Nutrient Inputs and Trophic Status of Larne Lough

M. Charlesworth,& M. Service*

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*Department of Agriculture (NI)

Executive Summary

Larne Lough is a coastal embayment on the north-east coast of Ireland, and is an important economic and environmental resource supporting a wide range of interests. The aims of this project were to investigate the trophic status of Larne Lough with regards to European legislation. This was achieved by the calculation of nutrient loads to the system, the collection of water quality, algal biomass, and hydrographic data. The data was then analysed using mathematical modelling.

The load of Dissolved Inorganic Nitrogen (DIN) to Larne Lough is dominated by contributions by riverine inputs. STWs contributed an average of 18% to the total load of DIN to the Lough during the spring and summer months. Salinity within the Lough is generally greater than 33 psu demonstrating the predominantly marine nature of the Lough. Soluble Reactive Phosphorous (SRP), Silicate (SiO_2), Nitrate (NO_3) and Ammonium (NH_4) concentrations are highest in the winter and lowest in the summer, due to greater loads during the winter and biological uptake during the summer. Winter concentrations of DIN and DIP show that they are not elevated above the background levels for this area. Winter N:P and N:Si ratios are not elevated. Chl a (Chlorophyll *a*) concentrations do not exceed > 10 μg l^{-1}. Higher concentrations are generally observed towards the southern part of the Lough.

Mathematical modelling shows that the flushing time of the Lough is less than 1 day, and therefore nutrient concentrations within the Lough are predominantly a reflection of concentrations in the North Channel. Predicted nutrient concentrations within the Lough were close to observed values, suggesting that the effect of internal processes on nutrient concentrations is small relative to the flushing time of the Lough. Significant negative relationships between Chl *a* and DIN were only observed on 2 sampling dates. This in combination with sufficient nutrient concentrations to maintain algal growth suggest that physical exchange is the predominant limitation to phytoplankton production in Larne Lough. It is suggest that the residence time is greater in the southern part of the Lough which gives rise to higher Chl *a* concentrations observed in this region. Classification of the Lough under criteria to assess trophic status (DEFRA, 2002) show that the Lough is presently not eutrophic or likely to become eutrophic in the future.

Contents

Acknowledgements

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The Environment and Heritage Service (DOENI) provided flow and nutrient data for STWs and rivers discharging into the Lough.

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Chapter

1

Introduction

Larne Lough is a shallow marine embayment on the east coast of Northern Ireland enclosed by the peninsula of Island Magee. Riverine, domestic and industrial inputs to the Lough have the potential to detrimentally effect the environmental quality within the Lough. The aims of this project were to investigate the trophic status by the collection of water quality, primary productivity and hydrographic data, in addition to calculation of nutrient loads into the system. The outputs of this report are then to use the data to classify the Lough under the Nitrates (91/676/EEC) and Urban Waste Water Treatment Directives (UWWT) (91/271/EEC).

1.1. Bathymetry, Hydrology and Catchment Characteristics.

The Lough is generally spilt into north and south embayments at Barneys Point (Figure 1.1.). The south embayment is generally < 5m in depth and largely composed of intertidal mud flats. The northern embayment has a deep channel running along the eastern shore of approximately 10m depth with the remainder of the Lough being predominantly < 5m depth with large mud flats to the west. The shipping channel at the mouth of the Lough is regularly dredged to maintain an adequate depth.

The Glynn and Larne Rivers are the predominant freshwater inputs (catchments of 27 and 43 km^2 respectively) which are relatively small in comparison to the large water exchange between Larne Lough and the North Channel with each tidal cycle which has a mean range of 2.4m. Therefore, the Lough is almost totally marine in nature (IRTU, 1995). Physical characteristics of Larne Lough are shown in Table 1.1.

