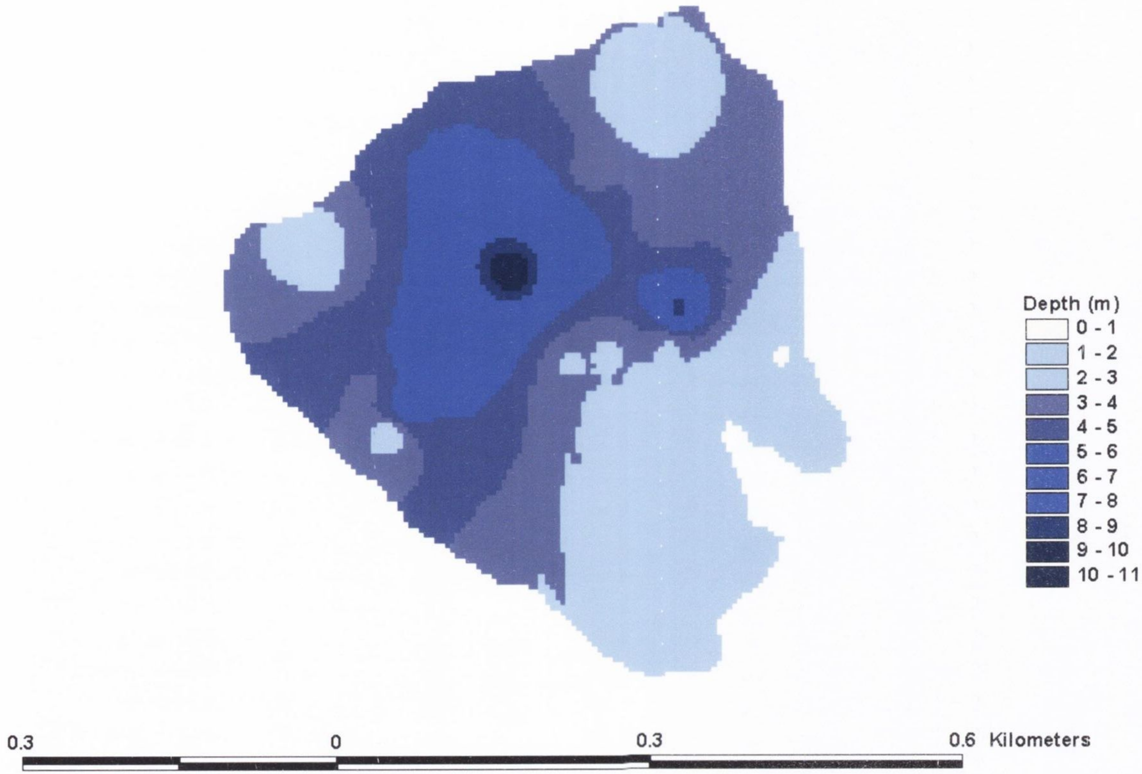
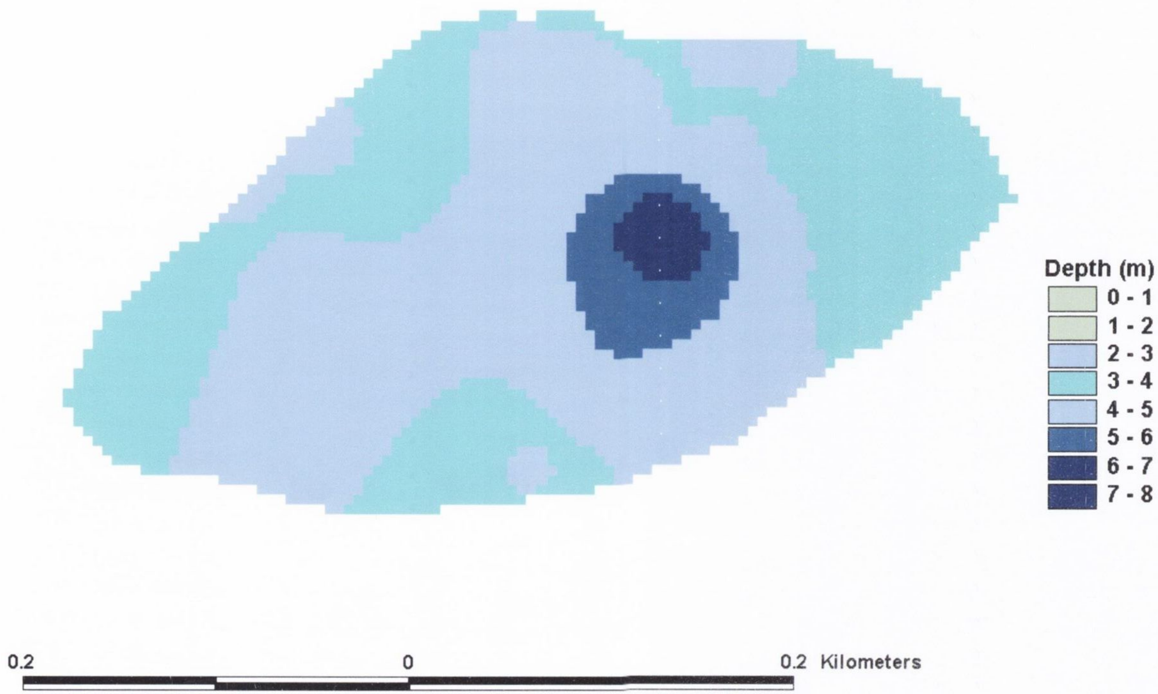


Figure 5: Lough Cloonmackan – Bathymetric map



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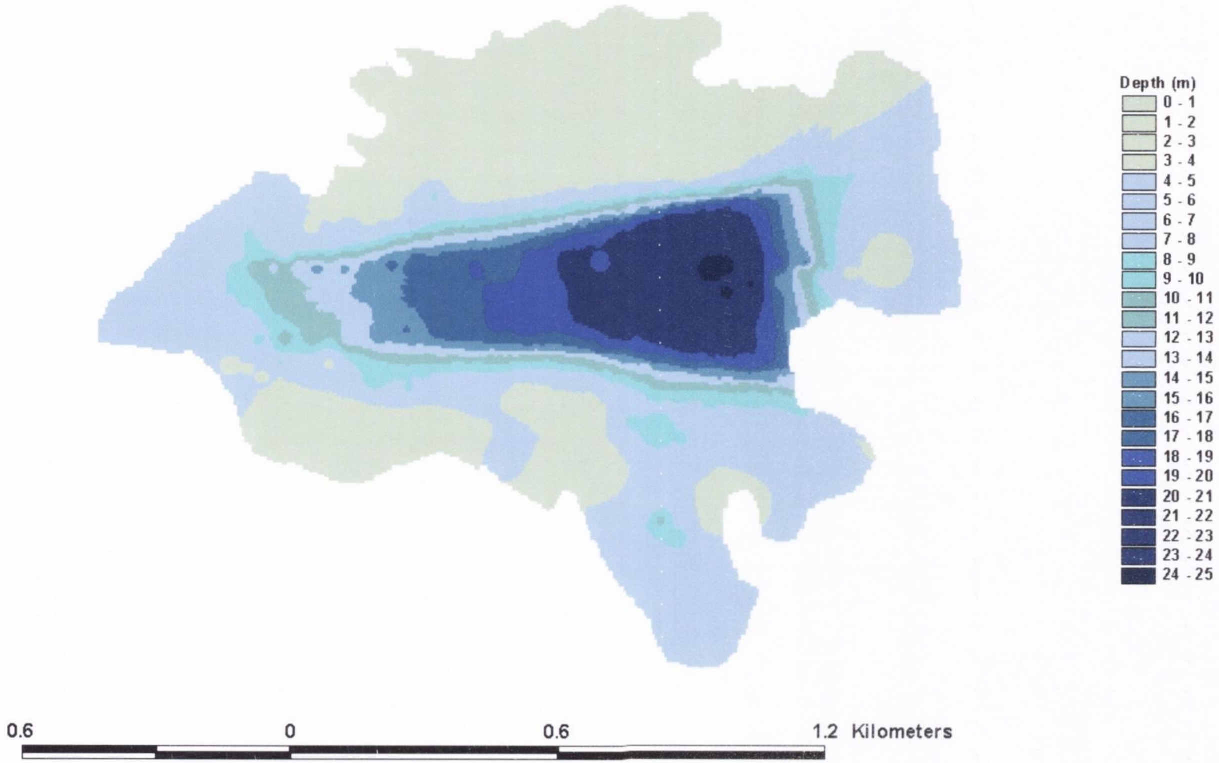

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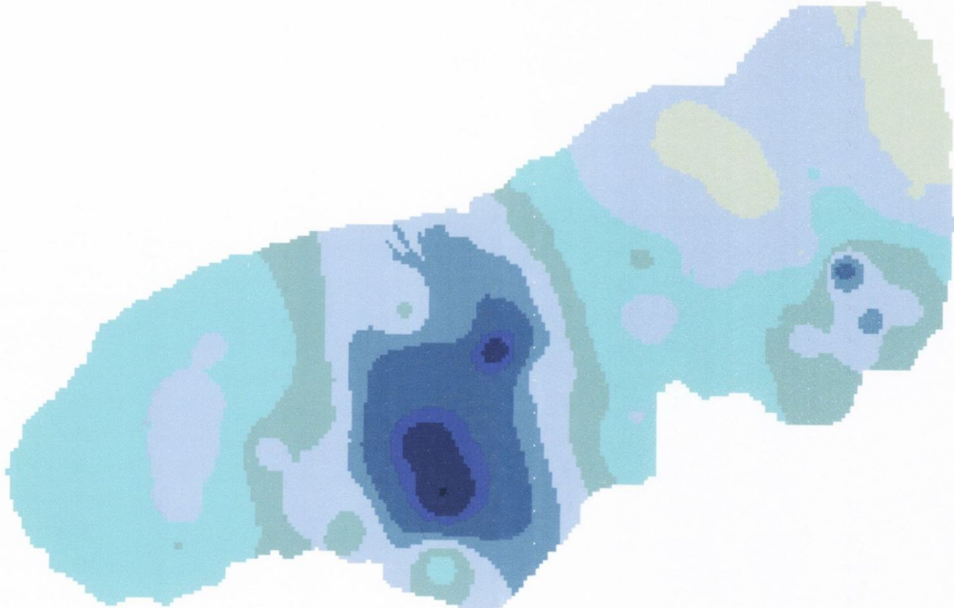