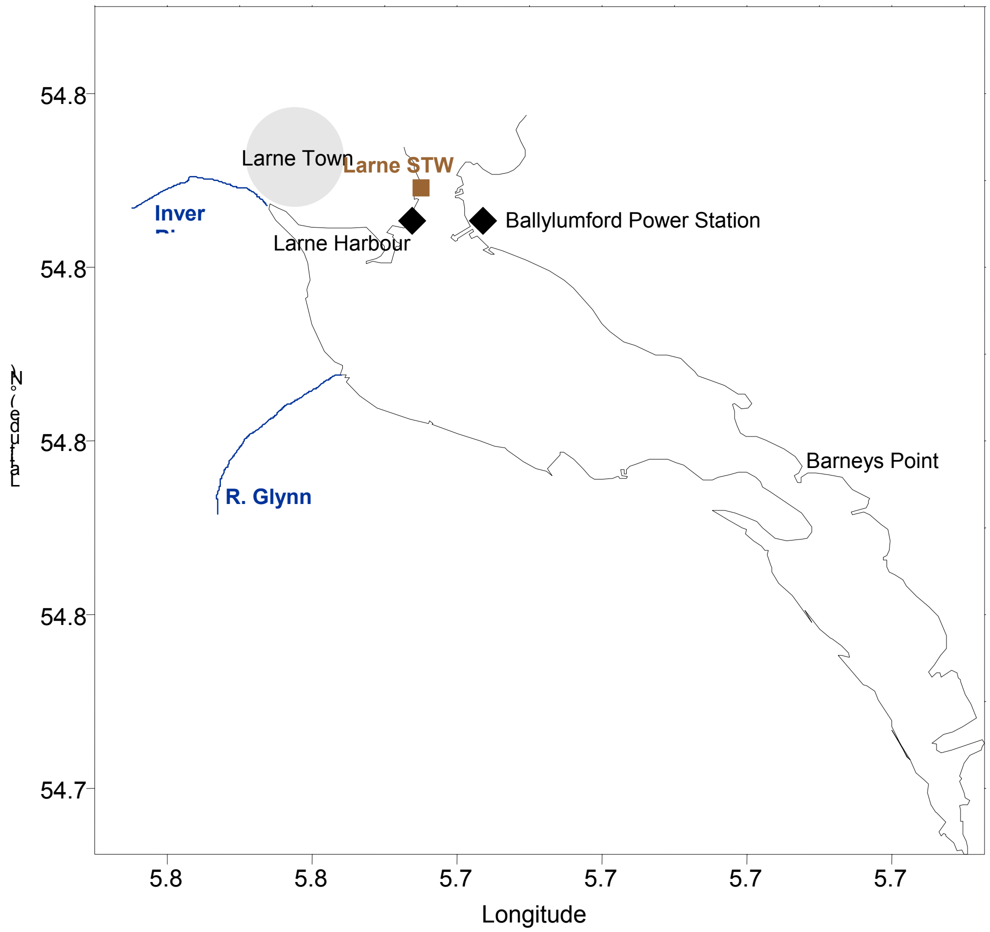

Figure 1.1. Larne Lough.

Table 1.1. Physical characteristics of Larne Lough and catchment (Buck and Donaghy, 1996; Service *et al.*, 1998).

Catchment area (km^2)	Low water volume ($10^6 m^3$)	Freshwater runoff ($10^6 m^3 yr^{-1}$)	Total area (ha)	Intertidal area (ha)
115	12	101	1,189	393

The catchment of Larne Lough is predominantly used for pasture. The largest conurbation is Larne Town which lies on the north-west corner of the Lough. Urban storm water from Larne Town drains into the Inver River.

1.2. Uses

1.2.1. Shellfisheries

There are six licenced shellfishery sites in Larne Lough occupying a combined total of 89ha centered around Barneys Point (Moore and Service, 2001). These sites produce native and pacific oysters (trestle) and mussels (bottom culture). Recreational fishing occurs within the Lough and mussel and winkles are picked at intertidal sites predominantly in the south of the Lough. There is also an active lobster pot fishery within the Lough.

1.2.2. Effluent Disposal

Of most relevance to this report is the discharge of nutrients needed for algal growth (C, N, P, and SiO_2) and chemical contaminants that may detrimentally effect the ecosystem. The sources of nutrients are detailed in Chapter 2, however a brief description will be given here. As previously discussed riverine inputs from the Larne and Glen are relatively small. The main sewage treatment works (STW) is based at Larne, which has a Population Equivalent (PE) of 26,345 and discharges preliminary treated sewage directly to the main shipping channel at Sandy Point. Other smaller STW include Glynn, Ballycarry and Ballystruder which have PEs of < 1500. There are no large inputs of nutrients from industrial sources but it is of note that the power station at Ballylumford removes and disposes of water at the mouth of the Lough for cooling.

1.2.3. Nature Conservation

With the exception of the build up areas at the mouth of the Lough, all of the intertidal zone covering an area of 398ha, has been designated as a SPA and ASSI. Much of this area covers the mud flats in the south and west of the Lough

1.2.4. Recreational

Power-boating, canoeing, and water-skiing are recreational pursuits that are largely concentrated on the eastern side of the Lough.

1.3. Previous Studies

IRTU (1995) reported that on 7 dates over the course of a year, maximum nutrient concentrations were observed in winter and maximum chlorophyll concentrations were observed in summer which is typical of other temperate marine environments. IRTU (1995) also suggested that due to the highly marine nature of Larne Lough, it had lower concentrations of nutrients relative to other Northern Irish sea-Loughs. Service *et al.* (1998) calculated that the DIN load to Larne Lough was dominated by loads from the catchment rather than inputs from STWs.