Figure 8: Lough Doon – Bathymetric map

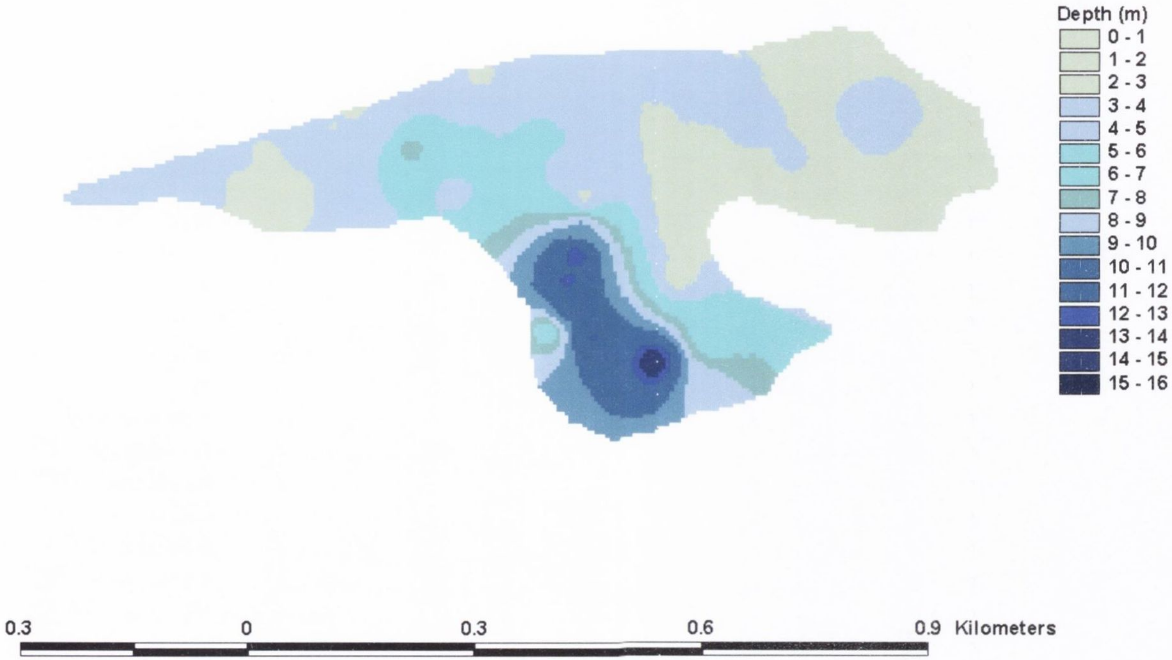

Figure 9: Lough Gortglass – Bathymetric map

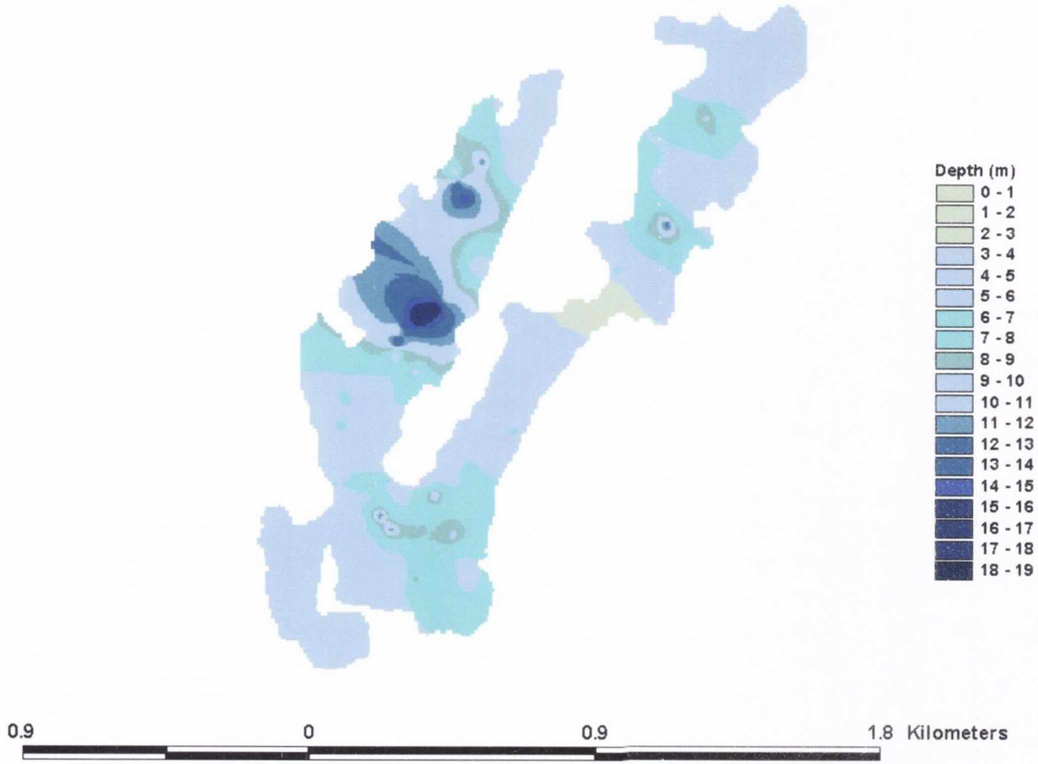

Figure 10: Lough Inchichronan – Bathymetric map

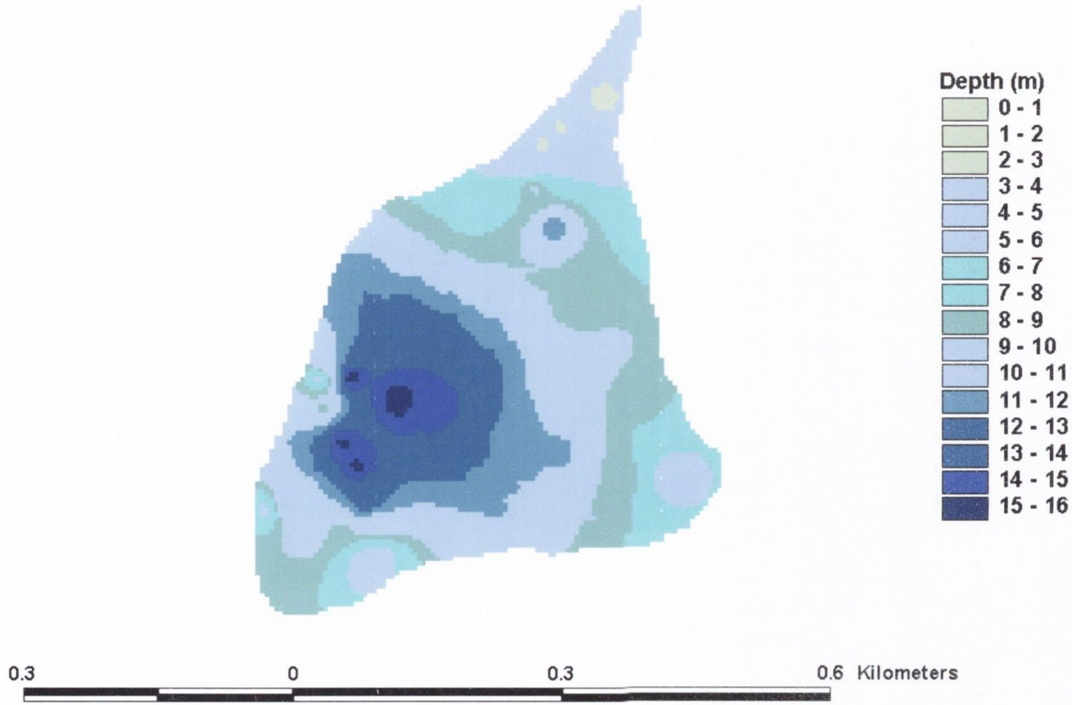

Figure 11: Lough Killone – Bathymetric map

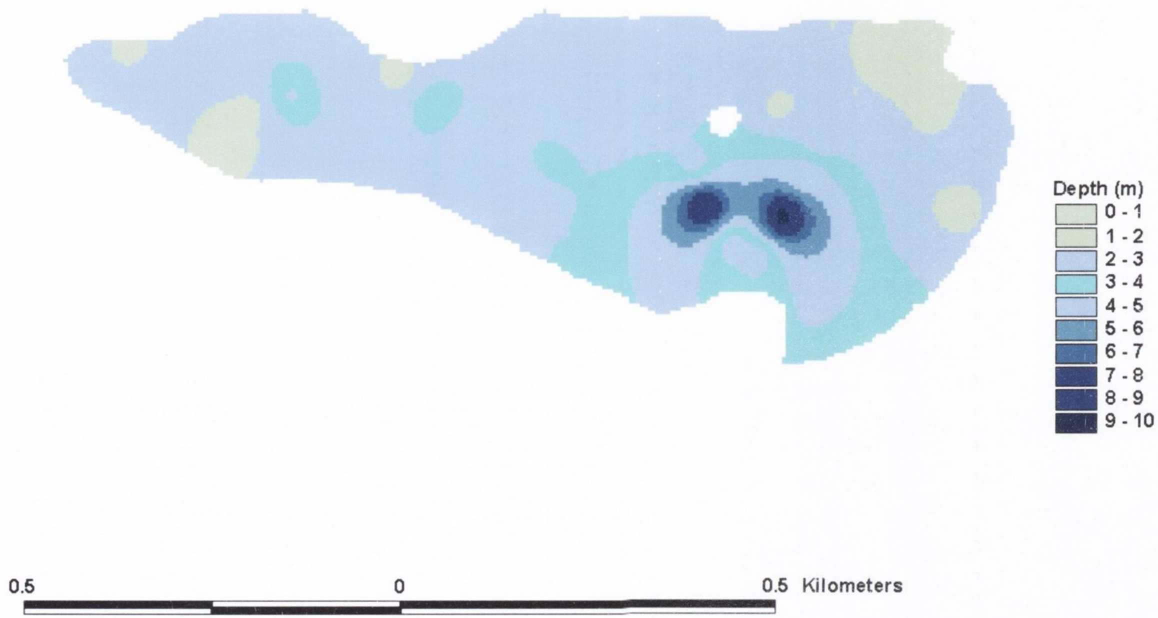

Figure 12: Knockalough – Bathymetric map

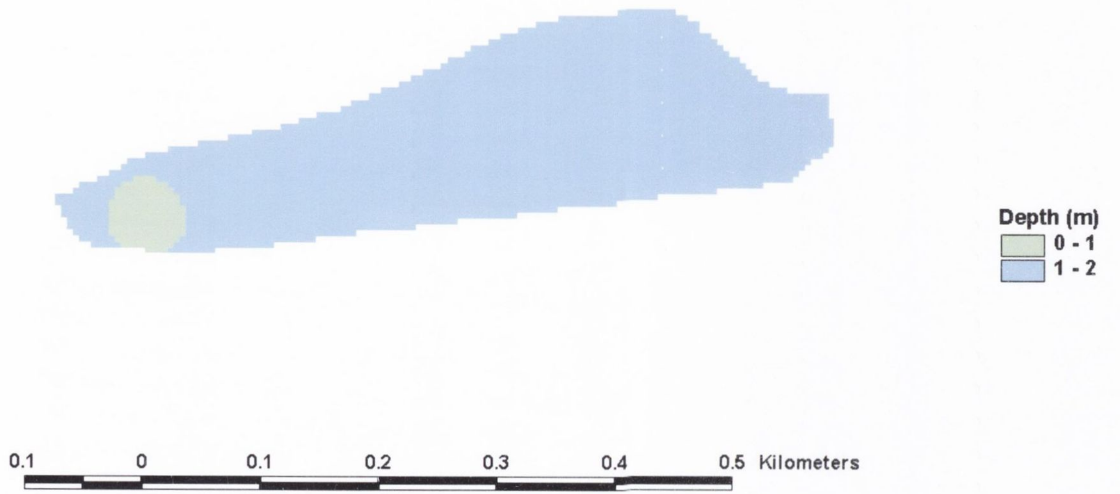

Figure 13: Lough Knockerra – Bathymetric map

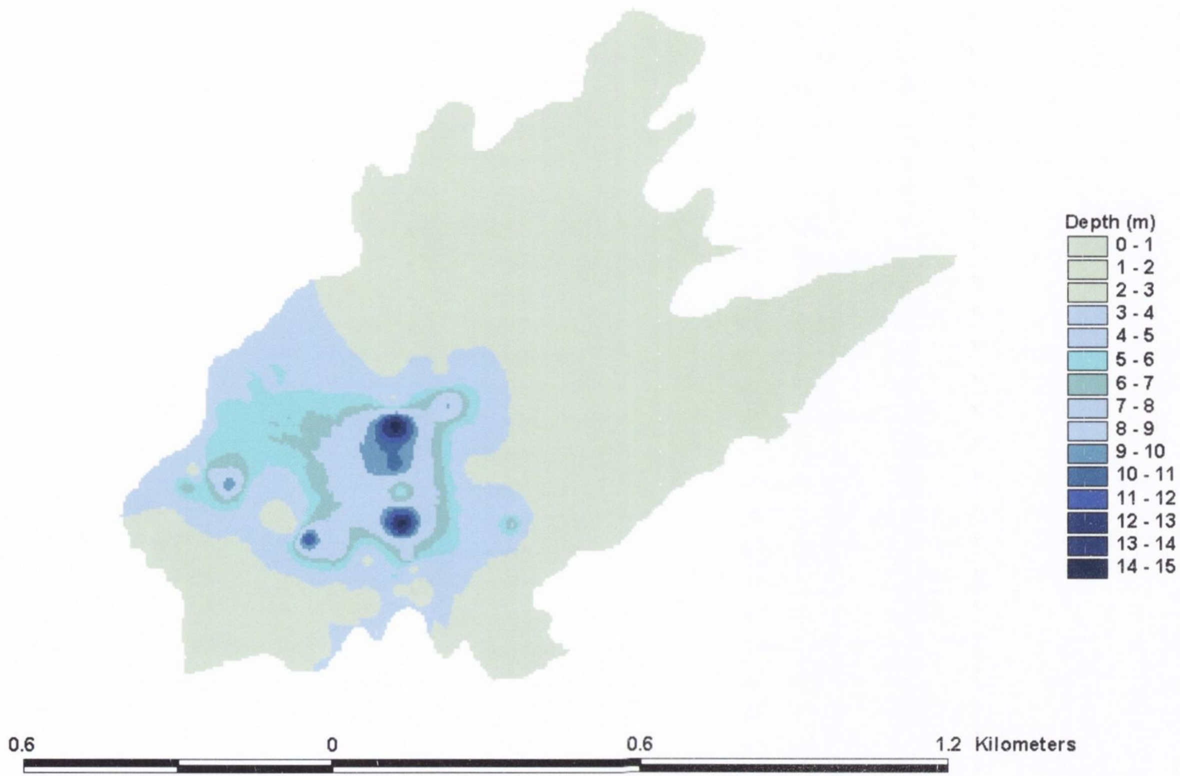

Figure 14: Lough Muckanagh – Bathymetric map

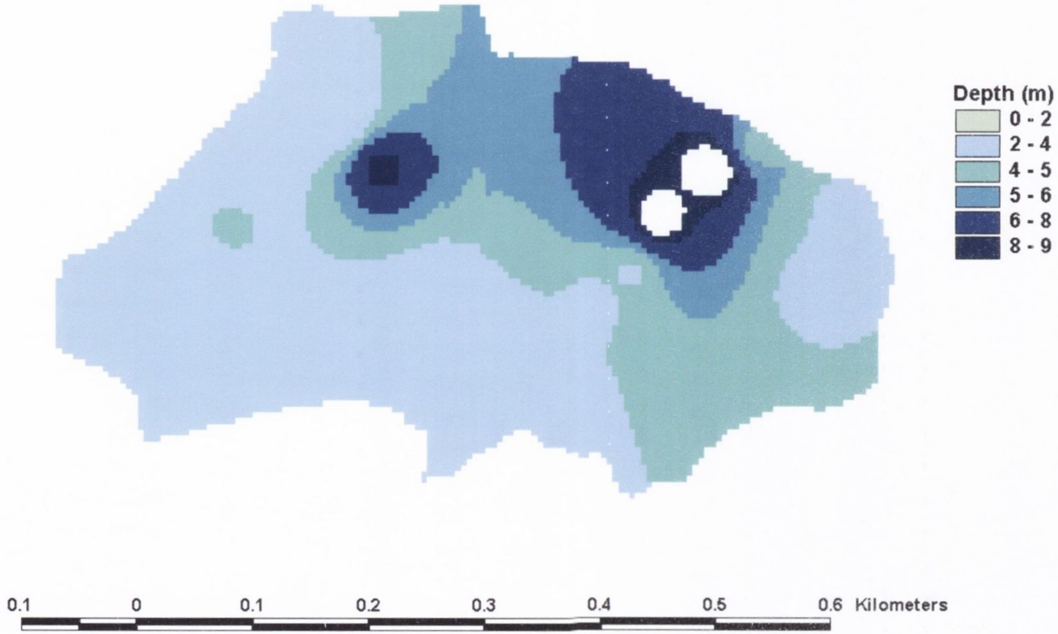

Figure 15: Lough Naminna – Bathymetric map

APPENDIX 1: Rainfall data

Table 2: Monthly past rainfall averages 1961-90, expressed as monthly and annual rainfall in mm

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1	Achryane	134.0	98.7	99.3	74.4	76.1	82.9	83.6	111.4	115.3	136.1	140.0	143.8	1294.6
2	Acrow	135.4	98.8	100.0	74.8	76.8	83.5	84.2	112.3	116.3	137.3	140.5	144.4	1303.3
3	Aillbrak	132.4	91.8	96.5	69.5	75.0	81.2	81.6	109.4	113.2	138.1	133.3	136.5	1258.3
4	Atedaun	144.8	98.1	106.3	77.9	84.2	85.7	86.1	121.4	125.1	148.5	144.2	149.3	1370.3
5	Ballyallia	119.9	86.3	89.0	66.4	73.2	73.7	72.3	98.5	104.0	120.6	119.8	124.2	1146.7
6	Ballybeg	118.0	85.1	87.2	64.7	71.1	72.5	70.5	95.3	101.2	116.8	117.7	122.3	1121.0
7	Ballycar	111.8	80.7	82.3	61.6	67.1	68.8	67.2	91.1	95.7	108.8	109.0	114.5	1057.9
8	Ballycullinan	130.8	92.1	96.2	71.3	77.2	78.1	77.6	107.8	112.7	133.8	130.4	136.4	1243.3
9	Ballydoolavan	127.9	92.1	92.9	70.1	72.2	78.7	79.4	104.9	108.8	129.0	132.0	135.4	1222.7
10	Ballyeighter	135.5	93.3	99.6	73.7	79.9	80.7	80.8	113.2	117.4	138.0	134.4	139.1	1284.5
11	Ballyleann	120.5	84.8	83.2	65.5	67.6	75.2	74.3	96.0	98.2	117.9	120.9	126.6	1128.9
12	Ballyteige	144.3	97.9	106.0	77.7	84.0	85.4	85.8	121.0	124.7	148.1	143.7	148.9	1366.2
13	Black *Kilk*	113.4	79.9	82.5	58.4	65.1	68.9	67.8	91.8	97.2	119.0	121.1	120.4	1085.4
14	Black *Dro*	123.0	87.9	91.2	68.4	75.0	75.1	74.5	102.4	107.4	125.1	122.6	127.1	1178.6
15	Bridget	115.2	83.6	85.5	65.1	72.4	71.2	70.8	96.0	97.2	112.5	111.8	116.8	1097.1
16	Bunny	144.4	97.2	105.8	77.4	83.7	84.7	85.2	120.5	124.2	146.2	142.8	147.4	1358.2
17	Burke	138.8	96.8	101.2	75.0	78.9	84.3	84.5	113.9	118.1	139.7	139.4	143.3	1313.0
18	Castle	115.1	83.7	85.9	65.5	72.3	71.5	70.8	96.3	96.6	112.1	112.3	117.3	1098.7
19	Caum	159.9	107.8	115.3	85.3	87.6	96.5	98.5	131.5	134.9	161.1	160.2	163.0	1500.7
20	Clonlea	112.4	82.1	84.1	64.1	70.4	70.7	69.8	94.6	96.2	110.5	110.1	115.1	1079.5
21	Cloonmackan	157.9	106.8	114.0	84.3	86.9	95.3	97.2	129.9	133.4	159.1	158.2	161.2	1483.2
22	Cloonsnaghta	121.9	86.5	85.8	66.6	68.5	75.6	75.4	98.1	101.1	120.6	123.7	128.3	1150.8
23	Cullaun	133.5	92.3	98.3	72.9	79.2	79.6	79.8	111.5	115.6	135.7	132.1	136.9	1266.2
24	Cullaunyheeda	112.6	82.2	83.8	64.5	71.3	70.9	71.3	95.3	98.6	110.7	110.5	114.5	1084.8
25	Curtins	149.8	102.4	108.7	80.3	83.8	90.6	91.8	123.4	127.2	151.7	150.2	153.8	1412.7
26	Doolough	145.3	100.3	105.1	77.8	80.5	88.3	89.7	119.2	123.0	147.1	147.2	149.9	1372.7
27	Doon	116.0	84.2	86.5	65.8	73.0	71.7	71.1	96.7	97.0	112.8	113.1	118.1	1105.3

Table 2 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
28	Dromoland	111.3	79.4	80.5	59.4	64.6	66.5	65.4	87.7	95.3	106.6	107.5	113.4	1036.6
29	Dromore	123.7	88.3	91.7	68.7	75.2	75.3	74.7	102.9	107.9	125.9	123.3	128.0	1184.8
30	Drumcullaun	149.0	102.0	108.1	80.0	83.4	90.0	91.1	122.5	126.4	150.3	149.4	152.9	1404.0
31	Druminure	140.9	97.3	103.1	75.8	80.8	84.6	84.8	116.4	120.6	143.7	141.0	145.7	1333.6
32	Eanagh	132.0	92.7	97.0	71.8	77.5	79.5	79.1	108.8	113.6	134.4	131.9	137.1	1254.5
33	Effernan	119.7	84.4	83.6	65.3	67.1	74.1	74.1	96.0	98.9	118.2	121.2	125.6	1127.0
34	Farrihy	113.3	79.8	82.4	58.3	65.1	68.9	67.8	91.7	97.2	118.8	120.9	120.3	1084.4
35	Finn	112.1	81.3	83.2	62.3	68.2	69.6	67.9	92.3	96.2	109.8	109.6	115.1	1067.0
36	Garvillaun	134.6	94.1	98.7	73.0	78.4	81.1	80.9	111.0	115.6	137.1	134.7	139.7	1277.7
37	Gash	111.6	80.1	81.4	60.6	65.9	67.9	66.3	89.6	95.4	107.8	108.5	114.1	1048.3
38	George	130.2	91.2	96.1	71.5	77.8	78.1	78.0	108.7	113.3	133.0	129.5	134.4	1241.0
39	Girroga	117.8	85.3	87.5	64.6	72.1	72.4	69.9	94.6	101.0	117.0	118.2	122.5	1121.2
40	Goller	143.9	98.6	106.2	76.9	83.6	87.0	87.1	121.2	124.5	149.8	145.4	150.4	1373.1
41	Gortaganniv	133.1	93.9	97.4	72.3	76.7	81.1	80.8	109.1	113.6	133.8	133.8	138.0	1262.5
42	Gorteen	110.8	81.5	83.3	64.2	69.6	70.7	69.5	94.9	93.4	108.9	108.8	113.7	1069.5
43	Gortglass	121.8	86.4	85.5	66.5	68.5	75.6	75.4	97.9	100.8	120.4	123.4	128.2	1149.0
44	Graney	119.1	85.3	87.9	66.2	73.8	71.6	71.6	97.9	99.0	116.6	114.8	120.8	1123.6
45	Inchichronan	117.0	84.8	87.2	66.3	73.3	72.7	72.5	98.8	103.4	119.4	116.4	120.0	1131.2
46	Inchiquin	154.7	102.8	113.5	82.5	88.9	91.1	91.9	130.6	133.7	159.4	154.5	159.5	1461.2
47	Keagh	133.7	92.7	97.1	70.0	75.4	82.2	82.7	110.2	114.1	139.5	134.8	137.3	1269.8
48	Kilgory	115.5	83.8	85.7	65.1	72.5	71.2	70.8	96.1	97.0	112.6	112.0	117.1	1098.5
49	Killone	118.3	85.3	87.2	64.9	70.8	72.7	71.0	95.9	101.4	117.0	117.9	122.6	1123.8
50	Knockalough	125.5	89.3	90.5	68.0	70.6	76.9	77.7	102.5	106.5	127.1	129.6	132.1	1195.5
51	Knockerra	115.9	82.6	83.6	62.1	65.5	70.1	71.3	94.5	98.3	119.1	122.7	123.4	1109.5
52	Lickeen	141.7	97.2	104.1	75.9	81.8	85.1	85.3	118.3	122.1	146.1	142.1	147.1	1345.4
53	Lisnahan	114.9	80.2	83.9	59.1	65.1	69.1	65.9	92.9	96.4	121.6	122.8	122.7	1093.0
54	Luirk	159.7	106.6	116.9	83.6	90.9	89.3	88.7	130.2	133.2	157.5	157.4	163.1	1476.1
55	Luogh	134.9	93.0	99.1	71.7	77.6	81.8	81.9	112.5	116.3	140.3	135.8	140.5	1284.6
56	Moanmore	112.5	80.1	81.7	58.7	64.7	68.3	68.6	91.6	96.8	117.2	120.5	119.9	1081.0
57	Mooghna	136.6	94.1	99.7	72.6	77.4	83.2	83.8	113.2	117.1	141.2	137.2	141.3	1296.7
58	More	126.0	89.4	91.0	68.0	71.0	77.1	77.9	103.0	107.0	127.9	130.1	132.5	1200.4

Table 2 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
59	Morgans	133.3	93.4	97.9	72.4	78.1	80.1	79.8	110.1	114.8	136.1	133.2	138.6	1266.8
60	Muckanagh	127.9	89.9	94.5	70.6	77.4	77.2	77.1	106.9	110.9	126.5	126.5	131.1	1218.5
61	Muckinish	161.8	108.3	118.4	84.1	91.8	88.5	87.4	130.1	133.1	157.0	158.7	165.0	1483.6
62	Naminna	140.8	99.3	102.6	76.4	78.9	86.1	87.1	115.9	119.8	142.3	143.7	147.0	1339.2
63	O'Briens *Big Lough*	117.0	84.6	87.1	65.6	72.4	72.6	71.9	97.7	102.4	117.5	116.0	120.2	1124.1
64	O'Grady	117.3	84.6	86.7	65.4	73.2	71.4	70.8	96.8	97.1	114.3	112.8	118.5	1108.1
65	Rask	164.4	109.9	120.1	84.9	92.8	88.4	86.8	130.8	133.7	157.5	160.6	167.2	1496.7
66	Rosconnell	142.9	98.8	104.1	77.0	81.1	86.6	87.1	117.6	121.8	144.7	143.4	147.4	1351.4
67	Rosroe	111.9	81.5	83.4	63.0	68.8	70.1	68.5	93.2	95.6	109.8	109.4	114.9	1069.7
68	Rushaun	133.0	93.4	97.4	72.2	77.1	80.8	80.4	109.1	113.8	134.3	133.3	137.8	1261.3
69	Tullabrack	113.6	81.4	82.5	60.3	64.7	68.5	69.5	93.0	96.8	117.7	121.7	121.7	1091.8

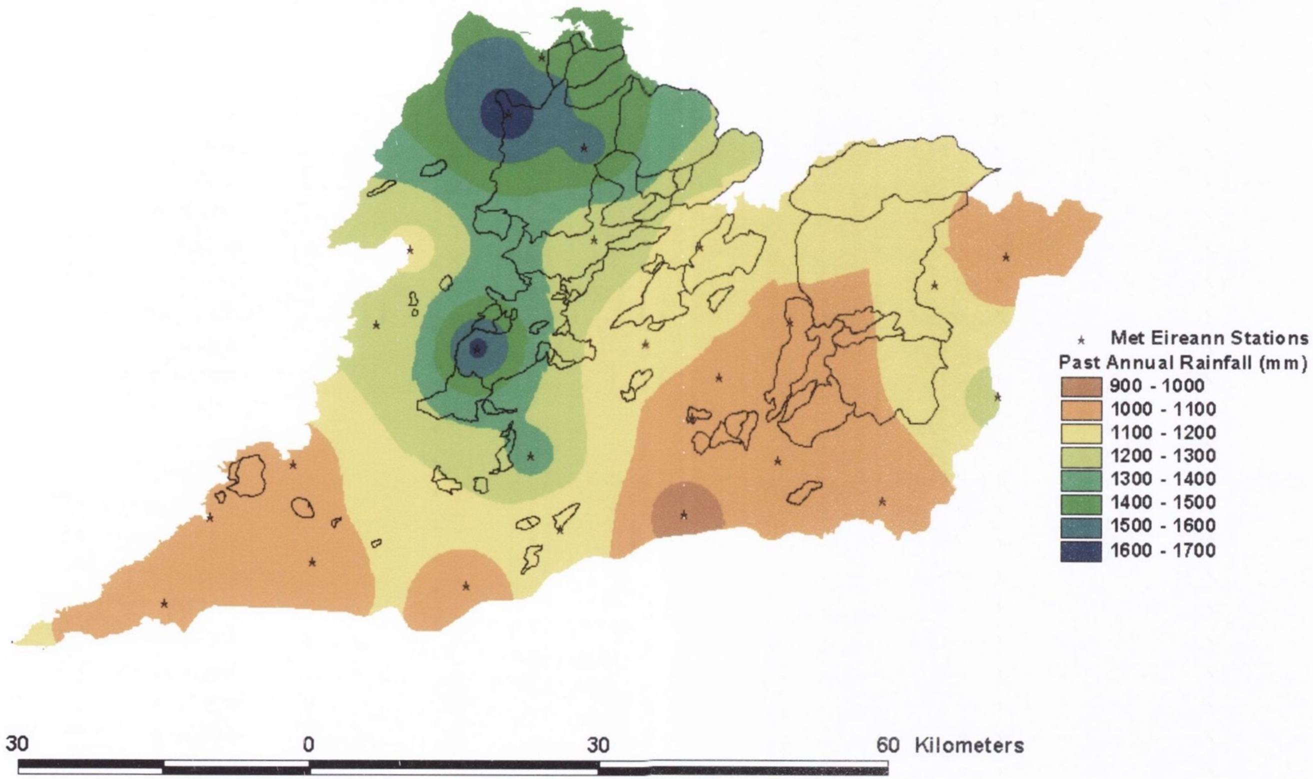

Figure 16: Annual Past average Rainfall Surface (1961-90)

Table 3: Monthly rainfall averages 2000, expressed as monthly and annual rainfall in mm

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1	Achryane	136.6	200.8	63.0	73.1	92.9	77.9	112.7	105.3	148.3	217.6	179.1	134.8	1542.1
2	Acrow	143.4	213.0	66.5	72.2	93.6	79.7	118.0	106.4	151.3	221.3	181.8	136.7	1583.9
3	Aillbrak	148.4	205.5	67.3	71.8	93.9	76.8	115.3	99.6	160.0	227.3	185.1	140.9	1591.9
4	Atedaun	137.8	199.1	59.7	63.9	78.6	69.3	99.2	99.1	145.9	263.8	190.3	152.7	1559.4
5	Ballyallia	119.8	177.6	51.4	59.5	76.4	68.9	108.0	84.4	130.0	233.5	174.2	128.6	1412.2
6	Ballybeg	117.7	168.3	52.8	62.5	81.2	70.2	108.9	84.5	126.1	217.4	166.0	118.0	1373.6
7	Ballycar	100.9	133.9	45.0	60.0	77.2	65.0	100.3	75.5	113.5	204.9	154.4	103.3	1233.9
8	Ballycullinan	130.7	204.2	56.1	57.5	79.2	68.6	128.8	93.7	130.8	249.3	186.1	144.6	1529.5
9	Ballydoolavan	128.5	185.4	58.7	75.5	92.5	76.2	103.0	106.6	146.8	214.2	177.1	133.8	1498.3
10	Ballyeighter	131.4	191.0	56.3	62.1	77.3	68.9	103.7	92.8	138.5	255.2	185.1	145.4	1507.6
11	Ballyleann	119.4	172.5	55.1	69.0	86.0	73.0	106.4	95.6	133.0	207.8	165.3	120.1	1403.0
12	Ballyteige	137.4	198.9	59.5	63.7	78.4	69.2	99.8	98.8	145.4	263.5	190.1	152.4	1557.0
13	Black *Kilk*	109.0	158.6	54.3	72.8	86.8	68.8	78.0	101.1	152.6	205.9	168.5	131.1	1387.5
14	Black *Dro*	118.8	177.5	49.8	58.6	74.1	68.5	107.2	83.2	129.3	238.5	176.6	131.9	1414.0
15	Bridget	104.5	158.3	49.0	54.1	71.5	58.8	93.4	85.6	125.2	213.4	166.6	109.0	1289.3
16	Bunny	138.0	195.4	60.1	65.4	78.6	69.5	94.2	99.2	146.2	262.4	188.4	150.7	1548.1
17	Burke	147.4	251.4	72.0	71.2	90.8	85.9	121.4	111.6	142.8	227.5	182.0	137.0	1640.9
18	Castle	105.9	155.5	50.3	55.2	72.4	69.7	93.7	92.6	125.3	212.8	168.8	108.0	1301.1
19	Caum	173.1	239.5	77.8	71.6	104.8	84.7	136.8	107.3	170.8	228.0	187.3	141.5	1723.1
20	Clonlea	99.3	139.8	44.3	54.2	75.2	58.3	109.7	88.7	124.2	209.4	159.2	104.6	1266.8
21	Cloonmackan	167.3	240.7	75.9	71.5	101.4	84.5	133.3	109.4	165.7	228.4	186.4	140.9	1705.4
22	Cloonsnaghta	123.1	177.9	56.7	72.5	89.6	74.5	103.8	100.3	139.9	209.4	170.1	126.3	1443.9
23	Cullaun	128.3	187.7	55.0	61.4	76.0	67.9	102.5	92.2	136.8	252.5	183.7	142.8	1486.8
24	Cullaunyheeda	98.3	146.4	43.9	52.1	74.2	56.8	100.3	78.4	124.7	208.3	157.0	102.6	1242.9
25	Curtins	159.7	235.3	73.0	70.6	97.2	82.7	127.8	107.1	159.5	230.7	186.1	141.1	1670.9
26	Doolough	145.8	205.5	66.9	72.7	94.8	78.8	121.9	107.0	159.8	222.7	189.4	142.7	1608.1
27	Doon	107.7	159.2	51.5	55.4	71.7	60.6	90.4	93.6	125.8	213.8	213.8	108.9	1309.9
28	Dromoland	100.0	124.8	43.4	62.6	78.9	66.7	95.9	66.9	108.5	203.8	152.7	102.9	1207.2
29	Dromore	119.9	180.1	50.3	58.4	74.4	68.4	108.9	84.2	129.5	240.3	177.8	133.6	1425.7

Table 3 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
30	Drumcullaun	158.3	237.4	72.9	70.0	96.5	83.0	128.9	106.8	156.2	230.2	185.0	140.0	1665.0
31	Druminure	146.6	215.3	65.7	66.5	88.2	76.3	119.5	100.2	150.9	240.1	186.5	142.9	1598.8
32	Eanagh	137.6	210.6	61.0	62.1	83.8	73.1	123.7	97.0	139.2	242.6	184.9	141.7	1557.2
33	Effernan	119.2	172.0	55.0	71.9	88.2	73.5	101.8	98.1	136.9	207.2	167.2	123.6	1414.7
34	Farrihy	108.8	158.2	54.3	72.8	86.8	68.8	77.7	101.1	152.7	205.7	168.4	131.0	1386.3
35	Finn	100.9	136.4	44.9	58.2	76.8	63.0	104.1	79.9	117.2	206.6	156.2	104.1	1248.4
36	Garvillaun	141.8	215.2	63.5	64.4	86.1	75.2	123.2	99.5	143.5	240.7	185.5	142.2	1580.8
37	Gash	100.4	130.3	44.5	61.4	77.7	66.2	98.3	71.8	110.8	203.8	153.0	102.9	1221.2
38	George	126.0	188.0	53.2	59.3	75.6	68.0	109.3	89.2	133.0	250.2	182.9	141.5	1476.3
39	Girroga	119.5	175.2	52.3	60.3	78.6	68.8	110.2	85.3	129.1	227.4	171.5	124.8	1403.2
40	Goller	136.7	194.3	60.0	65.9	76.7	72.0	85.5	100.5	158.7	255.4	189.4	146.0	1541.2
41	Gortaganniv	145.1	238.7	69.6	70.0	90.4	83.5	121.4	108.1	142.9	226.6	181.0	135.6	1612.8
42	Gorteen	98.4	146.8	51.1	55.1	73.5	63.5	95.3	96.4	121.1	207.9	162.2	104.8	1276.2
43	Gortglass	123.0	177.8	56.7	72.2	89.4	74.4	104.1	100.0	139.6	209.3	169.8	125.9	1442.2
44	Graney	110.6	166.0	51.4	56.3	70.0	60.4	92.0	91.6	128.2	224.1	174.5	119.1	1344.3
45	Inchichronan	111.5	164.8	46.4	58.5	71.0	68.0	96.3	78.3	128.5	231.1	171.8	124.3	1350.4
46	Inchiquin	145.4	203.9	63.7	67.6	80.2	70.7	87.8	104.5	156.0	272.8	194.5	159.5	1606.6
47	Keagh	151.5	208.2	68.9	72.4	96.5	77.6	119.1	99.1	161.3	224.9	185.3	141.0	1605.7
48	Kilgory	104.9	158.6	49.4	54.3	71.2	58.8	93.2	87.0	125.2	213.6	167.6	109.3	1293.2
49	Killone	118.3	170.1	53.3	63.0	82.0	71.0	109.4	85.8	126.6	215.9	165.9	117.7	1378.9
50	Knockalough	123.6	177.2	55.8	78.3	94.0	75.9	96.4	111.7	145.5	213.3	177.5	134.9	1483.9
51	Knockerra	107.9	159.5	49.4	78.5	91.7	73.9	83.8	97.9	135.7	202.2	164.5	127.7	1372.6
52	Lickeen	134.9	192.1	59.7	64.9	75.9	72.0	92.8	98.1	154.4	254.2	189.2	143.7	1531.8
53	Lisnahan	111.3	162.5	53.6	73.9	87.5	69.9	82.8	100.3	148.9	206.8	169.1	131.3	1397.8
54	Luirk	146.1	209.2	61.9	66.0	77.4	72.0	76.6	110.1	160.2	268.9	192.4	156.5	1597.2
55	Luogh	136.9	194.8	60.4	68.0	80.4	72.7	92.9	101.4	156.7	246.4	187.5	144.1	1542.3
56	Moanmore	108.0	157.3	53.5	73.9	87.9	69.8	78.1	101.0	149.7	204.6	167.4	130.1	1381.4
57	Mooghna	151.7	210.2	68.7	69.9	92.5	77.8	115.3	99.5	161.2	234.5	186.9	141.5	1609.7
58	More	122.4	174.8	54.8	79.6	94.9	76.0	94.2	114.8	145.2	213.5	178.2	135.7	1484.0
59	Morgans	138.3	210.5	61.0	62.3	83.8	72.9	124.3	97.7	140.0	244.0	185.9	143.3	1564.0
60	Muckanagh	122.3	180.0	52.3	60.4	74.2	67.6	97.7	89.2	135.6	243.3	179.0	135.0	1436.7

Table 3 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
61	Muckinish	145.8	213.2	60.3	64.5	75.2	72.6	70.3	113.7	163.1	267.0	191.8	155.3	1592.8
62	Naminna	150.4	221.5	69.7	72.3	96.1	81.3	123.0	107.0	155.8	222.8	184.1	138.6	1622.8
63	O'Briens *Big Lough*	110.3	163.0	47.6	57.3	73.8	65.5	100.6	79.6	126.9	224.1	167.7	118.9	1335.4
64	O'Grady	106.0	162.2	50.5	54.6	69.0	58.0	92.5	89.1	125.6	216.9	171.4	113.4	1309.2
65	Rask	146.5	215.4	59.9	64.1	74.2	72.8	65.9	116.1	165.3	268.0	192.2	156.0	1596.5
66	Rosconnell	151.7	239.5	71.3	70.2	92.9	83.3	123.8	108.2	149.8	230.7	184.2	139.4	1644.9
67	Rosroe	100.5	138.2	45.1	56.9	76.2	61.8	106.4	83.5	119.5	207.1	157.0	104.1	1256.2
68	Rushaun	146.0	228.6	67.8	68.0	89.6	80.2	122.0	104.3	145.9	233.2	183.6	139.1	1608.3
69	Tullabrack	108.9	159.4	51.2	77.0	90.3	72.2	82.2	100.5	141.9	203.9	166.7	129.3	1383.4

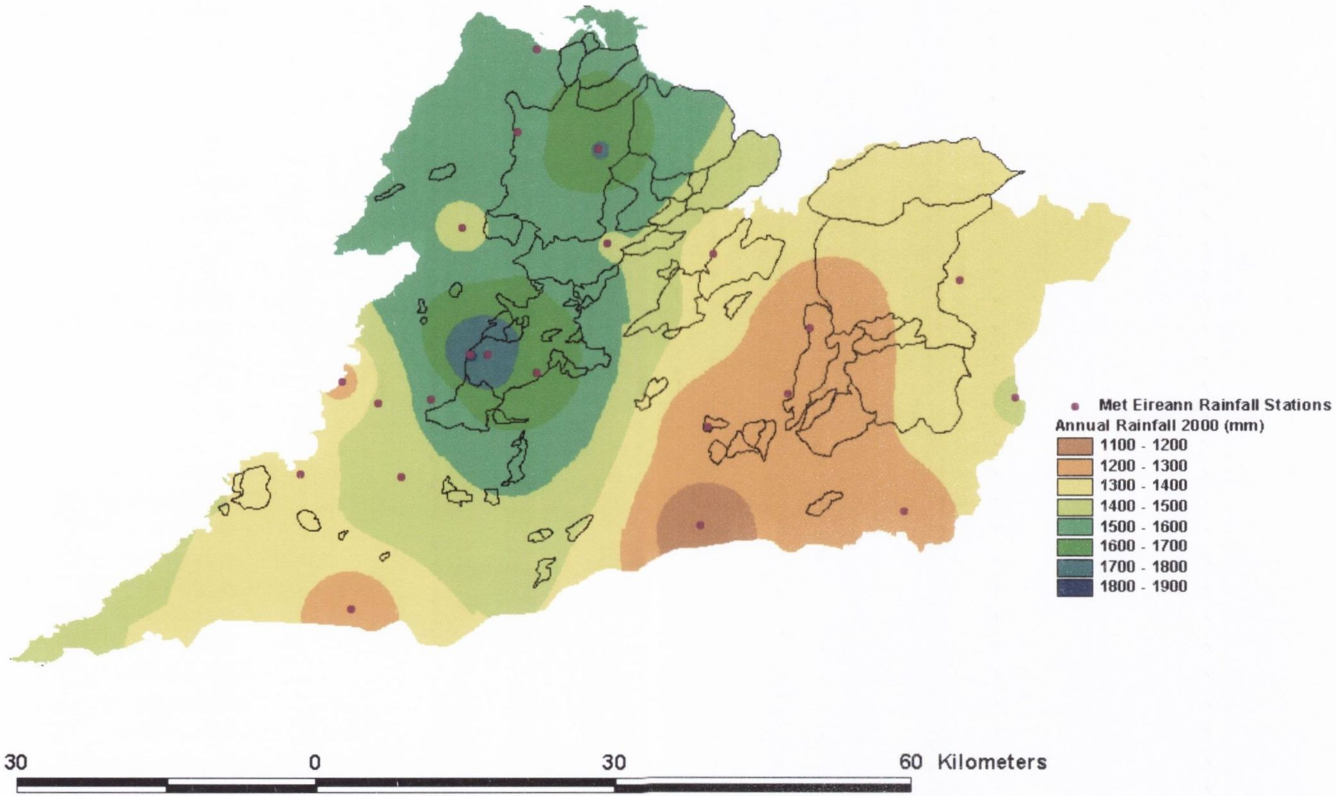

Figure 17: Annual Rainfall Surface 2000

Table 4: Monthly rainfall averages 2001, expressed as monthly and annual rainfall in mm