Kirk McClure and Morten Consultants (1992) built a mathematical model to evaluate the environmental impact of the discharge from Larne STW on the nieghbouring bathing water at Browns Bay.

IRTU (2002) undertook a survey of the seabed at the sewage outfall at Sandy Bay and compared this to a site within Larne Lough. They concluded that the Sandy Bay site was more impacted than the site within the Lough although both sites had elevated concentrations of metals and the biological data suggested that they were ‘unpolluted’ but showed a tendency towards ‘moderate’ pollution levels.

Several published studies have shown that sediments and mussels within the Lough have concentrations of contaminants at similar levels to that from other northern Irish coastal sediments However, a number of ‘hot spots’ of greater contamination do occur close to known sources of anthropogenic inputs and activities (Gault *et al.*, 1983; Charlesworth and Service, 2000; Charlesworth *et al.*, 2001; Guinan *et al.*, 2001; Charlesworth 2003).

1.4. Eutrophication and EC legislation

1.4.1. The Concept of Eutrophication

Eutrophication is defined by UWWTas " the enrichment of water by nutrients, especially by compounds of nitrogen and phosphorous, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable balance of organisms in the water concerned" (EEC, 1991). This definition shows that eutrophication encompases a number of effects that are caused by an enrichment in nutrients, which leads to an increase in algal growth that in turn leads to an undesirable balance. Eutrophication is not a recent phenomenon in Irish coastal waters and was identified in Belfast and Dublin harbours at the beginning of this century (Lett and Adeney, 1908; Adeney, 1908). Increased public awareness and the introduction of EC legislation has promoted eutrophication to be one of the most important concerns regarding the health of the coastal environment today.

The growth of aquatic plants is regulated by biological, chemical and physical factors. Of the chemical factors, N and P (and to a lesser extent Si and C^{org}) may only be available in limited amounts, and thus if other conditions are favorable, the growth of algae may also be limited. Thus, an increase of nutrient loading to a water body may induce a further increase in primary production and hence algal biomass. A schematic representation of the interaction between phytoplankton growth and nutrient dynamics is shown in Fig 1.2.

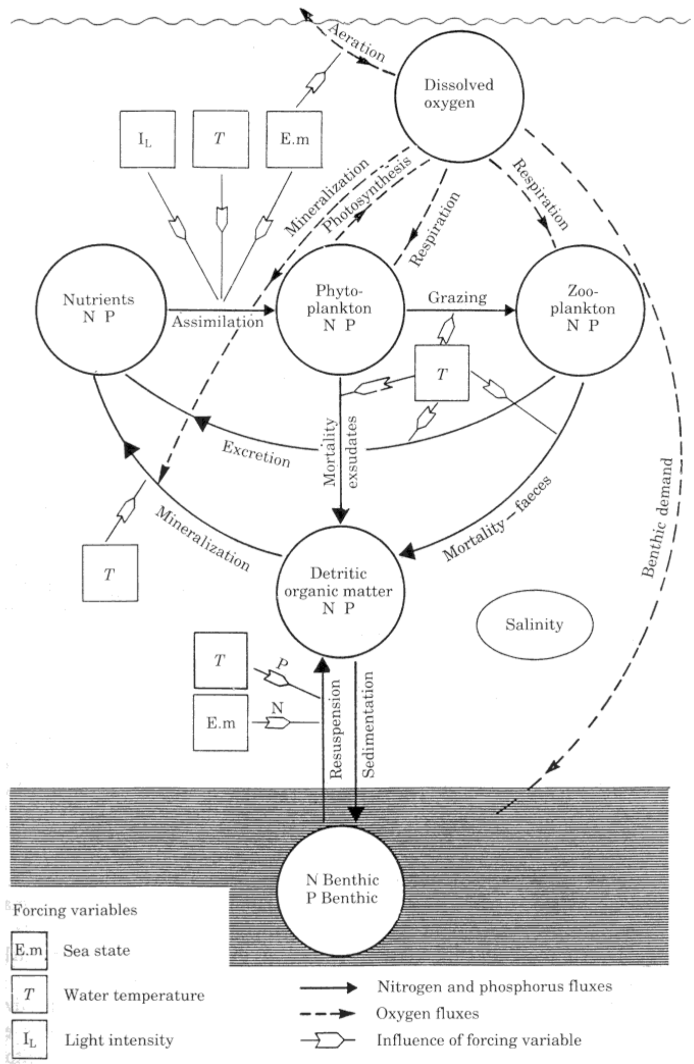

Figure 1.2. Conceptual diagram of phytoplankton growth and nutrient dynamics (from Chapelle *et. al.* 1994).

An increase in primary production may be beneficial to an ecosystem, however too much may lead to eutrophication which could result in adverse effects to the health of the aquatic environment (Ryther and Officer, 1981). Defining the point at which a water body may be considered eutrophic is obviously difficult and is often operationally defined.

The detrimental effect of eutrophication manifests itself in a number of guises stemming from increased primary productivity such as the localised growth of filamentous macro-algae as found in Dublin Bay (Jeffrey, 1998) or extensive and sustained blooms of dinoflagellates as found in the Tidal Lagan impoundment (Charlesworth and Service, 1999). The effects of eutrophication can include: changes in species composition, toxic algal blooms, oxygen depletion leading to the death of aquatic life, and the formation of algal scums. These effects have economic and environmental consequences.

Direct sources of nutrients to coastal waters include agricultural run-off via stream and riverine inputs, domestic sewage, atmospheric inputs, and industrial sources. The importance of each source varies greatly between different systems. Nutrients are subject to many internal biogeochemical processes. Some of these processes recycle nutrients in the water column and sediments, from unavailable chemical species to those that may be used for algal growth. The importance of the internal processes regenerating nutrients compared to the external inputs of nutrients largely depends on the residence time of the water body compared to the time scales of the internal processes.

Other factors that are important in controlling algal growth are light, temperature, water column physical characteristics, and physical exchange. Factors that induce a loss of suspended algal cells include grazing pressure from sessile and motile organisms, sedimentation, and loss by physical exchange out of the system of consideration.

1.4.2. Identification and classification of eutrophication in marine waters.

As previously discussed the classification of marine waters is somewhat arbitary, however a number of schemes have been proposed that aim to simplify and make the comparison between different spatial and temporal trophic situations more consistant. Karydis, (1994) suggested the use of a numerical classification scheme utilising outlying observations of nitrate, ammonia, phosphate and chlorophyll 'a'. Vollenweider *et. al.*

(1998) proposed the use of an index based on chlorophyll, oxygen saturation, mineral and total nitrogen and phosphorous.

To specifically assess the trophic status of Northern Irish coastal waters in accordance with EC Directives a number of criteria were defined by the DOE(NI) (1993) in line with other UK authorities:

- Nitrate-N concentrations significantly enhanced relative to background
- Occurrence of exceptional algal blooms
- Duration of algal blooms
- Oxygen deficiency
- Changes in fauna
- Changes in macrophyte growth
- Occurance of Paralytic Shellfish Poisoning (PSP)
- Formation of algal scums.

The UK issued further guidance in 1997 (MPMMG, 1997) and this was updated in 2002 (DEFRA, 2002) which aligns more closely with the OSPAR Common Assessment Criteria for Eutrophication. These criteria to identify eutrophic areas are:

Category 1. Causative parameters and prediction of potential adverse effects

- Trends and source apportionment of DIN and DIP (Dissolved inorganic phosphate) loadings.
- Winter concentrations of DIN and DIP elevated 50% above region specific background
- Winter ratios of N:P and N:Si elevated 50% above region specific background.

Category 2. Response Parameters

- Planktonic algal biomass and duration of blooms. Concentrations above 10µg chl *a* l^{-1} are considered elevated.
- Occurrence of exceptional or unusual algae blooms. Phytoplankton species which have the potential to cause toxins.

- Changes in Macrophyte/Macroalgae growth. Presence of opportunistic species indicative of nutrient enrichment conditions.

Category 3. Parameters for secondary and other effects

- Oxygen deficiency
- Changes in fauna
- Formation of algae scums on beaches
- Occurrence and magnitude of PSP

1.4.3. Legislation

The EC controls eutrophication in marine waters under two Directives. These Directives state that where a water body is found to be eutrophic, or may become eutrophic if preventative action is not taken, management strategies must be implemented. These two directives are:

- 91/676/EEC on the protection of waters against pollution caused by nitrates from agricultural sources. If a water body is found to be eutrophic or may become eutrophic in the future if preventative action is not taken then it must be designated as a 'polluted water' and then codes of good agricultural practice to reduce water pollution within the catchment area must be implemented.
- 91/271/EEC concerning urban waste water treatment directive (UWWT). This Directive lays down minimum standards for sewerage systems and treatment, which vary according to the size of the sewage works and nature of the receiving water. If the water body is found to be eutrophic or may become eutrophic in the future then the area must be designated as a 'sensitive'.

The Water Framework Directive (WFD) aims to have good ecological status status in water bodies by 2015. The WFD does not specifically mention eutrophication but under the WFD, the primary difference between 'good' and 'moderate ecological status' for plant quality elements in coastal waters is linked to the terms 'accelerated growth' and 'undesirable disturbance'.