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
1	Achryane	80.8	66.2	105.7	103.9	39.4	78.3	88.6	111.6	67.2	133.0	146.1	84.7	1131.1
2	Acrow	83.6	67.3	108.7	106.1	38.8	80.6	92.2	115.1	69.7	135.8	152.9	88.1	1159.8
3	Aillbrak	78.8	65.6	113.9	99.6	41.1	83.6	79.9	119.3	67.2	133.2	154.0	82.9	1130.2
4	Atedaun	71.5	65.9	107.6	100.9	41.6	74.9	81.1	106.5	65.3	127.3	129.8	77.8	1059.6
5	Ballyallia	65.9	60.5	92.9	104.8	42.3	65.3	83.4	95.0	58.3	118.0	110.7	69.7	978.3
6	Ballybeg	67.3	63.2	89.2	101.2	41.8	62.7	84.3	83.8	58.1	120.1	106.9	66.8	975.1
7	Ballycar	60.3	62.9	83.6	99.6	42.4	57.3	82.4	75.6	54.7	115.1	95.7	62.2	893.1
8	Ballycullinan	75.0	65.4	104.4	103.9	40.6	74.9	86.2	106.5	65.2	128.4	134.5	79.3	1081.0
9	Ballydoolavan	78.0	64.6	102.5	100.6	39.9	76.7	83.5	109.3	64.4	130.4	140.5	81.9	1100.8
10	Ballyeighter	67.0	61.0	97.1	104.4	42.3	68.0	82.5	99.9	59.9	119.4	114.9	71.7	994.5
11	Ballyleann	73.0	64.6	97.4	101.1	40.7	70.0	83.9	97.9	61.7	125.7	124.3	74.8	1046.1
12	Ballyteige	71.4	65.8	107.2	101.0	41.6	74.7	81.2	106.3	65.1	127.1	129.4	77.6	1057.6
13	Black *Kilk*	65.7	55.7	80.5	78.7	41.1	75.4	61.2	105.2	57.6	123.1	129.9	79.3	1035.8
14	Black *Dro*	65.1	57.9	91.7	106.5	42.9	65.3	83.7	97.0	57.6	115.4	109.1	69.6	966.6
15	Bridget	56.9	66.6	98.3	99.2	39.0	59.7	72.2	91.8	52.5	114.8	92.1	56.2	900.3
16	Bunny	69.4	64.8	103.3	102.4	41.7	70.6	82.0	103.1	63.0	124.3	121.0	74.7	1029.5
17	Burke	88.5	71.8	108.5	109.3	34.9	83.7	101.5	112.3	73.8	141.5	156.3	98.4	1186.5
18	Castle	57.8	66.2	96.1	99.3	40.6	59.8	73.9	92.1	52.7	116.2	93.3	58.0	908.2
19	Caum	90.7	67.1	127.5	114.1	42.1	89.4	98.9	141.1	78.4	143.4	187.9	90.4	1277.6
20	Clonlea	56.1	66.9	93.2	101.3	45.7	57.5	75.8	94.3	53.2	120.1	97.5	63.5	927.6
21	Cloonmackan	90.1	68.0	123.3	113.0	40.6	88.0	99.3	134.7	77.3	142.8	180.7	91.9	1257.0
22	Cloonsnaghta	74.8	64.5	99.4	100.5	40.4	72.7	83.2	102.6	62.7	127.5	130.5	77.6	1067.6
23	Cullaun	66.7	61.6	97.6	103.9	42.1	67.8	81.9	99.7	59.7	119.5	114.3	71.2	992.5
24	Cullaunyheeda	53.8	67.9	97.6	102.0	43.3	56.7	73.0	93.2	54.0	118.7	99.1	62.2	922.7
25	Curtins	87.2	68.4	117.9	109.9	39.6	85.5	96.3	126.1	74.6	140.3	168.9	91.0	1215.3
26	Doolough	85.9	65.6	114.9	107.0	40.4	84.1	90.6	126.5	70.5	137.6	165.8	88.0	1189.7
27	Doon	58.1	66.2	97.0	98.7	39.4	60.3	73.2	91.9	52.3	115.2	91.7	56.4	902.0
28	Dromoland	60.4	62.0	79.4	98.9	41.5	55.7	84.0	68.3	54.2	112.2	92.7	61.4	864.0
29	Dromore	65.4	58.3	92.2	106.3	42.8	65.6	83.7	97.2	57.9	115.9	109.9	69.9	970.4

Table 4 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
30	Drumcullaun	87.6	68.6	117.2	110.7	39.3	85.1	97.8	125.3	74.7	140.5	168.4	91.5	1215.7
31	Druminure	79.6	67.3	113.5	103.5	40.3	82.2	86.6	116.7	69.7	134.3	152.5	84.5	1143.4
32	Eanagh	78.0	66.5	106.2	104.8	39.9	76.9	88.6	108.8	67.1	131.1	140.5	82.4	1108.9
33	Effernan	73.2	64.2	98.1	99.8	40.6	71.3	82.0	100.5	61.7	126.2	126.7	75.8	1051.1
34	Farrihy	65.5	55.6	80.2	78.4	41.1	75.4	61.1	105.2	57.6	123.0	129.9	79.3	1035.6
35	Finn	59.1	63.9	86.2	100.1	43.4	57.6	80.8	80.7	54.4	116.7	96.5	62.7	906.7
36	Garvillaun	79.8	67.2	108.6	105.2	39.6	79.0	89.7	111.8	68.6	133.1	146.0	84.5	1129.8
37	Gash	60.8	62.3	81.6	99.3	41.8	56.8	83.4	71.9	54.7	113.9	94.7	61.9	880.5
38	George	66.2	59.5	94.8	105.4	42.6	67.0	83.0	99.0	58.9	117.5	112.7	70.9	982.7
39	Girroga	66.1	62.7	92.7	102.8	42.0	64.4	83.1	91.1	58.4	119.7	110.0	68.6	980.2
40	Goller	68.8	68.3	116.8	89.9	41.7	84.6	67.1	108.8	66.0	129.3	139.2	77.8	1063.2
41	Gortaganniv	86.0	70.3	107.2	108.1	36.2	81.4	98.3	110.7	71.8	138.6	151.5	93.8	1167.6
42	Gorteen	60.6	64.9	91.9	100.4	42.6	60.4	78.8	88.7	55.3	118.7	101.0	63.9	936.3
43	Gortglass	74.7	64.5	99.3	100.6	40.4	72.6	83.3	102.3	62.7	127.4	130.2	77.4	1066.6
44	Graney	61.1	65.2	98.4	97.9	37.5	63.3	73.5	93.9	52.4	114.0	91.0	55.2	905.0
45	Inchichronan	62.8	56.7	90.0	107.3	43.2	63.4	82.8	96.0	56.1	112.8	104.5	67.7	945.1
46	Inchiquin	73.6	68.6	113.5	98.8	41.5	78.5	80.1	110.1	68.5	131.5	136.9	81.4	1092.8
47	Keagh	80.8	65.2	113.9	101.5	41.0	83.5	82.3	121.7	67.6	134.2	157.2	84.0	1144.6
48	Kilgory	57.1	66.5	98.2	98.8	38.7	59.9	72.0	91.8	52.0	114.4	90.6	55.2	895.9
49	Killone	68.2	63.5	89.7	101.3	41.6	63.3	84.7	84.6	58.6	120.6	108.4	67.7	984.2
50	Knockalough	77.1	63.4	100.6	97.9	39.9	76.9	79.8	109.4	62.5	129.4	139.3	81.8	1086.9
51	Knockerra	71.7	60.3	92.1	89.9	40.4	75.0	71.3	105.7	59.5	125.9	131.8	79.3	1051.4
52	Lickeen	67.9	68.1	117.4	88.9	41.8	85.6	65.3	108.5	65.5	128.6	139.9	76.9	1058.1
53	Lisnahan	67.4	57.3	84.5	82.3	40.9	75.2	64.3	105.4	58.7	123.9	130.4	78.9	1041.5
54	Luirk	79.0	73.5	121.8	101.5	41.8	79.2	87.2	116.1	75.9	139.4	143.0	89.6	1155.6
55	Luogh	70.6	67.3	114.1	91.8	41.4	83.3	69.9	109.5	65.6	129.4	139.8	78.5	1069.5
56	Moanmore	65.7	55.7	80.3	78.6	41.1	75.2	61.2	105.1	57.4	123.1	129.9	79.4	1035.5
57	Mooghna	77.1	66.9	118.0	98.7	41.5	85.5	78.6	119.6	69.1	133.6	155.7	82.2	1134.4
58	More	77.3	63.0	100.2	97.1	39.8	77.2	78.6	109.8	61.7	129.3	139.3	82.1	1082.7
59	Morgans	78.2	66.6	107.6	104.5	40.0	77.9	88.1	110.4	67.5	131.7	142.6	82.8	1114.9
60	Muckanagh	65.0	60.9	95.7	104.2	42.0	66.0	81.3	97.9	58.2	117.7	109.9	69.0	973.2

Table 4 (continued)

ID	Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
61	Muckinish	81.0	75.4	125.8	101.9	41.9	80.6	88.9	118.9	78.8	142.6	147.1	92.9	1181.1
62	Naminna	86.6	67.9	113.3	108.5	38.9	83.6	95.3	121.8	72.5	138.9	163.0	90.9	1195.9
63	O'Briens *Big Lough*	61.3	60.9	92.4	104.6	42.6	62.0	80.4	93.2	56.2	115.8	104.2	66.2	945.0
64	O'Grady	58.3	66.1	98.7	96.7	36.3	61.3	70.5	92.0	50.0	111.6	83.6	50.1	875.6
65	Rask	82.2	76.6	128.3	102.1	42.0	81.5	90.0	120.6	80.6	144.6	149.7	95.0	1197.0
66	Rosconnell	86.8	69.9	111.4	108.9	37.2	83.4	98.0	116.7	73.2	139.7	158.7	93.7	1187.5
67	Rosroe	58.4	64.7	88.4	100.5	44.1	57.8	79.4	85.2	54.2	118.0	97.3	63.2	917.2
68	Rushaun	83.3	68.7	107.8	107.1	37.9	80.0	94.5	111.4	70.3	136.0	149.0	89.2	1151.8
69	Tullabrack	68.5	57.7	85.6	83.6	40.7	75.2	65.4	105.3	58.0	124.3	130.6	79.5	1040.4

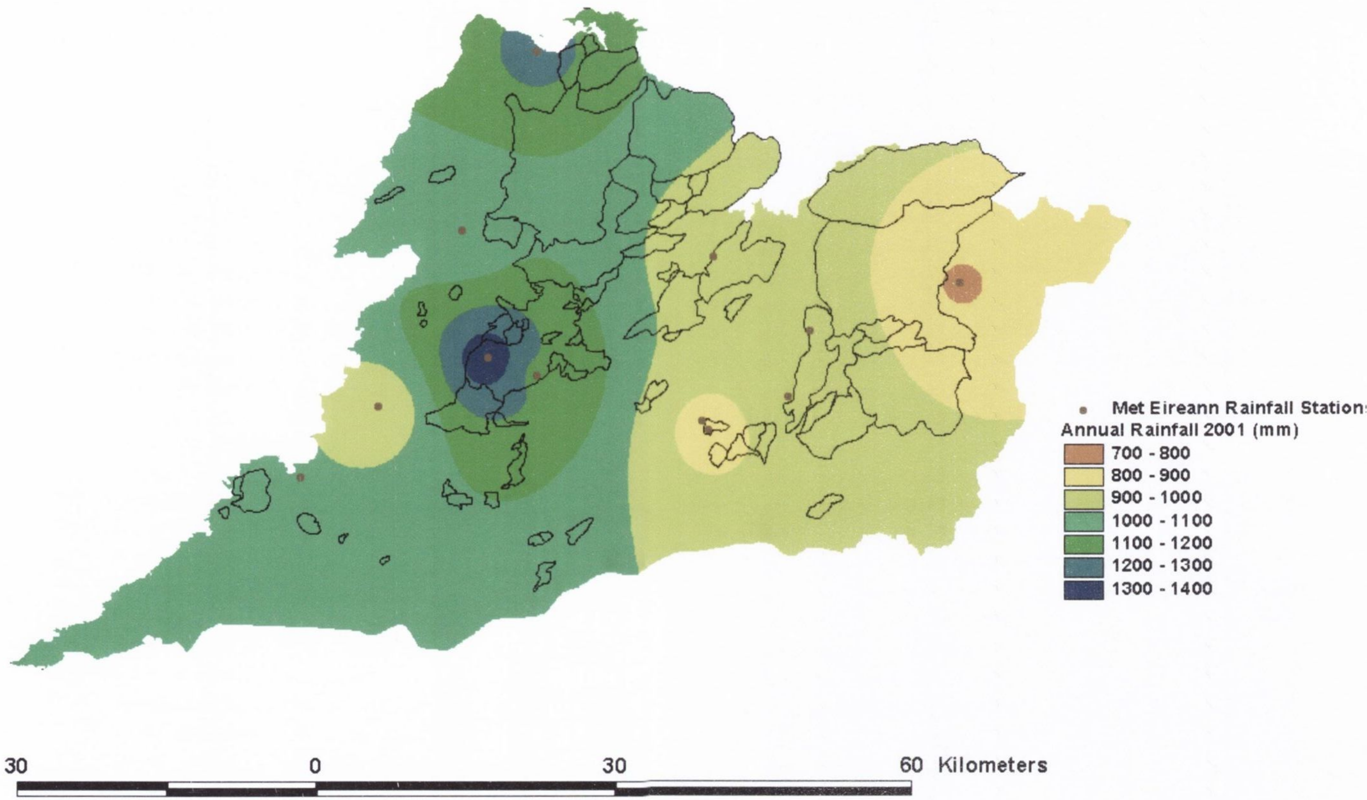

Figure 18: Annual Rainfall Surface 2001

APPENDIX 2: Previous studies on the lakes of County Clare

Table 1: Summary of previous estimates of concentrations of median pH, mean alkalinity, range of total phosphorus (TP), mean nitrates (NO_3-N) and mean chlorophyll-*a* (Chla) from lakes (excl. Lough Derg) in County Clare

Lake	Date	No. Samples	pH	Alkalinity (mg $CaCO_3$ l^{-1})	TP (μg l^{-1})	NO_3-N (mg l^{-1})	Max Chla (μg l^{-1})	References
Achryane	1996/97	1	6.7	7	9		7	Irvine *et al*, 2001
Acrow	1987						17	Clabby *et al*, 1992
Atedaun	1996/97	1	7.8	102	23		16	Irvine *et al*, 2001
Ballyallia	1996/97	1	8	133	11		6	Irvine *et al*, 2001
Ballybeg	1994	4					11	Bowman *et al*, 1996; Lucey *et al*, 1999
	1995	3					10	
	1997	1					62	
Ballycullinan	1996/97	7-10	8.0-8.6	145-232	16-52	< 1.4	68	Lucey *et al*, 1999; Irvine *et al*, 2001
Ballyc. North	1981	8		170	16-26		12	Allott 1986, 1990
	1982	9			19-40		22	
Ballyc. South	1981	8		125	35-49		11	Allott 1986, 1990
	1982	9			18-52		12	
Ballydoolavan	1987						10	Clabby *et al*, 1992
Ballyleann	1987						26	Clabby *et al*, 1992
Black	1981	8		155	12-33		19	Allott 1986, 1990
	1982	9			12-38		41	
Bunny	1965			140				Kennedy & Fitzmaurice, 1971
	1996/97	7-10	8.2-8.4	93-164	<5	<1.0	2	Irvine et al, 2001
Burke	1987						23	Clabby *et al*, 1992
	1996/97	1	7.6	50	10		8	Irvine *et al*, 2001
Castle	1976		8.16			0.6		Clare County Council, unpublished
Caum	1996/97	1	6.7	13	16		7	Irvine *et al*, 2001
Clonlea	1990	3	8.17	229		0.380		Clare County Council, 1993
	1993	6	8.49	228		0.25		
Cloomackan	1987						8	Clabby *et al*, 1992
Cloonsnaghta	1987						26	Clabby *et al*, 1992

Table 1 (continued)

Lake	Date	No. Samples	pH	Alkalinity (mg $CaCO_3$ l^{-1})	TP ($\mu g\ l^{-1}$)	NO_3-N (mg l^{-1})	Max Chla ($\mu g\ l^{-1}$)	References
Craggaunkeel	1985	1	8.0		<20	0.82		IIRS, 1985
	1986	1	8.1		70	0.83	0	IIRS, 1986
	1989	12	7.7		30-100	1.17	47.55	EOLAS, 1990
	1995	1	7.1		70	1.47	6.1	Forbairt, 1996
	1996	1	9.2		78	0.73	0.8	Forbairt, 1997a
	1997	3	7.6		16-180	1.37	34	Forbairt, 1997b, c, d
	1998	1	7.8		10	1.7	8.8	Enterprise Ireland, 1998
	1999	2	7.8		15	1.18	10	Enterprise Ireland, 1999a, b
Cullaun	1981	8		150	5-11		5	Allott 1986, 1990
	1982	9			5-9		3	
	1996/97	7-10	8.2-8.5	136-172	<5	0.2-1.1	5	Irvine *et al*, 2001
Cullaunyheeda	1996	1	8.4	152	9		21	Irvine *et al*, 2001
	1997	1	8.2	171	14		7	
Doolough	1976		6.77			0.25		Clare County Council, 1987
	1982	7	6.36	11.4	23		4.03	Bowman *et al*, 1983
	1983	10	6.22	11.6	25		2.68	
	1986	9	5.72	13		0.1		Clare County Council, 1987
	1987	50	6.66	13.9		0.05		
	1987	10		11			14	Bowman *et al*, 1996 ; Clabby *et al*, 1992
	1988	10					20	
	1989	10					45	
	1996/97	13-18	6.4-7.7	3-7	10-26	0.1-0.3	12	Irvine *et al*, 2001
Dromore	1965	1		185				Kennedy & Fitzmaurice, 1971
	1976				25-29		20	T. Champ, unpublished
	1977			160	16-55		41	T. Champ, 1977
	1978				4-67		15	
	1979				19-50		23	
	1981	8			2-36		31	Allott 1986, 1990
	1982	9			14-43		50	
	1985	14			11-34		34	
	1996/97	7-10	8.0-8.6	130-192	7-31	<1.5	43	Irvine *et al*, 2001, Lucey *et al*, 1999

Table 1 (continued)