<table>
<tr><td colspan="3">Annex V - WFD</td></tr>
<tr><td colspan="3">Extract from 1.2.4 – Definitions for good and moderate status in coastal waters</td></tr>
<tr><td></td><td>Good Status</td><td>Moderate Status</td></tr>
<tr><td>Phytoplankton</td><td>The composition and abundance of phytoplanktonic taxa show slight signs of disturbance.

There are slight changes in biomass compared to type specific conditions. Such changes do not indicate any accelerated growth of algae resulting in an undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water.

A slight increase in the frequency and intensity of type specific planktonic blooms may occur.</td><td>The composition and abundance of planktonic taxa show signs of moderate disturbance.

Algal biomass is substantially outside the range associated with type-specific reference conditions and is such as to impact on other biological quality elements.

A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur in summer months.</td></tr>
<tr><td>Macroalgae and angiosperms</td><td>Most disturbance-sensitive macroalgal and angiosperm associated with undisturbed conditions are present.

The level of macroalgal cover and angiosperm abundance show slight signs of disturbance.</td><td><u>A moderate number of disturbance-sensitive macroalgal and angiosperm associated with undisturbed conditions are absent.</u>

Macroalgal cover and angiosperm abundance is moderately disturbed and may be such as to result in an undesirable disturbance in the balance of organisms present in the water body.</td></tr>
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</table>

The WFD implies that a eutrophic water body i.e. one with accelerated growth of algae and higher forms of plant life and/or an undesirable disturbance to the balance of organisms present by definition could not be described as being at ‘good status’ under the WFD. The WFD works on a ‘one out – all out’ principle at the quality element level, so an undesirable disturbance in macroalgae & angiosperms **or** a downgrading in the phytoplankton quality element, would constitute a failure to meet good ecological status. At this stage, classification tools for each of these quality elements are still under development.

Chapter 2

Nutrient Inputs

2.1. Introduction

Nutrient loads to Larne Lough have been calculated so that seasonal trends may be identified and the importance of each source quantified. This data may then be used to aid the explanation of trends in chemical parameters in the water body. When considering the magnitude and impact of inputs from the various sources, it must be borne in mind the volume of water it is discharged into, and the dispersive capacity of that water. The data used for the production of this chapter can be found in the attached disk under the directory '*Inputs*'.

2.2. Methods

Calculation of nitrogen and phosphorus inputs to Larne Lough were conducted in the following manner. Analytical methods follow that of Taylor *et. al.* (1999).

- *Sewage Treatment Works*. The STWs considered in this study are, Larne (Sandy Bay), Glynn, Ballycarry and Ballystrudder with PE's of 26345, 875, 1153 and 900 respectively as shown in Figure 2.1. Nutrient monitoring data was provided by the Water Service. In months when more than one data point is available the average has been taken. If data was only available on a bimonthly basis then the average of the two months has been used. Flow data is not available for any STWs. An analysis of the PEs and detailed flow data for other STWs in the Foyle catchment suggests that 250l per person per day is a reasonable estimate to calculate flows (Appendix 1). Flow data has then been multiplied by nutrient concentration to give loads in t $month^{-1}$.

  Monitoring data for Larne STWs is only available from April 1996 to April 1999 and so does not cover the period of this study. To estimate loads from Larne STW from April 1999 onwards the monthly average of the monitored period has been used. Larne STWs discharges to the main shipping channel at Sandy Bay in Larne and thus is not considered a direct input to the Lough itself but clearly much of the effluent enters the Lough. The discharge is buoyant and subject to wind conditions (KMM, 1992) however, the tidal regime will predominantly transfer half of this discharge into the Lough on the flood tide while half will be washed out on the ebb. Therefore 50% the total load has been taken as contribution to nutrient loading from Larne STW to the Lough.

- *Rivers*. Nutrient monitoring data for the Larne and Glynn Rivers was provided by EHS and supplemented by sampling during the period of this project. Flow data has been estimated and provided by EHS on a monthly basis. Nutrient concentrations were then multiplied by flow to give loads in t month^{-1}. The catchment of the Larne and Glynn rivers are 43 and 27 km^2 respectively and the total catchment of Larne Lough is 115km^2. To account for riverine loads from the remaining unmonitored catchment, the total load from the Larne and Glynn Rivers has multiplied on a pro-rata basis for the remainder of the catchment.

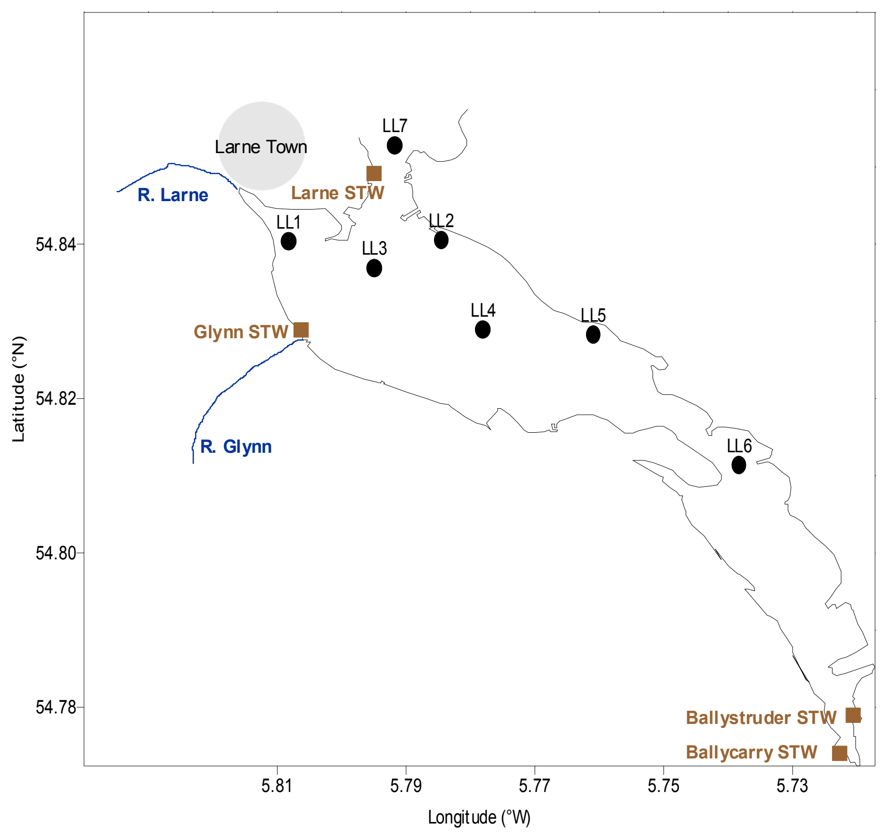


Figure 2.1. Considered inputs of nutrients to Larne Lough. Marine monitoring stations also shown.

2.3. Results

2.3.1. TON

The average monthly load of TON from the rivers is 15 t $month^{-1}$ which represents 98% of the load to the Lough. STWs only contribute an average of 0.34 t $month^{-1}$. As would be expected the load from the rivers is seasonal with highest loads in the winter months (Figure 2.2). Figure 2.3. shows that the load of TON is roughly similar from the Rivers Inver and Glynn and the remaining catchment.

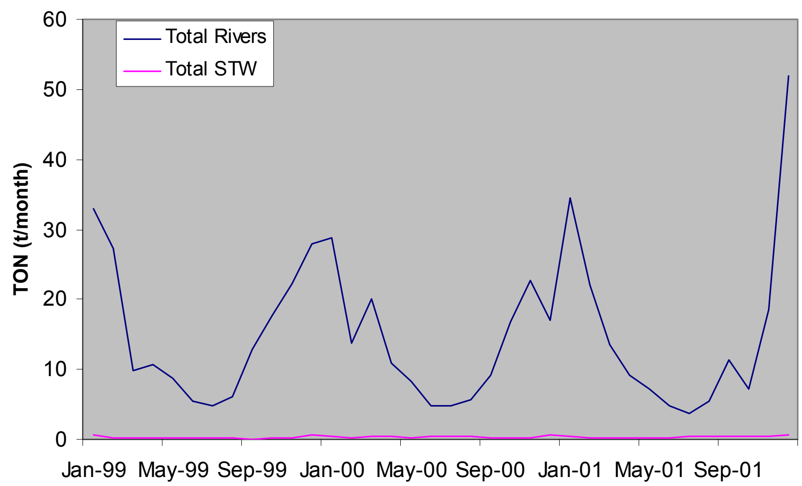


Figure 2.2. Loads of TON from rivers and STWs.