Lake	Date	No. Samples	pH	Alkalinity (mg $CaCO_3$ l^{-1})	TP (µg l^{-1})	NO_3-N (mg l^{-1})	Max Chla (µg l^{-1})	References
Effernan	1987						21	Clabby *et al*, 1992
Finn	1996/97	1	9.4	68	20		6	Irvine *et al*, 2001
Gortglass	1995	6					54	Lucey *et al*, 1999
Gortglass	1997	2					13.3	Lucey *et al*, 1999
Gortaganniv	1976		8.38			0.7		Clare County Council, unpublished
Graney	1974	2		50-60	75-147		9	Flanagan & Toner, 1975
	1994	4					9	Clabby *et al*, 1992
	1995	7					18	
	1996/97	7-10	7.4-8.4	22-31	8-30	<0.4	15	Irvine *et al*, 2001; Lucey *et al*, 1999
Inchiquin	1965			185				Kennedy & Fitzmaurice, 1971
	1973	1		165	78-124*		1	Flanagan & Toner, 1975
	1974	1		150	52-117*		4	Flanagan & Toner, 1975
	1975						14	Champ, 1979
	1976				28-37		10	Champ, 1977
	1976		8.36			1		Clare County Council, unpublished
	1977				16-58		24	Champ, 1979
	1978				4-70		9	Champ, 1979
	1979				50-95		6	
	1981	8		150	13-43		6	Allott 1986, 1990
	1982	9			11-36		7	
	1985	14			13-28		5	
	1994	9					15	Bowman *et al*, 1996
	1995	10					15	Lucey *et al*, 1999
	1996/97	12-17	8.0-8.6	124-171	5-41	0.6-1.7	15	Irvine *et al*, 2001; Lucey *et al*, 1999
Keagh	1996/97	1	6.1	3	28		8	Irvine *et al*, 2001
Knocka	1987						11	Clabby *et al*, 1992
	1996/97	1	7.3	23	11		3	Irvine *et al*, 2001
Knockerra	1987						8	Clabby *et al*, 1992
Lickeen	1976		7.44			0.250		Clare County Council, unpublished
	1986	1		36	43		7	CFB, pers. com.
	1994	8					16	Lucey *et al*, 1999

Table 1 (continued)

Lake	Date	No. Samples	pH	Alkalinity (mg $CaCO_3$ l^{-1})	TP (µg l^{-1})	NO_3-N (mg l^{-1})	Max Chla (µg l^{-1})	References
	1996/97	13-18		17-23	10-25	<0.3	48	Irvine *et al*, 2001
Moanmore	1996/97	1	6.5	11	53		10	Irvine *et al*, 2001
Muckinish	1996/97	1	8.1	136	5		1	Irvine *et al*, 2001
Rosslara	1885	8	8.38		52	0.45		IIRS, 1985
	1986	8	8.39		<20	0.38	2.6	IIRS, 1986
	1989	96	8.07		20-320	0.49	11.75	EOLAS, 1990
	1995	8	7.71		5-85	0.44	6.8	Forbairt, 1996
	1996	8	8.94		25-190	0.03	4.5	Forbairt, 1997a
	1997	24	8.24		16-32	0.97	9	Forbairt, 1997b, c, d
	1998	8	8.14		9-15	1.29	6	Enterprise Ireland, 1998
	1999	16	7.94		15-36	0.43	26	Enterprise Ireland, 1999a, b
Rushaun	1987						25	Clabby *et al*, 1992
Tullabrack	1987						18	Clabby *et al*, 1992

*: *Values of TP for Lough Inchiquin in 1973 & 1974 seem very high relative to chlorophyll a value for the same period and should be treated with caution.*

APPENDIX 2: Seasonal spread of monitoring

Table 2: Variations in sampling frequency among the HFM lakes, giving the sampling months and total number of samples taken (n). Numbers of lakes included in each class are also given.

Months	HFM n=16	HFM n=15	HFM n=11	HFM n=13	HFM n=6
Mar-00	X	X		X	
Apr-00	X	X	X	X	
May-00	X	X		X	
Jun-00	X	X	X	X	
Jul-00	X	X	X	X	
Aug-00	X	X		X	
Sep-00	X	X	X	X	
Oct-00	X	X		X	
Jan-01	X	X		X	
Apr-01	X		X	X	
May-01	X	X	X	X	X
Jun-01	X	X	X	X	X
Jul-01	X	X	X		X
Aug-01	X	X	X	X	X
Sep-01	X	X	X	X	X
Oct-01	X	X	X		X
Lakes	7	2	1	1	1

Table 3: Variations in sampling frequency among the MFM lakes, giving the sampling months and total number of samples taken (n). Numbers of lakes included in each class are also given.

Months	MFM 00 n=4	MFM 00 n=5	MFM 01-a n=4	MFM 01-b n=4	MFM 01-a n=5	MFM 01-b n=5
Apr-00	X	X				
Jun-00	X	X				
Jul-00	X	X				
Aug-00					X	X
Sep-00	X	X				
Apr-01			X		X	
Jun-01			X	X	X	X
Aug-01		X	X	X	X	X
Sep-01			X	X	X	X
Oct-01				X		X
Lakes	7	2	1	2	4	2

Table 4: Variations in sampling frequency among the LFM lakes, listing the sampling months and total number of samples taken (n). Numbers of lakes included in each class are also given.

Date	LFM 00-a n=1	LFM 00-b n=1	LFM 01 n=1	LFM-a n=2	LFM-b n=2
Aug-00	X			X	
Sep-00		X			X
Aug-01			X	X	X
Lakes	10	1	15	11	2

APPENDIX 2: Vertical profiles

Table 5: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Ballybeg

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	12.8	21.2	13.3	17.9
1	12.8	21.2	13.1	17.8
2	11.4	19.4	13.3	17.8
3	8.7	17.8	13.3	17.8
4	5.1	16.9	13.2	17.8
5	4.1	16.3	9.9	17.2
6	4.2	14.4	3.8	16.3
7	4.3	13.1	3.5	15.5
8	4.4	12.0	3.6	13.9
9	4.5	12.0	3.8	13.9
10	4.3	12.0	3.8	13.9

Table 6: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Ballycullinan

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	14.4	20.8	10.7	18.1
1	12.1	21.2	10.9	18.1
2	11.8	20.5	10.8	17.6
3	11.6	18.3	10.6	17.1
4	11.0	17.6	9.4	16.8
5	7.2	16.7	8.0	16.6
6	4.3	15.5	6.5	15.9
7	3.7	13.1	3.2	13.7
8	3.7	11.1	2.9	11.5
9	4.0	10.7	2.9	10.3
10	4.2	10.6	3.1	10.0

Table 7: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2001 in Lough Castle

	2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**
0	11.8	18.8
1	11.8	17.5
2	11.0	17.2
3	10.2	16.9
4	9.6	16.8
5	9.0	17.0
6	8.8	17.0
7	8.8	16.9

Table 8: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Cullaunyheeda

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	13.1	22.4	11.3	16.8
1	12.5	21.2	11.5	16.8
2	11.9	20.6	11.5	16.8
3	11.5	19.8	11.5	16.8
4	11.0	18.3	11.9	16.8
5	10.4	17.0	11.9	16.8
6	10.0	16.8	11.9	16.7
7	9.8	16.2	12.0	16.6
8	9.6	15.9	11.8	16.3
9	9.6	15.5	11.5	16.1
10	9.7	15.1	11.6	16.0

Table 9: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2001 in Doolough

	2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**
0	12.6	16.3
1	12.6	16.3
2	12.7	16.3
3	12.9	16.2
4	12.8	16.2
5	13.0	16.2
6	13.0	16.2
7	13.2	16.2
8	13.3	16.2
9	13.2	16.2
10	13.3	16.2

Table 10: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Dromore

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	14.3	20.0	13.3	18.3
1	12.7	20.0	13.1	18.1
2	12.2	20.0	13.2	18.1
3	12.1	19.0	13.3	17.8
4	11.4	17.9	12.8	17.3
5	10.7	17.3	12.4	17.1
6	11.2	16.9	11.4	16.9
7	7.7	16.3	10.6	16.8
8	6.9	16.0	10.9	16.7
9	6.6	15.8	10.7	16.5
10	6.3	15.5	10.5	16.8

Table 11: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Gortglass

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	13.4	21.2	11.9	17.6
1	12.5	20.9	12.0	17.5
2	12.2	20.5	12.1	17.2
3	10.5	18.6	12.1	17.0
4	9.3	16.3	12.4	16.9
5	8.3	15.9	12.0	16.8
6	8.2	15.8	11.2	16.4
7	7.9	15.8	11.4	16.0
8	7.8	15.7	10.8	15.8
9	6.9	15.4	10.5	15.7
10	4.8	14.7	10.2	15.6

Table 12: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Graney

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	13.1	19.8	10.4	17.1
1	12.7	19.8	10.6	17.1
2	12.5	19.6	10.9	16.9
3	12.4	19.0	10.9	16.7
4	11.2	17.3	10.9	16.6
5	11.3	16.8	10.5	16.6
6	11.1	16.6	10.2	16.5
7	11.1	16.4	10.4	16.4
8	11.0	16.2	10.8	16.3
9	10.8	16.1	10.5	16.3
10	10.6	15.8	10.8	16.3

Table 13: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Inchiquin

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	16.1	20.0	12.3	16.3
1	15.6	19.9	12.4	16.3
2	15.6	19.7	12.6	16.3
3	13.9	17.9	12.7	16.3
4	12.5	16.6	12.8	16.3
5	12.1	16.2	12.9	16.2
6	12.2	15.9	12.6	16.1
7	11.9	15.7	11.7	15.2
8	11.6	15.6	11.9	14.9
9	11.6	15.3	11.4	14.6
10	11.6	15.0	11.8	14.4

Table 14: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2001 in Lough Killone

	2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**
0	12.5	17.6
1	12.6	17.7
2	12.8	17.7
3	12.8	17.6
4	12.9	17.6
5	12.9	17.6
6	10.5	16.8
7	3.7	14.7
8	3.3	11.5
9	3.5	10.1
10	3.6	9.7

Table 15: Dissolved Oxygen (mg l^{-1}) and Temperature (°C) vertical profiles results – July 2000 and 2001 in Lough Lickeen

	2000		2001	
Depth m	**DO_2 mg l^{-1}**	**Temp °C**	**DO_2 mg l^{-1}**	**Temp °C**
0	14.7	19.0	11.8	17.3
1	13.6	18.9	12.0	17.2
2	12.7	18.9	12.2	17.1
3	12.5	18.7	12.6	16.8
4	12.0	18.4	12.7	16.6
5	11.6	16.5	12.6	16.4
6	11.2	15.8	12.6	16.3
7	11.1	15.4	12.8	16.2
8	10.6	15.3	12.8	16.1
9	10.5	15.2	13.0	16.0
10	10.7	15.1	13.0	16.0

Table 16: Secchi Disc Measurements (m) – July 2000 and 2001

Lake	Jul-00	Jul-01
Ballybeg	0.4	1.1
Ballycullinan	1.0	2.0
Castle		
Cullaunyheeda	3.2	3.7
Doolough		1.0
Dromore	3.1	3.0
Gortglass	0.8	2.9
Graney	1.8	1.2
Inchiquin	1.6	2.2
Killone		2.3
Lickeen	2.0	1.8

APPENDIX 2: Influence of the seasonal spread of monitoring

Table 17: Comparison between means of the chemical variables obtained from the monitoring 2000-2001 (n=15-16 samples) (Mean HFM: in bold) with means calculated using the different seasonal spreads of HFM monitoring (n=11, n=13 and n=6), as described in Table 2 - Appendix 2, for the lakes included in the high frequency monitoring in 2000 and 2001. 95% CI of the monitoring means are also given in italics. Estimated means outside the 95% CI range are underlined.

Variables	Lakes	Mean HFM	*Mean + 95% CI*	*Mean - 95% CI*	HFM n=11	HFM n=13	HFM n=6
NH_4-N	Ballybeg	**0.04**	*0.09*	*0.00*	0.07	0.01	0.07
(mg l^{-1})	Ballycullinan	**0.05**	*0.09*	*0.00*	0.06	0.03	0.06
	Cullaunyheeda	**0.06**	*0.16*	*0.00*	0.11	0.02	0.11
	Doolough	**0.01**	*0.02*	*0.00*	0.00	0.01	0.00
	Dromore	**0.01**	*0.03*	*0.00*	0.01	0.02	0.01
	Gortglass	**0.01**	*0.01*	*0.00*	0.00	0.01	0.00
	Graney	**0.02**	*0.03*	*0.00*	0.02	0.01	0.02
	Inchiquin	**0.02**	*0.03*	*0.01*	0.02	0.02	0.02
	Lickeen	**0.01**	*0.02*	*0.00*	0.00	0.01	0.00
NO_3-N	Ballybeg	**0.08**	*0.18*	*0.00*	0.03	0.07	0.05
(mg l^{-1})	Ballycullinan	**0.04**	*0.07*	*0.01*	0.02	0.04	0.02
	Cullaunyheeda	**0.14**	*0.28*	*0.00*	0.06	0.16	0.02
	Doolough	**0.08**	*0.11*	*0.04*	0.07	0.08	0.06
	Dromore	**0.16**	*0.28*	*0.04*	0.09	0.16	0.08
	Gortglass	**0.06**	*0.10*	*0.01*	0.04	0.05	0.06
	Graney	**0.11**	*0.17*	*0.06*	0.10	0.12	0.09
	Inchiquin	**0.35**	*0.45*	*0.24*	0.30	0.34	0.31
	Lickeen	**0.07**	*0.10*	*0.03*	0.05	0.07	0.03
TN	Ballybeg	**1.29**	*1.62*	*0.96*	1.35	1.26	1.54
(mg l^{-1})	Ballycullinan	**0.50**	*0.55*	*0.44*	0.51	0.48	0.53
	Cullaunyheeda	**0.75**	*0.87*	*0.62*	0.69	0.77	0.68
	Doolough	**0.70**	*1.09*	*0.32*	0.54	0.72	0.54

Table 17 (continued)

Variables	Lakes	Mean HFM	*Mean + 95% CI*	*Mean - 95% CI*	HFM n=11	HFM n=13	HFM n=6
	Dromore	**0.55**	*0.65*	*0.46*	0.51	0.56	0.52
	Gortglass	**0.65**	*0.71*	*0.59*	0.63	0.66	0.60
	Graney	**0.61**	*0.73*	*0.50*	0.64	0.62	0.71
	Inchiquin	**0.74**	*0.83*	*0.64*	0.72	0.71	0.79
	Lickeen	**0.72**	*0.79*	*0.65*	0.74	0.72	0.78
TOC	Ballybeg	**9.30**	*15.85*	*2.75*	11.01	10.07	11.01
(mg l^{-1})	Ballycullinan	**5.17**	*6.30*	*4.04*	5.43	4.87	5.43
	Cullaunyheeda	**14.98**	*27.05*	*2.90*	17.81	16.12	17.81
	Doolough	**7.53**	*8.76*	*6.29*	8.24	7.15	8.24
	Dromore	**5.75**	*7.64*	*3.87*	4.74	5.93	4.74
	Gortglass	**6.72**	*7.38*	*6.07*	6.63	6.84	6.63
	Graney	**9.01**	*9.75*	*8.27*	9.10	8.97	9.10
	Inchiquin	**4.73**	*5.50*	*3.96*	4.80	4.52	4.80
	Lickeen	**9.84**	*10.51*	*9.17*	10.08	9.53	10.08
TP	Ballybeg	**79.0**	*102.3*	*55.8*	80.6	79.0	87.5
(µg l^{-1})	Ballycullinan	**30.1**	*39.5*	*20.7*	26.0	29.1	27.8
	Cullaunyheeda	**22.9**	*27.8*	*18.1*	21.9	23.9	24.5
	Doolough	**22.3**	*24.8*	*19.8*	21.2	22.8	21.1
	Dromore	**19.9**	*23.5*	*16.3*	20.5	19.2	21.3
	Gortglass	**23.9**	*26.9*	*21.0*	23.8	24.3	21.8
	Graney	**19.0**	*21.5*	*16.5*	19.1	19.3	20.9
	Inchiquin	**19.7**	*23.6*	*15.9*	17.8	19.8	17.7
	Lickeen	**21.5**	*23.8*	*19.1*	21.9	21.7	21.6
SiO_4-Si	Ballybeg	**2.41**	*4.06*	*0.75*	2.62	2.81	2.62
(mg l^{-1})	Ballycullinan	**1.95**	*3.19*	*0.70*	2.68	1.80	2.68
	Cullaunyheeda	**2.05**	*3.53*	*0.58*	2.90	2.07	2.90
	Doolough	**0.90**	*1.50*	*0.30*	0.93	0.96	0.93
	Dromore	**1.30**	*2.25*	*0.36*	1.70	1.02	1.70

Table 17 (continued)

Variables	Lakes	Mean HFM	*Mean + 95% CI*	*Mean - 95% CI*	HFM n=11	HFM n=13	HFM n=6
	Gortglass	**1.81**	***2.85***	***0.77***	2.38	1.65	2.38
	Graney	**1.39**	***2.54***	***0.24***	1.84	1.06	1.84
	Inchiquin	**0.93**	***1.54***	***0.32***	1.44	0.85	1.44
	Lickeen	**0.66**	***1.38***	***0.00***	1.10	0.35	1.10
Chla	Ballybeg	**36.2**	***54.4***	***18.0***	30.6	37.3	28.2
($\mu g\ l^{-1}$)	Ballycullinan	**7.9**	***10.2***	***5.6***	8.0	7.1	7.7
	Cullaunyheeda	**3.4**	***4.9***	***2.0***	3.4	3.6	3.4
	Doolough	**7.3**	***9.6***	***4.9***	8.7	6.7	9.4
	Dromore	**9.1**	***13.4***	***4.8***	9.1	8.1	10.5
	Gortglass	**13.5**	***17.1***	***9.9***	13.0	13.5	12.0
	Graney	**7.7**	***10.7***	***4.7***	8.8	7.4	9.5
	Inchiquin	**4.8**	***7.4***	***2.1***	6.2	4.2	5.8
	Lickeen	**12.4**	***18.7***	***6.1***	14.6	10.0	16.8
pH	Ballybeg	**8.13**	***8.45***	***7.80***	8.10	8.20	7.92
	Ballycullinan	**8.04**	***8.13***	***7.95***	8.07	8.05	8.02
	Cullaunyheeda	**8.35**	***8.49***	***8.20***	8.33	8.36	8.27
	Doolough	**6.88**	***7.01***	***6.74***	<u>7.02</u>	6.85	<u>7.12</u>
	Dromore	**8.15**	***8.24***	***8.06***	8.21	8.14	8.20
	Gortglass	**7.42**	***7.50***	***7.35***	7.48	7.41	7.49
	Graney	**7.66**	***7.75***	***7.56***	7.73	7.64	7.74
	Inchiquin	**8.21**	***8.33***	***8.09***	8.27	8.21	8.26
	Lickeen	**7.59**	***7.73***	***7.46***	7.69	7.59	7.69
Alkalinity	Ballybeg	**116.6**	***137.4***	***95.9***	109.6	112.0	127.4
(mg $CaCO_3\ l^{-1}$)	Ballycullinan	**196.3**	***203.1***	***189.4***	195.9	195.8	200.6
	Cullaunyheeda	**175.8**	***190.1***	***161.5***	171.0	175.8	167.8
	Doolough	**5.1**	***6.4***	***3.9***	5.7	4.6	5.8
	Dromore	**161.4**	***168.7***	***154.0***	159.7	161.2	160.3
	Gortglass	**18.7**	***19.5***	***17.9***	19.1	18.5	19.2

Table 17 (continued)

Variables	Lakes	Mean HFM	*Mean + 95% CI*	*Mean - 95% CI*	HFM n=11	HFM n=13	HFM n=6
	Graney	**29.5**	***32.0***	***27.0***	30.5	28.7	31.4
	Inchiquin	**151.0**	***160.9***	***141.2***	153.4	149.0	160.9
	Lickeen	**23.7**	***24.7***	***22.7***	24.2	23.4	25.2
Conductivity	Ballybeg	**299.4**	***338.9***	***259.9***	277.3	295.7	293.8
(µS cm^{-1})	Ballycullinan	**422.1**	***439.7***	***404.5***	411.6	424.0	399.0
	Cullaunyheeda	**394.6**	***418.9***	***370.3***	379.7	397.3	361.5
	Doolough	**94.0**	***100.2***	***87.9***	90.9	94.7	83.2
	Dromore	**363.7**	***385.4***	***341.9***	348.6	366.2	332.2
	Gortglass	**131.4**	***136.6***	***126.2***	128.5	131.9	122.7
	Graney	**115.5**	***122.0***	***109.1***	113.5	115.7	106.0
	Inchiquin	**342.3**	***360.9***	***323.6***	336.4	341.1	327.4
	Lickeen	**139.3**	***144.6***	***134.0***	135.9	140.0	129.4
Colour	Ballybeg	**31**	***41***	***22***	28	33	28
(PtCo)	Ballycullinan	**17**	***20***	***14***	15	16	15
	Cullaunyheeda	**39**	***48***	***31***	34	40	32
	Doolough	**76**	***87***	***65***	69	76	67
	Dromore	**20**	***27***	***14***	20	20	23
	Gortglass	**31**	***39***	***23***	28	34	27
	Graney	**70**	***85***	***55***	65	72	73
	Inchiquin	**22**	***26***	***18***	20	21	22
	Lickeen	**64**	***72***	***56***	61	64	61
Turbidity	Ballybeg	**16.2**	***25.6***	***6.8***	17.3	17.3	19.5
(NTU)	Ballycullinan	**1.8**	***2.2***	***1.3***	1.8	1.7	1.9
	Cullaunyheeda	**4.2**	***7.9***	***0.4***	5.7	2.9	9.00
	Doolough	**2.4**	***2.9***	***1.9***	2.4	2.3	2.6
	Dromore	**6.1**	***15.9***	***0.0***	8.6	6.7	1.8
	Gortglass	**3.7**	***4.7***	***2.6***	3.5	3.9	3.1
	Graney	**3.8**	***4.6***	***3.1***	3.9	3.7	4.3

Table 17 (continued)

Variables	Lakes	Mean HFM	*Mean + 95% CI*	*Mean - 95% CI*	HFM n=11	HFM n=13	HFM n=6
	Inchiquin	**1.2**	*1.5*	*0.9*	1.2	1.2	1.3
	Lickeen	**3.7**	*4.6*	*2.8*	4.1	3.6	4.4

Table 18: Annual means 2000 and 2001 of NH_4-N, NO_3-N and TN concentrations (mg l^{-1}) for the HFM lakes. 95% CI are also given in italics.

Lakes	NH_4-N 2000	*95% CI*	NH_4-N 2001	*95% CI*	NO_3-N 2000	*95% CI*	NO_3-N 2001	*95% CI*	TN 2000	*95% CI*	TN 2001	*95% CI*
Ballybeg	0.01	*0.01*	0.06	*0.12*	0.10	*0.20*	0.05	*0.09*	1.15	*0.54*	1.45	*0.48*
Ballycullinan	0.04	*0.17*	0.05	*0.07*	0.04	*0.05*	0.05	*0.06*	0.47	*0.08*	0.53	*0.09*
Castle			0.14	*0.54*	0.24	*0.48*	0.26	*0.16*	0.73	*0.38*	0.75	*0.20*
Cullaunyheeda	0.03	*0.04*	0.09	*0.19*	0.19	*0.26*	0.09	*0.17*	0.75	*0.23*	0.74	*0.18*
Doolough	0.02	*0.02*	0.01	*0.02*	0.08	*0.05*	0.07	*0.05*	0.52	*0.06*	0.89	*0.84*
Dromore	0.01	*0.02*	0.02	*0.02*	0.19	*0.21*	0.13	*0.16*	0.54	*0.15*	0.57	*0.16*
Gortglass	0.01	*0.01*	0.01	*0.01*	0.03	*0.03*	0.08	*0.09*	0.67	*0.11*	0.62	*0.09*
Graney	0.01	*0.02*	0.02	*0.02*	0.12	*0.09*	0.11	*0.08*	0.53	*0.11*	0.70	*0.20*
Inchiquin	0.02	*0.04*	0.01	*0.01*	0.35	*0.20*	0.35	*0.13*	0.66	*0.16*	0.81	*0.12*
Keagh	0.01	*0.01*	0.01		0.05	*0.04*	0.03	*0.06*	0.57	*0.06*	0.69	*0.26*
Lickeen	0.01	*0.01*	0.01	*0.02*	0.09	*0.07*	0.04	*0.05*	0.66	*0.08*	0.77	*0.13*

Table 19: Annual means 2000 and 2001 of TDOC (mg l^{-1}), TP (μg l^{-1}) and SiO_4-Si (mg l^{-1}) concentrations for the HFM lakes. 95% CI are also given in italics.

	TDOC 2000	*95% CI*	TDOC 2001	*95% CI*	TP 2000	*95% CI*	TP 2001	*95% CI*	SiO_4-Si 2000	*95% CI*	SiO_4-Si 2001	*95% CI*
Ballybeg	6.59	*0.85*	10.07	*8.95*	74.5	*44.5*	84.3	*25.4*	2.05	*5.37*	2.67	*2.80*
Ballycullinan	5.51	*3.33*	5.09	*1.48*	25.4	*9.5*	34.9	*18.4*	0.95	*2.12*	2.69	*1.89*
Castle	6.66		7.35	*1.49*	33.9	*15.6*	27.0	*3.4*			2.50	*3.69*
Cullaunyheeda	9.43	*12.33*	16.56	*16.43*	20.6	*5.5*	25.6	*9.7*	0.94	*1.45*	2.89	*2.27*
Doolough	4.91	*15.88*	8.18	*0.81*	22.0	*2.3*	22.6	*5.2*	0.45	*0.58*	1.24	*0.94*
Dromore	9.68	*21.35*	4.63	*0.64*	19.1	*6.0*	20.8	*5.6*	0.53	*0.68*	1.88	*1.38*
Gortglass	7.10	*5.39*	6.63	*0.83*	26.2	*4.5*	21.7	*4.0*	0.93	*0.95*	2.47	*1.43*
Graney	8.17	*18.63*	9.22	*0.59*	17.3	*2.7*	20.6	*4.6*	0.54	*0.78*	2.02	*1.86*
Inchiquin	4.76	*14.93*	4.72	*0.87*	20.2	*7.8*	19.3	*4.3*	0.47	*1.02*	1.27	*0.86*
Keagh	13.02	*32.02*	12.41	*0.91*	39.5	*5.3*	41.3	*9.7*	0.31	*0.39*	0.44	
Lickeen	9.36	*5.41*	9.96	*0.83*	20.8	*3.8*	22.1	*3.8*	0.31	*0.45*	0.93	*1.35*

Table 20: Annual means 2000 and 2001 of chlorophyll-*a* concentrations (μg l^{-1}), colour (PtCo) and turbidity (NTU) for the HFM lakes. 95% CI are given in italics. Annual maximum chlorophyll-*a* are also listed.

	Chl a 2000	*95% CI*	Max Chla 2000	Chla 2001	*95% CI*	Max Chla 2001	Colour 2000	*95% CI*	Colour 2001	*95% CI*	Turb 2000	*95% CI*	Turb 2001	*95% CI*
Ballybeg	42.2	*36.1*	108.4	29.3	*14.3*	50.8	35	*19*	27	*9*	14.6	*15.1*	17.9	*15.6*
Ballycullinan	8.4	*3.8*	16.4	7.3	*3.5*	13.5	19	*6*	15	*4*	1.7	*0.8*	1.8	*0.7*
Castle	25.2	*5.9*	28.3	15.9	*8.1*	33.9	39	*13*	39	*20*	3.2	*0.5*	3.6	*1.2*
Cullaunyheeda	3.7	*2.8*	11.0	3.1	*1.5*	6.5	42	*14*	36	*13*	0.8	*0.2*	7.9	*8.2*
Doolough	6.2	*2.6*	10.2	8.3	*4.5*	17.5	78	*10*	74	*22*	2.1	*0.9*	2.6	*0.6*
Dromore	9.0	*7.0*	28.5	9.2	*7.0*	22.8	18	*5*	23	*15*	10.0	*20.3*	1.7	*0.9*
Gortglass	15.8	*6.4*	27.5	11.2	*4.2*	18.5	33	*8*	29	*17*	4.4	*1.7*	2.9	*1.5*
Graney	7.1	*2.9*	11.1	8.4	*6.2*	21.0	60	*17*	80	*27*	3.7	*1.3*	4.0	*1.0*
Inchiquin	4.4	*4.2*	16.3	5.1	*4.4*	14.3	21	*6*	23	*7*	1.1	*0.5*	1.3	*0.4*
Keagh	6.8	*3.6*	13.3	4.1	*2.8*	6.9	139	*21*	149	*32*	2.9	*1.0*	2.2	*1.3*
Lickeen	9.3	*3.2*	14.3	15.5	*13.6*	49.0	64	*11*	64	*15*	3.3	*1.4*	4.1	*1.5*

Table 21: Annual means 2000 and 2001 of pH, alkalinity (mg $CaCO_3$ l^{-1}) and conductivity (µS cm^{-1}) for the HFM lakes. 95% CI are given in italics.

	pH 2000	*95% CI*	pH 2001	*95% CI*	Alk. 2000	*95% CI*	Alk. 2001	*95% CI*	Cond. 2000	*95% CI*	Cond. 2001	*95% CI*
Ballybeg	8.41	*0.50*	7.94	*0.22*	106.7	*38.5*	128.0	*21.3*	299.4	*77.8*	299.4	*38.7*
Ballycullinan	8.08	*0.15*	8.01	*0.12*	191.5	*11.5*	201.1	*8.9*	438.6	*22.6*	405.6	*26.3*
Castle	8.17	*0.32*	7.97	*0.14*	127.2	*3.7*	121.1	*11.6*	313.8	*12.6*	267.9	*17.0*
Cullaunyheeda	8.37	*0.13*	8.32	*0.34*	177.9	*18.2*	173.3	*29.1*	411.8	*31.8*	375.0	*41.0*
Doolough	6.76	*0.23*	7.04	*0.15*	4.8	*1.8*	5.5	*2.0*	104.4	*1.9*	83.7	*5.1*
Dromore	8.16	*0.12*	8.13	*0.18*	159.7	*12.4*	163.3	*11.2*	381.0	*25.5*	343.9	*37.6*
Gortglass	7.42	*0.10*	7.42	*0.14*	18.6	*1.1*	18.8	*1.6*	138.6	*3.2*	124.1	*6.9*
Graney	7.67	*0.14*	7.64	*0.17*	28.3	*3.4*	30.7	*4.5*	124.9	*5.7*	106.1	*6.8*
Inchiquin	8.21	*0.21*	8.21	*0.18*	140.3	*16.1*	161.8	*8.1*	350.5	*30.3*	334.0	*28.6*
Keagh	6.03	*0.31*	6.40	*0.52*	2.0	*1.1*	3.7	*2.1*	113.5	*3.8*	91.2	*12.5*
Lickeen	7.59	*0.18*	7.60	*0.25*	22.6	*0.8*	24.9	*1.5*	147.7	*2.4*	130.9	*5.3*

Table 22: Comparison between means of the chemical variables obtained from the monitoring 2000-2001 (n=15-16 samples) (Mean HFM: in bold) with means calculated using the different seasonal spreads of MFM monitoring (n=4 (2000, 2001a and 2001b) and n=5 (2000, 2001a and 2001b)), as described in Table 3 - Appendix 2, for the lakes included in the high frequency monitoring in 2000 and 2001. 95% CI of the monitoring means are also given in italics. Estimated means outside the 95% CI range are underlined.

	Lakes	Mean n=15-16	*Mean + 95% CI*	*Mean - 95% CI*	MFM 00 n=4	MFM 01-a n=4	MFM 01-b n=4	MFM 00 n=5	MFM 01=a n=5	MFM 01-b n=5
NO_3-N	Ballybeg	**0.08**	*0.18*	*0.00*	0.01	0.01	0.07	0.00	0.01	0.05
(mg l^{-1})	Ballycullinan	**0.04**	*0.07*	*0.01*	0.01	0.02	0.03	0.01	0.01	0.03
	Castle	**0.25**	*0.39*	*0.11*	0.24	0.25	0.21	0.21	0.25	0.21
	Cullaunyheeda	**0.14**	*0.28*	*0.00*	0.13	0.01	0.01	0.11	0.01	0.01
	Doolough	**0.08**	*0.11*	*0.04*	0.08	0.05	0.05	0.07	0.05	0.05
	Dromore	**0.16**	*0.28*	*0.04*	0.10	0.02	0.09	0.09	0.02	0.07
	Gortglass	**0.06**	*0.10*	*0.01*	0.01	0.04	0.08	0.01	0.04	0.07
	Graney	**0.11**	*0.17*	*0.06*	0.11	0.08	0.06	0.09	0.07	0.05

Table 22 (continued)

	Lakes	Mean n=15-16	*Mean + 95% CI*	*Mean - 95% CI*	MFM 00 n=4	MFM 01-a n=4	MFM 01-b n=4	MFM 00 n=5	MFM 01=a n=5	MFM 01-b n=5
	Inchiquin	**0.35**	*0.45*	*0.24*	0.28	0.28	0.32	0.26	0.26	0.29
	Keagh	**0.04**	*0.07*	*0.01*	0.04	0.01	0.01	0.03	0.01	0.01
	Killone	**0.01**	*0.02*	*0.00*		0.01	0.01	0.01	0.01	0.01
	Lickeen	**0.07**	*0.10*	*0.03*	0.08	0.05	0.01	0.07	0.04	0.02
TN ($mg\ l^{-1}$)	Ballybeg	**1.29**	*1.62*	*0.96*	1.07	1.57	1.59	1.05	1.52	1.54
	Ballycullinan	**0.50**	*0.55*	*0.44*	0.49	0.50	0.59	0.49	0.49	0.56
	Castle	**0.74**	*0.88*	*0.60*	0.73	0.71	0.68	0.67	0.71	0.68
	Cullaunyheeda	**0.75**	*0.87*	*0.62*	0.70	0.70	0.68	0.68	0.66	0.65
	Doolough	**0.70**	*1.09*	*0.32*	0.53	0.51	0.53	0.51	0.49	0.51
	Dromore	**0.55**	*0.65*	*0.46*	0.50	0.49	0.53	0.47	0.45	0.49
	Gortglass	**0.65**	*0.71*	*0.59*	0.70	0.60	0.60	0.65	0.57	0.58
	Graney	**0.61**	*0.73*	*0.50*	0.52	0.78	0.79	0.56	0.70	0.71
	Inchiquin	**0.74**	*0.83*	*0.64*	0.59	0.72	0.79	0.59	0.69	0.75
	Keagh	**0.61**	*0.70*	*0.52*	0.56	0.74	0.74	0.55	0.68	0.68
	Killone	**0.67**	*0.84*	*0.50*		0.65	0.67	0.46	0.65	0.67
	Lickeen	**0.72**	*0.79*	*0.65*	0.67	0.83	0.81	0.64	0.77	0.75
TDOC ($mg\ l^{-1}$)	Ballybeg	**9.30**	*15.85*	*2.75*		6.98	6.91	7.57	6.86	6.83
	Ballycullinan	**5.17**	*6.30*	*4.04*		5.21	6.22	6.49	5.22	6.03
	Castle	**7.27**	*8.53*	*6.00*	6.66	7.43	8.10	7.34	7.43	8.10
	Cullaunyheeda	**14.98**	*27.05*	*2.90*		9.36	9.90	9.06	9.14	9.61
	Doolough	**7.53**	*8.76*	*6.29*		7.99	8.28	9.27	7.12	7.35
	Dromore	**5.75**	*7.64*	*3.87*		4.88	4.95	5.19	5.66	5.56
	Gortglass	**6.72**	*7.38*	*6.07*		6.92	6.62	6.60	6.87	6.63
	Graney	**9.01**	*9.75*	*8.27*		8.98	8.67	9.24	8.53	8.28
	Inchiquin	**4.73**	*5.50*	*3.96*		4.73	5.29	5.85	4.50	4.95
	Keagh	**12.59**	*14.07*	*11.11*		12.68	12.68	13.66	12.13	12.13
	Killone	**5.43**	*6.97*	*3.89*		5.53	5.06	5.81	5.53	5.06
	Lickeen	**9.84**	*10.51*	*9.17*		9.79	10.12	10.12	9.62	9.88

Table 22 (continued)