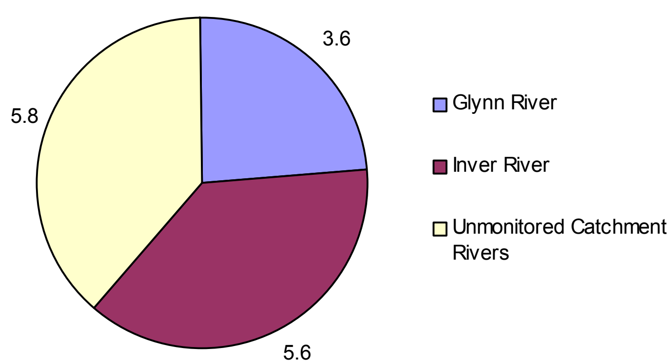


Figure 2.3. Average loads (1999-2001) of TON from the Rivers Inver, Glynn and the remaining catchment

2.3.2. NH_4

Inputs of NH_4 to Larne Lough are predominantly from the STWs with an average load of 1.2 t month^{-1} representing 67% of the total load to the Lough. The riverine sources contribute an average load of 0.58 t month^{-1}. Inputs from STWs remain similar throughout the year whereas riverine sources are seasonal (Figure 2.4). Larne STW accounts for 75% of the NH_4 input from STWs (Figure 2.5), whereas the rivers and remaining catchment contribute approximately equal proportions

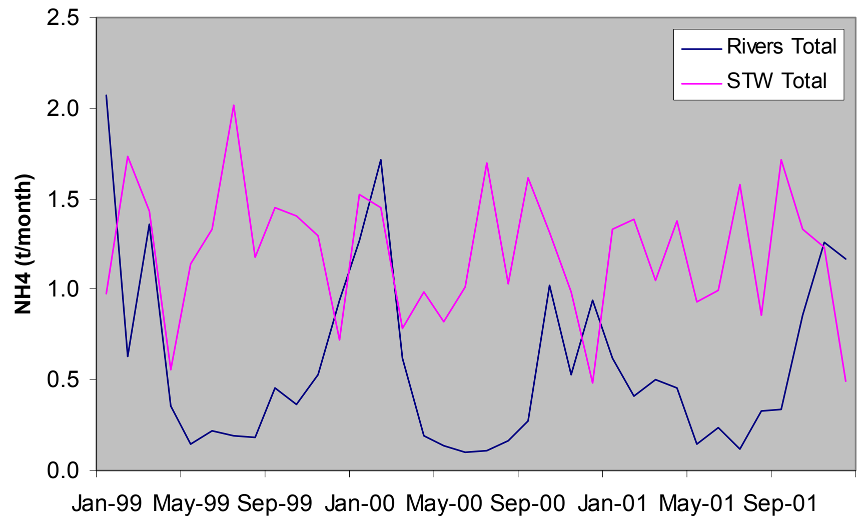


Figure 2.4. Seasonal loads of NH_4.

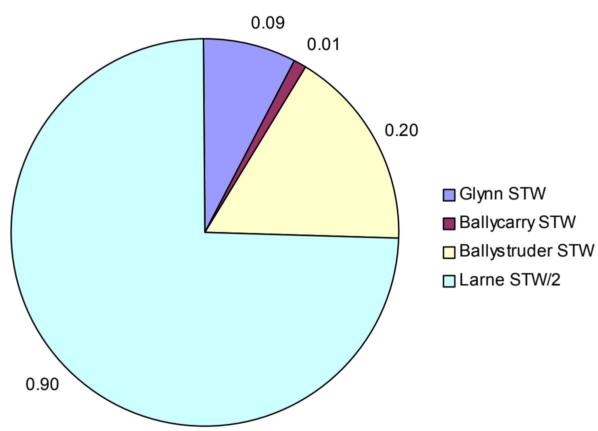


Figure 2.5. Loads of NH_4 from the STWs (t month^{-1}).

2.3.3. DIN

The loads of DIN are shown in Figure 2.6. DIN loads to Larne Lough are greatest in the winter due to the rivers being the predominant contributor to DIN inputs. NO_3 contributes the greatest amount of N to DIN. During the spring and summer months of 1999-2002 STWs contributed an average of 18% of the DIN load to Larne Lough

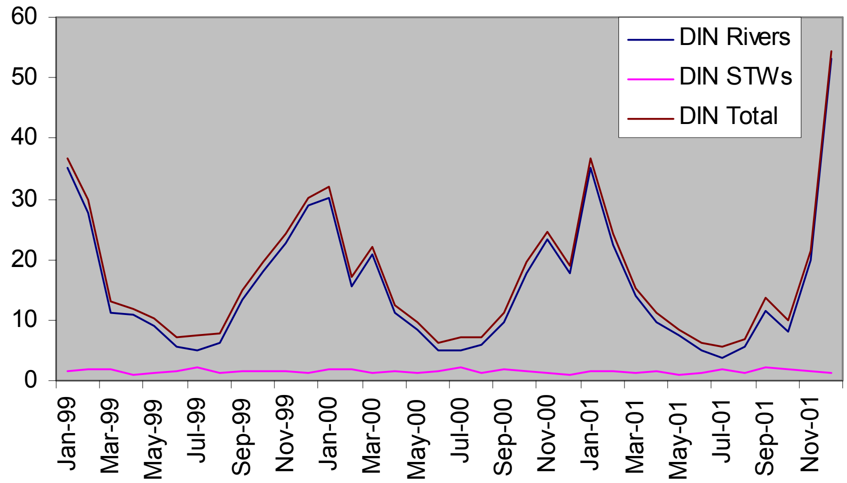


Figure 2.6. DIN loads to Larne Lough (t $month^{-1}$).