	Lakes	Mean n=15-16	*Mean + 95% CI*	*Mean - 95% CI*	MFM 00 n=4	MFM 01-a n=4	MFM 01-b n=4	MFM 00 n=5	MFM 01=a n=5	MFM 01-b n=5
TP	Ballybeg	**79.0**	*102.3*	*55.8*	70.2	80.6	79.9	66.1	88.5	86.4
($\mu g\ l^{-1}$)	Ballycullinan	**30.1**	*39.5*	*20.7*	22.9	23.0	28.9	22.8	22.9	27.6
	Castle	**29.5**	*34.2*	*24.8*	33.9	24.7	24.7	32.2	24.7	24.7
	Cullaunyheeda	**22.9**	*27.8*	*18.1*	17.9	24.5	23.2	17.4	22.3	21.7
	Doolough	**22.3**	*24.8*	*19.8*	21.2	22.2	19.1	20.2	22.4	19.9
	Dromore	**19.9**	*23.5*	*16.3*	19.3	21.1	24.0	19.7	21.4	23.6
	Gortglass	**23.9**	*26.9*	*21.0*	27.3	21.7	21.7	24.9	21.4	21.3
	Graney	**19.0**	*21.5*	*16.5*	16.1	23.5	22.1	19.5	22.6	21.5
	Inchiquin	**19.7**	*23.6*	*15.9*	18.1	16.5	16.8	18.4	16.3	16.5
	Keagh	**40.2**	*44.3*	*36.1*	39.8	36.3	36.3	38.0	36.0	36.0
	Killone	**36.8**	*51.9*	*21.6*		27.4	32.0	22.5	27.4	32.0
	Lickeen	**21.5**	*23.8*	*19.1*	22.6	20.8	20.2	20.9	20.1	19.6
Chla	Ballybeg	**36.2**	*54.4*	*18.0*	34.2	25.5	29.8	30.3	32.4	34.4
($\mu g\ l^{-1}$)	Ballycullinan	**7.9**	*10.2*	*5.6*	8.6	6.5	7.9	8.2	8.5	9.6
	Castle	**19.3**	*25.0*	*13.6*	25.2	15.0	13.0	23.4	15.0	13.0
	Cullaunyheeda	**3.4**	*4.9*	*2.0*	3.4	2.9	3.0	3.3	2.8	2.9
	Doolough	**7.3**	*9.6*	*4.9*	7.5	9.7	7.7	7.2	9.7	8.1
	Dromore	**9.1**	*13.4*	*4.8*	6.9	9.5	12.9	7.0	9.3	12.0
	Gortglass	**13.5**	*17.1*	*9.9*	14.8	9.5	10.8	12.9	9.7	10.7
	Graney	**7.7**	*10.7*	*4.7*	7.7	10.7	9.3	10.3	10.3	9.2
	Inchiquin	**4.8**	*7.4*	*2.1*	6.9	5.5	5.6	8.0	4.7	4.8
	Keagh	**5.7**	*8.0*	*3.4*	7.3	5.6	5.6	6.9	7.5	7.5
	Killone	**18.2**	*34.6*	*1.9*		9.7	11.9	8.6	9.7	11.9
	Lickeen	**12.4**	*18.7*	*6.1*	10.7	14.0	15.1	9.8	12.5	13.4
pH	Ballybeg	**8.13**	*8.45*	*7.80*	8.72	8.04	7.90	8.50	8.15	7.99
	Ballycullinan	**8.04**	*8.13*	*7.95*	8.15	8.00	7.99	8.12	8.02	8.00
	Castle	**8.04**	*8.17*	*7.91*	8.17	7.95	7.94	8.13	7.95	7.94
	Cullaunyheeda	**8.35**	*8.49*	*8.20*	8.44	8.20	8.20	8.42	8.25	8.24

Table 22 (continued)

	Lakes	Mean n=15-16	*Mean + 95% CI*	*Mean - 95% CI*	MFM 00 n=4	MFM 01-a n=4	MFM 01-b n=4	MFM 00 n=5	MFM 01=a n=5	MFM 01-b n=5
	Doolough	**6.88**	*7.01*	*6.74*	6.89	7.09	7.17	6.94	7.07	7.13
	Dromore	**8.15**	*8.24*	*8.06*	8.23	8.19	8.18	8.22	8.20	8.19
	Gortglass	**7.42**	*7.50*	*7.35*	7.46	7.45	7.52	7.47	7.46	7.51
	Graney	**7.66**	*7.75*	*7.56*	7.73	7.72	7.76	7.76	7.75	7.78
	Inchiquin	**8.21**	*8.33*	*8.09*	8.28	8.25	8.16	8.27	8.27	8.20
	Keagh	**6.14**	*6.39*	*5.89*	6.23	6.81	6.81	6.30	6.72	6.72
	Killone	**8.26**	*8.57*	*7.96*		8.22	8.17	8.36	8.22	8.17
	Lickeen	**7.59**	*7.73*	*7.46*	7.68	7.67	7.59	7.64	7.68	7.61
Alkalinity ($mg\ CaCO_3\ l^{-1}$)	Ballybeg	**116.6**	*137.4*	*95.9*	83.0	116.4	130.4	91.3	108.2	121.0
	Ballycullinan	**196.3**	*203.1*	*189.4*	187.6	198.6	196.3	186.4	194.0	192.2
	Castle	**123.3**	*130.2*	*116.4*	127.2	123.6	118.4	123.2	123.6	118.4
	Cullaunyheeda	**175.8**	*190.1*	*161.5*	175.7	152.4	156.3	163.7	152.7	155.8
	Doolough	**5.1**	*6.4*	*3.9*	5.5	4.0	5.3	5.2	4.6	5.7
	Dromore	**161.4**	*168.7*	*154.0*	158.9	154.4	158.6	156.5	149.9	154.2
	Gortglass	**18.7**	*19.5*	*17.9*	18.9	19.3	20.4	19.1	19.4	20.3
	Graney	**29.5**	*32.0*	*27.0*	28.8	32.0	34.4	30.0	31.8	33.7
	Inchiquin	**151.0**	*160.9*	*141.2*	140.4	160.8	165.3	145.0	156.7	160.3
	Keagh	**2.6**	*3.6*	*1.6*	2.4	4.8	4.8	3.0	4.4	4.4
	Killone	**107.9**	*111.8*	*104.1*		105.3	106.6	102.8	105.3	106.6
	Lickeen	**23.7**	*24.7*	*22.7*	22.4	25.2	26.0	23.2	24.9	25.5
Conductivity ($\mu S\ cm^{-1}$)	Ballybeg	**299.4**	*338.9*	*259.9*	252.5	275.3	298.3	259.4	267.8	287.6
	Ballycullinan	**422.1**	*439.7*	*404.5*	433.8	391.3	394.5	420.4	394.8	397.4
	Castle	**284.5**	*303.0*	*266.0*	313.8	268.5	264.0	298.4	268.5	264.0
	Cullaunyheeda	**394.6**	*418.9*	*370.3*	407.0	341.7	352.3	391.4	348.8	355.8
	Doolough	**94.0**	*100.2*	*87.9*	104.3	81.5	85.5	99.8	86.8	90.0
	Dromore	**363.7**	*385.4*	*341.9*	373.3	316.0	332.5	360.0	323.8	335.4
	Gortglass	**131.4**	*136.6*	*126.2*	138.8	120.5	126.5	136.0	124.6	129.4
	Graney	**115.5**	*122.0*	*109.1*	126.8	103.0	109.8	122.6	108.2	113.6

Table 22 (continued)

	Lakes	Mean n=15-16	*Mean + 95% CI*	*Mean - 95% CI*	MFM 00 n=4	MFM 01-a n=4	MFM 01-b n=4	MFM 00 n=5	MFM 01=a n=5	MFM 01-b n=5
	Inchiquin	**342.3**	*360.9*	*323.6*	352.0	320.0	340.3	346.4	324.8	341.0
	Keagh	**104.9**	*112.9*	*97.0*	114.3	88.7	88.7	109.6	94.5	94.5
	Killone	**265.7**	*282.4*	*248.9*		257.3	267.3	253.0	257.3	267.3
	Lickeen	**139.3**	*144.6*	*134.0*	147.3	127.3	130.8	143.4	131.8	134.6
Colour (PtCo)	Ballybeg	**31**	*41*	*22*	28	30	30	27	31	31
	Ballycullinan	**17**	*20*	*14*	15	15	17	15	17	19
	Castle	**39**	*51*	*28*	39	30	32	31	30	32
	Cullaunyheeda	**39**	*48*	*31*	37	29	29	32	31	30
	Doolough	**76**	*87*	*65*	72	64	62	73	67	65
	Dromore	**20**	*27*	*14*	15	31	29	17	27	26
	Gortglass	**31**	*39*	*23*	30	35	28	27	33	28
	Graney	**70**	*85*	*55*	52	73	58	53	67	55
	Inchiquin	**22**	*26*	*18*	16	20	22	17	20	22
	Keagh	**143**	*158*	*128*	130	133	133	130	126	126
	Killone	**12**	*19*	*5*		7	9	8	7	9
	Lickeen	**64**	*72*	*56*	61	57	56	61	56	55
Turbidity (NTU)	Ballybeg	**16.2**	*25.6*	*6.8*	14.1	16.2	14.1	12.2	18.0	15.9
	Ballycullinan	**1.8**	*2.2*	*1.3*	1.6	1.5	1.5	1.6	1.9	1.9
	Castle	**3.5**	*4.1*	*2.8*	3.2	2.8	3.0	3.1	2.8	3.0
	Cullaunyheeda	**4.2**	*7.9*	*0.4*	0.7	4.3	9.3	1.3	3.5	7.7
	Doolough	**2.4**	*2.9*	*1.9*	2.0	2.6	2.3	2.0	2.5	2.2
	Dromore	**6.1**	*15.9*	*0.0*	18.7	1.9	2.1	15.1	1.9	2.1
	Gortglass	**3.7**	*4.7*	*2.6*	4.3	3.1	3.1	3.7	3.0	3.0
	Graney	**3.8**	*4.6*	*3.1*	3.2	4.2	3.8	3.3	4.6	4.3
	Inchiquin	**1.2**	*1.5*	*0.9*	0.8	1.5	1.3	0.9	1.4	1.2
	Keagh	**2.6**	*3.3*	*1.9*	2.4	2.6	2.6	2.3	3.1	3.1
	Killone	**4.3**	*6.7*	*1.9*		4.0	3.7	1.1	4.0	3.7
	Lickeen	**3.7**	*4.6*	*2.8*	3.5	3.9	4.0	3.2	3.7	3.8

APPENDIX 3: Modelling

Table 1: Models Incorporating Nutrient Fate and Transport Elements (adapted from WERF, 2000) (Jennings *et al*, 2002)

Model Acronym	Model Name	Sponsor/Developer
AGNPS-98	Agricultural Non-Point Source Pollution Modeling System – continuous version	USDA ARS
ANSWERS	Areal Nonpoint Source Watershed Environmental Response Simulation	North Carolina State University
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems	USDA ARS
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems	USDA ARS
HSPF	Hydrological Simulation Program-Fortran	U.S. EPA; USDA
MIKE SHE	Distributed and Physically Based Modeling System for Flow, Water Quality and Sediment	UK Institute of Hydrology and Danish Hydraulic Institute
SHE/SHESED	Basin Scale Water Flow and Sediment	University of Newcastle, UK
SWAT	Soil and Water Assessment Tool	Texas A&M, USDA ARS
SWRRBWQ	Simulator for Water Resources in Rural Basins	USDA ARS

Table 2: Details of Models sponsored by USDA which consider Phosphorus (selected information extracted from UDSA NCRS (2000), Jennings *et al* (2002))

Model Attributes	AGNPS98	SWAT	APEX	EPIC	GLEAMS	REMM	SRFR	WEND
HYDROLOGY								
Integrated Climate Generation	M	M	M	M		Y		
Surface water								
Overland flow	M	L	M	L	M	Y		
Channel Flow	L	L	M	L	M			
Lakes	L	L	M					
Wetlands	L		M					
Estuaries			M					
Subsurface Flow								
Soil moisture	M	L	M	M	M	Y		Y
Groundwater storage (aquifer)		L	M		L	Y		
Artificial drainage		L	M	L				
Lateral flow		L	M	L		Y		
SEDIMENT								
Erosion								
Sheet & Rill	M	M	M	M	M	M		
Stream Bed and Bank	M		M		L			
Transport								
Suspended	M	M	M		M		H	
Bed load	M		M			H	H	
Deposition	M	M	M		M		H	
Characteristics								
Particle size distribution	M	M	M		M	Y	H	
Organic/inorganic	M		M		M	M		
Yield	M	M			M	Y		
NUTRIENTS								
Phosphorus-Surface Water								
Fertiliser (inorganic)	M	M	M	M	H	Y	H	L
Manure (organic)	M	M	M	M	M	Y	H	L
Dissolved/particulate	M	M	M	M	M	Y	H	L
Total P	M	M	M	M	M		H	L
Phosphorus - Groundwater								
Fertiliser (inorganic)	?	?	M	M	M	Y	H	L

Table 2 (continued)

Model Attributes	AGNPS98	SWAT	APEX	EPIC	GLEAMS	REMM	SRFR	WEND
Manure (organic)	?	?	M	M	M	Y		L
Dissolved/particulate	?	?	M	M	M	Y	H	N
Total P	?	?	M	M	M	N	H	N
DATA REQUIREMENTS								
Climate								
precipitation	Y	Y	Y	Y	Y	N	Y	Y
temperature	Y	Y	Y	Y	Y	Y		N
Wind speed	Y		Y	Y	Y	Y		N
Humidity/dew pt./wet bulb temp	Y		Y	Y	N	Y		N
Solar radiation/sky cover/% cloud	Y		Y	Y	Y			N
Spatially distributed ?	Y	Y		N	N			N
Landscape characteristics								
Topography	Y	Y	Y	N	Y	Y	H	N
Soils	Y	Y	Y	Y	Y	N	H	Y
Land use/ landcover	Y	Y	Y	Y	Y		H	Y
Spatially distributed ?	Y	Y	Y			N	M	N
Management Activities								
Tillage	Y	Y	Y	Y	Y	N	L	Y
Crop rotation	Y	Y	Y	Y	Y	N		Y
Nutrient management	Y	Y	Y	Y	Y	N		Y
Conservation practices	Y	Y	Y	Y	Y	N		Y
MODEL OUTPUT								
Watershed Mass Balance								
Phosphorus		Y	Y			Y		Y
Nitrogen		Y	Y			Y		N
Lumped								
Time	Y	Y	Y	Y	Y	Y		Y
Spatial	Y	Y	Y	Y	Y	Y		Y
Distributed								
Time	Y	Y	Y	Y	Y	N		N
Spatial	Y	Y	Y		Y			N
Source tracking	Y				Y	N		N
Format								
Statistical		Y	Y	Y		Y		N
Graphical		Y				Y	Y	Y

Table 2 (continued)

Model Attributes	AGNPS98	SWAT	APEX	EPIC	GLEAMS	REMM	SRFR	WEND
Tabular	Y	Y	Y	Y	Y		Y	Y
GIS	Y	Y						N
Time Step								
Subdaily			Y			Y	Y	N
Daily	Y	Y	Y	Y	Y	Y		N
Monthly			Y		Y	N		N
Average annual			Y		Y	N	Y	Y
APPLICATION SPATIAL SCALE								
Point				Y	Y	N	Y	Y
Field	Y		Y	Y			Y	Y
Small watershed (<10 sq mile)	Y		Y					Y
Large watershed (10-400 sq mile)	Y	Y	Y			N		Y
River basin (>400 sq mile)		Y				Y		Y
APPLICATION TIME SCALE								
Continuous	Y	Y	Y	Y	Y			Y
Event	Y				Y	N	Y	N
Accumulative events	Y					Y		

L = Model element present, with a simplistic, empirical representation
M = Model element present, with a conceptual or moderately complex representation
H = Model element present, with a very detailed, sophisticated, physically based representation
? = model element present, complexity level unknown; Y = Yes; N = No; blank = No; - where applied

Table 3: Multiple Linear Regressions Table between Predicted and Calculated Log (TP export rates) (kg P ha^{-1} yr^{-1}) using equations *Jordan-1* and *Jordan-2* models.

Equation	Dependent variable is:	LExp			
4.12a	30 total cases of which 2 are missing R squared = 48.1% R squared (adjusted) = 39.1% s = 0.2303 with 28 - 5 = 23 degrees of freedom				
	Source	**Sum of Squares**	**df**	**Mean Square**	**F-ratio**
	Regression	1.132	4	0.283	5.34
	Residual	1.220	23	0.053	
	Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
	Constant	-2.689	0.577	-4.66	0.000
	LJ1	-0.785	0.296	-2.65	0.014
	Mean Elev	-0.005	0.001	-3.92	0.001
	Mean slope	0.196	0.050	3.95	0.001
	Rainfall	0.001	0.000	2.99	0.007
4.12b	R squared = 43.9% R squared (adjusted) = 34.9% s = 0.2331 with 30 - 5 = 25 degrees of freedom				
	Source	**Sum of Squares**	**df**	**Mean Square**	**F-ratio**
	Regression	1.061	4	0.265	4.88
	Residual	1.358	25	0.054	
	Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
	Constant	-2.282	0.544	-4.19	0.000
	LJ2	-1.045	0.426	-2.45	0.022
	Mean Elev	-0.005	0.001	-3.95	0.001
	Mean slope	0.189	0.051	3.69	0.001
	Rainfall	0.001	0.000	2.31	0.030

Table 4: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for all catchments (n=30) – Model 1

R squared = 67.3% R squared (adjusted) = 58.7%

s = 0.101 with 30 - 7 = 23 degrees of freedom

Source	**Sum of Squares**	**df**	**Mean Square**	**F-ratio**
Regression	0.482	6	0.080	7.87
Residual	0.235	23	0.010	

Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
Constant	-0.914	0.422	-2.16	0.041
Elevation	-0.002	0.001	-3.55	0.002
Slope	0.085	0.027	3.16	0.004
Soil Morgan P	0.055	0.026	2.13	0.044
Soil P Desorption Index	-0.292	0.089	-3.29	0.003
Rainfall 00-01	0.001	0.000	3.98	0.001
Mixed Grasslands	0.004	0.001	2.74	0.012

Table 5: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for acidic catchments (n=13) – Model 2

R squared = 87.2% R squared (adjusted) = 80.8%

s = 0.04749 with 13 - 5 = 8 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	0.123	4	0.031	13.6
Residual	0.018	8	0.002	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	-0.316	0.266	-1.18	0.270
Elevation	-0.002	0.000	-4.26	0.003
Rainfall 00-01	0.001	0.000	4.43	0.002
Soil P Desorption Index	-0.260	0.069	-3.77	0.006
Peatlands	-0.003	0.001	-4.08	0.004

Table 6: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for calcareous catchments (n=11) – Model 3

R squared = 96.1% R squared (adjusted) = 92.2%
s = 0.05468 with 11 - 6 = 5 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	0.370	5	0.074	24.8
Residual	0.015	5	0.003	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	-2.077	0.383	-5.42	0.003
Slope	0.255	0.048	5.33	0.003
Soil Morgan P	0.256	0.044	5.78	0.002
Mixed Grassland	0.007	0.003	2.71	0.042
Mixed Agri.	-0.012	0.003	-3.63	0.015
Peats	0.006	0.002	2.65	0.045

Table 7: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for non-peaty catchments (n=25) – Model 4

R squared = 68.5% R squared (adjusted) = 60.2%
s = 0.1044 with 25 - 6 = 19 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	0.450	5	0.090	8.26
Residual	0.207	19	0.011	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	-0.807	0.444	-1.82	0.085
Elevation	-0.005	0.001	-4.1	0.001
Slope	0.173	0.035	4.96	≤ 0.0001
Soil Morgan P	0.062	0.027	2.26	0.036
Soil P Desorption Index	-0.424	0.102	-4.15	0.001
Rainfall 00-01	0.001	0.000	4.02	0.001

Table 8: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for poorly drained catchments (n=12) – Model 5

R squared = 87.7% R squared (adjusted) = 81.5%

s = 0.08644 with 13 - 5 = 8 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	0.424	4	0.106	14.2
Residual	0.060	8	0.007	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	-1.833	0.500	-3.66	0.006
Elevation	-0.009	0.001	-5.91	0.000
Slope	0.151	0.031	4.82	0.001
Rainfall 00-01	0.002	0.000	4.47	0.002
Peatlands	0.013	0.005	2.61	0.031

Table 9: Multiple Linear Regressions Table predicting annual average TP export rates (kg P ha^{-1} yr^{-1}) for moderately drained catchments (n=13) – Model 6

R squared = 93.4% R squared (adjusted) = 85.4%

s = 0.04111 with 12 - 7 = 5 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	0.119	6	0.020	11.8
Residual	0.008	5	0.002	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	-1.091	0.421	-2.59	0.049
Peatlands	-0.006	0.001	-6.11	0.002
Conifers	-0.004	0.001	-3.71	0.014
Soil Morgan P	0.084	0.022	3.84	0.012
Soil P Desorption Index	-0.416	0.101	-4.11	0.009
Rainfall 00-01	0.001	0.000	4.89	0.005
Improved Grassland	-0.002	0.001	-3.14	0.026

APPENDIX 4: Lough Lickeen catchment

Table 1: M-ANOVA table (2 way-interactions), carried out on the lake water chemistry recorded between February 2002 and March 2003 among the four lakes of the Lough Lickeen catchment. In order to limit the influence of missing data on the analyses, an insignificant small quantity (10^{-6}) was added to the NO_3-N concentrations, to remove the "0" values from the datasets (corresponding at samples for which NO_3-N concentrations were lower than the detection limit), so that Log(NO_3-N) refers to Log(NO_3-N concentrations + 10^{-6}). Log(TN) was analysed separately, as 5 data were missing.

Results for Multivariate Test: Wilks Lambda Criterion

Source	Lambda	Prob	Approx F	df	err df
Const	0.0010	0.0000	17100.0	8	143
Season	0.7305	0.0000	6.6	8	143
Sampling Date	0.0360	0.0000	5.9	104	996
Lake	0.0450	0.0000	33.1	24	415
Season * Lake	0.5312	0.0000	4.2	24	415
Sampling Date * Lake	0.0151	0.0000	3.1	264	1131

Source	df	Wilks	Log(NO_3-N)	Log(TP)	Log(TDP)	Log(SRP)	Log(Chla)	Log(TDOC)	Log(Colour)	Log(Turbidity)
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Season	1	0.00	0.00	0.55	0.92	0.02	0.18	0.91	0.00	0.10
Sampling Date	13	0.00	0.00	0.00	0.00	0.00	0.00	0.92	0.00	0.00
Lake	3	0.00	0.30	0.00	0.00	0.00	0.65	0.00	0.00	0.00
Season * Lake	3	0.00	0.00	0.75	0.39	0.01	0.01	0.74	0.00	0.00
Sampling Date * Lake	33	0.00	0.00	0.00	0.00	0.00	0.00	0.97	0.00	0.00

Analysis of Variance ForLogTN 204 total cases of which 5 are missing
No Selector

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	0.969	0.969	93.92	≤0.0001
Season	1	0.001	0.001	0.08	0.7817
Sampling Date	13	0.304	0.023	2.26	0.0097
Lake	3	0.135	0.045	4.36	0.0057
Season * Lake	3	0.290	0.097	9.38	≤0.0001
Sampling Date * Lake	32	0.721	0.023	2.18	0.001
Error	146	1.507	0.010		
Total	198	3.449			

Table 2: Results of M-ANOVA (2 way-interactions) carried out on lake water chemistry results obtained for the shore lake samples in Lickeen (12 lake sites, 4 sampling occasions) between February and May 2002. In order to limit the influence of missing data on the analyses, Log(TN) was analysed separately.

Results for Multivariate Test: Wilks Lambda Criterion

Source	**Lambda**	**Prob**	**Approx F**	**df**	**err df**
Const	0.00000		-635000.0	3	
Sampling Date	0.00000	0.0000	5920.0	9	3
Replicate	0.93800	0.5693	0.7	3	31
Sampling Date*Replicate	0.87090	0.8764	0.5	9	76
Site	0.00023	0.0000	13.4	33	27
Sampling Date*Site	0.00010	0.0000	19.3	99	94
Replicate*Site	0.27040	0.0510	1.6	33	92

Source	**df**	**Wilks**	**Log(TP)**	**Log(SRP)**	**Log(NO_3-N)**
Const	1		0	0	0.01
Sampling Trip	3	0.00	0.00	0.00	0.00
Replicates	1	0.57	0.66	0.49	0.31
Sampling Trip * Replicates	3	0.88	0.83	0.84	0.41
Site	11	0.00	0.00	0.00	0.02
Sampling Trip * Site	33	0.00	0.00	0.00	0.00
Replicates * Site	11	0.05	0.35	0.01	0.48

Analysis of Variance For **Log(TN)** *96 total cases of which 1 is missing*

No Selector

Source	**df**	**Sums of Squares**	**Mean Square**	**F-ratio**	**Prob**
Const	1	1.153	1.153	1183.1	0.0185
Sampling Trip	3	0.125	0.042	21.9	0.0153
Replicates	1	0.001	0.001	1.0	0.3331
Sampling Trip * Replicates	3	0.006	0.002	1.9	0.1503
Site	11	0.498	0.045	37.4	≤0.0001
Sampling Trip * Site	33	0.861	0.026	25.9	≤0.0001
Replicates * Site	11	0.013	0.001	1.2	0.3266
Error	32	0.032	0.001		
Total	94	1.546			

Table 3: Results of M-ANOVA (2 way-interactions) carried out on lake water chemistry results obtained for the shore and middle-lake samples in Lickeen (12 lake sites, 10 sampling occasions). In order to limit the influence of missing data on the analyses, Log(TN) was analysed separately.

Results for Multivariate Test: Wilks Lambda Criterion

Source	Lambda	Prob	Approx F	df	err df
Const	0.0000	0.00	322000.0	11	78
Sampling Date	0.0006	0.00	10.4	99	561
Lake sample	0.7899	0.05	1.9	11	78
Sampling Date * Lake sample	0.2207	0.02	1.4	99	561

Source	df	Wilks	Log(NO_3-N)	Log(TP)	Log(TDP)	Log(SRP)	Log(Chla)	Log(TDOC)	pH	Log(Alk)	Log(Cond)	Log(Colour)	Log(Turb)
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sampling Date	9	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.53	0.92	0.00	0.00	0.00
Lake sample	1	0.05	0.99	0.13	0.84	0.31	0.65	0.41	0.74	0.89	0.15	0.02	0.15
Sampling Date * Lake sample	9	0.02	0.38	0.34	0.99	0.45	0.94	0.10	0.92	0.84	1.00	0.00	0.30

Analysis of Variance For **Log(TN)** ***108 total cases of which 4 are missing***

No Selector

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	0.415	0.415	64.806	$\leq$0.0001
Sampling Date	9	0.330	0.037	5.726	$\leq$ 0.0001
Lake sample	1	0.003	0.003	0.539	0.4647
Sampling Date * Lake sample	8	0.210	0.026	4.101	0.0004
Error	85	0.544	0.006		

Table 4: M-ANOVA table (2 way-interactions), carried out on the lake water chemistry recorded between July 2002 and March 2003 between the site lake Middle B and overall lake averages. In order to limit the influence of missing data on the analyses, an insignificant small quantity (10^{-6}) was added to the NO_3-N concentrations, to suppress the "0" values from the datasets (corresponding at samples for which NO_3-N concentrations were lower than the detection limit), so that Log(NO_3-N) refers to Log(NO_3-N concentrations + 10^{-6}). Log(TN) was analysed separately, as 1 set of data was missing.

Results for Multivariate Test: Wilks Lambda Criterion

Source	Lambda	Prob	Approx F	df	err df
Const	0.000	0.00	31100.0	7	3
Sampling Date	0.000	0.00	22.0	63	23
Site type	0.463	0.80	0.5	7	3

Source	df	Wilks	Log(NO_3-N)	Log(TP)	Log(TDP)	Log(SRP)	Log(Chla)	Log(Alk)	Log(Colour)
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SD	9	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00
ST	1	0.80	0.58	0.51	0.96	0.24	0.84	0.35	0.20

Analysis of Variance For **Log(TN)**

20 total cases of which 1 is missing

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Const	1	0.084	0.084	23.8	0.0012
Sampling Date	9	0.070	0.008	2.2	0.1373
Site type	1	0.004	0.004	1.3	0.2916
Error	8	0.028	0.004		
Total	18	0.102			

Table 5: M-ANOVA table (2 way-interactions), carried out on the shore-lake water chemistry recorded between February 2002 and March 2003, differentiating the sites between "inlet stream" and "no stream" sites. In order to limit the influence of missing data on the analyses, an insignificant small quantity (10^{-6}) was added to the NO_3-N concentrations, to suppress the "0" values from the datasets (corresponding at samples for which NO_3-N concentrations were lower than the detection limit), so that Log(NO_3-N) refers to Log(NO_3-N concentrations + 10^{-6}).

Results for Multivariate Test:	**Wilks**	**Lambda**	**Criterion**		
Source	**Lambda**	**Prob**	**Approx F**	**df**	**err df**
Const	0.000	0.00	172000.0	12	95
Season	0.167	0.00	39.4	12	95
Sampling Date	0.000	0.00	10.3	156	865
Inlet	0.802	0.04	2.0	12	95
Season * Inlet	0.884	0.42	1.0	12	95
Sampling date * Inlet	0.194	0.16	1.1	156	865

Source	**df**	**Wilks**	**Log(NO_3-N)**	**Log(TN)**	**Log(TP)**	**Log(TDP)**	**Log(SRP)**	**Log(Chla)**	**Log(TDOC)**	**pH**	**Log(Alk)**	**Log(Cond)**	**Log(Colour)**	**Log(Turb)**
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Season	1	0.00	0.00	0.06	0.58	0.39	0.00	0.00	0.09	0.00	0.00	0.09	0.00	0.07
Sampling Date	13	0.00	0.00	0.00	0.13	0.00	0.00	0.08	0.00	0.00	0.03	0.00	0.00	0.00
Inlet	1	0.04	0.07	0.16	0.15	0.84	0.81	0.73	0.80	0.02	0.34	0.13	0.55	0.05
Season * Inlet	1	0.42	0.40	0.79	0.67	0.85	0.61	0.45	0.85	0.13	0.92	0.03	0.56	0.88
Sampling date * Inlet	13	0.16	0.33	0.29	0.30	0.99	0.97	0.57	1.00	0.00	0.63	0.11	0.52	0.00

Table 6: Results of Stepwise multiple linear regression carried out on the different lake chemical variables to predict the variations of Log(Chl-a)

Dependent variable is:	**LogChla**			
No Selector				
165 total cases of which 24 are missing				
R squared = 53.2% R squared (adjusted) = 51.9%				
s = 0.1972 with 141 - 5 = 136 degrees of freedom				
Source	**Sum of Squares**	**df**	**Mean Square**	**F-ratio**
Regression	6.0201	4	1.5050	38.7
Residual	5.2886	136	0.0389	
Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
Constant	-2.1897	0.4303	-5.09	≤ 0.0001
LogTP	0.6903	0.0933	7.40	≤ 0.0001
LogAlk	1.6371	0.2722	6.01	≤ 0.0001
LogNO_3	-0.2575	0.0456	-5.65	≤ 0.0001
LogColour	-0.2458	0.0674	-3.65	0.0004

Table 7: M-ANOVA table (2 way-interactions), carried out on the stream water chemistry, derived from the monitoring between February 2002 - March 2003. In order to limit the influence of missing data on the analyses, an insignificant small quantity (10^{-6}) was added to the NO_3-N concentrations as well as to the alkalinity levels, to suppress the "0" values from the datasets (corresponding at samples for which NO_3-N concentrations were lower than the detection limit), so that Log(NO_3-N) refers to Log(NO_3-N concentrations + 10^{-6}) and Log(Alk) to Log(Alk + 10^{-6}).

Results for Multivariate Test: Wilks Lambda Criterion

Source	Lambda	Prob	Approx F	df	err df
Const	0.000	0.000	54300.0	11	292
Stream	0.073	0.000	10.7	88	1924
Season	0.409	0.000	38.4	11	292
Stream * Season	0.560	0.000	2.0	88	1924
Sampling Date	0.118	0.000	5.0	143	2492
Stream * Sampling Date	0.032	0.183	1.0	1144	3237

Source	df	Wilks	Log(NO_3-N)	Log(TN)	Log(TP)	Log(TDP)	Log(SRP)	Log(TDOC)	pH	Log(Alk)	Log(Cond)	Log(Colour)	Log(Turb)
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stream	8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Season	1	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stream * Season	8	0.00	0.58	0.02	0.00	0.00	0.00	0.36	0.97	0.99	0.99	0.77	0.02
Sampling Date	13	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.71	0.89	0.00	0.00	0.00
Stream * Sampling Date	104	0.18	0.97	0.00	0.05	0.35	1.00	0.25	1.00	1.00	1.00	1.00	0.36

Table 8: M-ANOVA table (2 way-interactions), carried out on the site water chemistry, recorded from February 2002 until March 2003. In order to limit the influence of missing data on the analyses, an insignificant small quantity (10^{-6}) was added to the NO_3-N concentrations as well as to the alkalinity levels, to suppress the "0" values from the datasets (corresponding at samples for which NO_3-N concentrations were lower than the detection limit), so that Log(NO_3-N) refers to Log(NO_3-N concentrations + 10^{-6}) and Log(Alk) to Log(Alk + 10^{-6}).

Results for Multivariate Test: Wilks Lambda Criterion

Source	Lambda	Prob	Approx F	df	err df
Const	0.001	0.000	59800.0	11	367
Sampling Site	0.005	0.000	7.9	319	3817
Season	0.433	0.000	43.7	11	367
Sampling Site * Season	0.262	0.000	1.7	319	3817

Source	df	Wilks	Log(NO_3-N)	Log(TN)	Log(TP)	Log(TDP)	Log(SRP)	Log(TDOC)	pH	Log(Alk)	Log(Cond)	Log(Colour)	Log(Turb)
Const	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sampling Site	29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Season	1	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sampling Site * Season	29	0.00	0.00	0.18	0.05	0.02	0.00	0.90	0.56	0.40	0.00	0.02	0.00

Table 9: M-ANOVA carried out on the results for soil SRPw, TDPw and soil Morgan P analyses carried out on replicates of samples (n=262) collated in February, July and October 2002 in the Lough Lickeen Catchment.

Results for Multivariate Test: Wilks Lambda Criterion					
Source	**Lambda**	**Prob**	**Approx F**	**df**	**err df**
Constant	0.0002	0.0000	129000.0	3	77
Date	0.0160	0.0000	177.0	6	154
Site	0.0004	0.0000	21.3	132	232
Date*Site	0.0004	0.0000	11.8	246	232
Replicates	0.9812	0.6885	0.5	3	77
Date*Replicates	0.9370	0.5341	0.8	6	154
Site*Replicates	0.2092	0.1111	1.2	132	232

Source	**df**	**Wilks**	**Log(SRPw)**	**Log(TDPw)**	**Log(Morgan P)**
Constant	1	0.00	0.00	0.00	0.00
Date	2	0.00	0.00	0.00	0.00
Site	44	0.00	0.00	0.00	0.00
Date*Site	82	0.00	0.00	0.00	0.00
Replicates	1	0.69	0.26	0.33	0.90
Date*Replicates	2	0.53	0.18	0.40	0.63
Site*Replicates	44	0.11	0.57	0.07	0.05

Table 10: Stepwise multiple regression (Equation 5.8) carried out on the sub-catchment datasets (n=31), predicting the variations of Log(annual average TP loading rates) (n=31).

Dependent variable is: **Log(TP loading rates)**

No Selector

R squared = 59.9% **R squared (adjusted) = 53.7%**
s = 0.1969 with 31 - 5 = 26 degrees of freedom

Source	**Sum of Squares**	**df**	**Mean Square**	**F-ratio**
Regression	1.505	4	0.376	9.71
Residual	1.008	26	0.039	

Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
Constant	0.056	0.429	0.13	0.896
Mean Elevation	-0.007	0.002	-3.64	0.001
Soil P Desorption Index	-0.292	0.126	-2.32	0.029
Log(Soil %OM)	0.328	0.157	2.09	0.047
% Mixed grassland	0.004	0.001	2.84	0.009

Table 11: Stepwise multiple regression (Equation 5.9) carried out on the sub-catchment datasets (n=31), predicting the variations of Log(annual average TP loading rates) (n=31).

Dependent variable is:	**Log(TP loading rates)**
No Selector	

R squared = 53.2% R squared (adjusted) = 48.0%
s = 0.2087 with 31 - 4 = 27 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	1.337	3	0.446	10.20
Residual	1.176	27	0.044	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	0.608	0.358	1.70	0.101
Mean Elevation	-0.008	0.002	-3.83	0.001
Soil P Desorption Index	-0.318	0.133	-2.39	0.024
% Mixed grassland	0.004	0.001	3.07	0.005

Table 12: Stepwise multiple regression (Equation 5.14) carried out on the sub-catchment datasets, excluding site 6a (n=30), predicting the variations of Log(annual average TP loading rates) (n=30).

Dependent variable is:	**Log(Calculated TP Loading Rates)**
No Selector	

R squared = 55.6% R squared (adjusted) = 50.4%
s = 0.1756 with 30 - 4 = 26 degrees of freedom

Source	Sum of Squares	df	Mean Square	F-ratio
Regression	1.002	3	0.334	10.80
Residual	0.801	26	0.031	

Variable	Coefficient	s.e. of Coeff	t-ratio	prob
Constant	1.351	0.343	3.94	0.001
Log(GIS-Model1 TP Loading Rates)	0.978	0.364	2.69	0.012
Soil P Desorption Index	-0.394	0.112	-3.51	0.002
Mean elevation (m)	-0.007	0.002	-3.92	0.001