2.3.4. SRP

57% of the total load of SRP is from the rivers and the remainder from the STWs. Figure 2.7 shows that the load from the rivers is seasonal so that they are the predominant source in winter whereas STWs are the predominant source in summer. The Rivers Glynn, Larne and the remaining catchment contribute approximately equal proportions of SRP whereas Larne STW dominates the contribution from the STW (Figure 2.8).

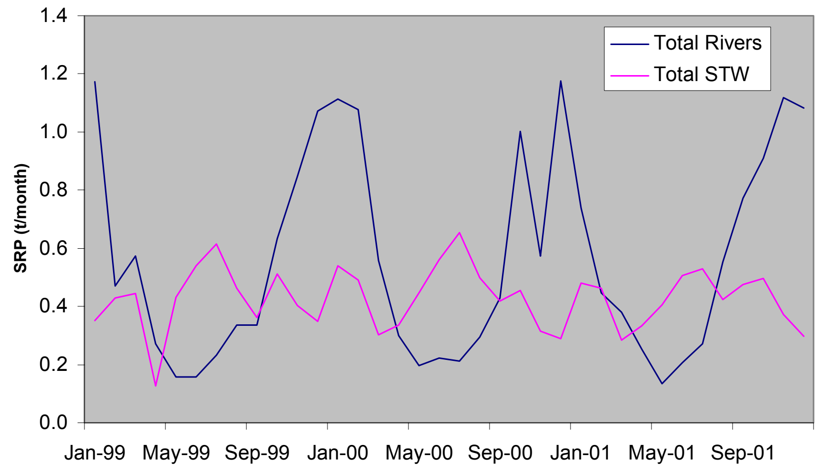


Figure 2.7. Seasonal load of SRP from rivers and STWs.

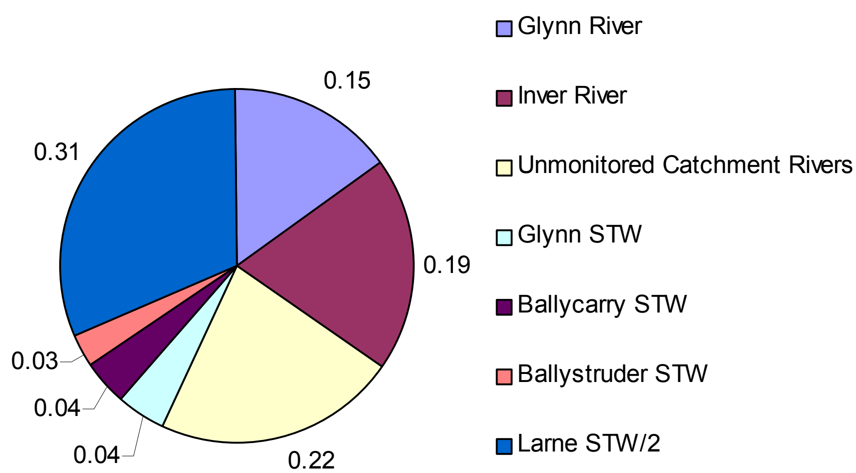


Figure 2.8. Loads of SRP (average t/month) from the rivers and STWs

2.4. Conclusion

Inputs of nutrients to Larne Lough are predominantly from riverine sources particularly in winter during high flow conditions, which is in accordance with Service *et al.* (1998). Larne STW contributes the largest proportion of loads from STWs which can significantly contribute to the nutrient loading during the spring and summer months.

Chapter
3

Marine Water Quality Monitoring

3.1 Introduction

Sampling of Larne Lough was initiated in Jan-1999 and sampled 7 times until Aug-1999. Sampling was then suspended and recommenced in Feb-2000 and completed in April-2001 encompassing a further 23 sampling dates. Samples were taken at 6 sites within the Lough. In May-2000 another sampling site was added in the mouth of the Lough (LL7). The data used to produce this chapter can be found in the attached disk in the file '*watqual.xls*'.

3.2. Methods

The sampling stations are shown in Fig 3.2.1. The sample collection and analytical procedures employed to produce the monitoring data can be found in Taylor *et. al.* (1999). At all sites a CTD cast was completed and samples taken at 1m depth from the surface and from 1m above the bottom. Samples were taken at high tide to facilitate access to shallow areas of the Lough.

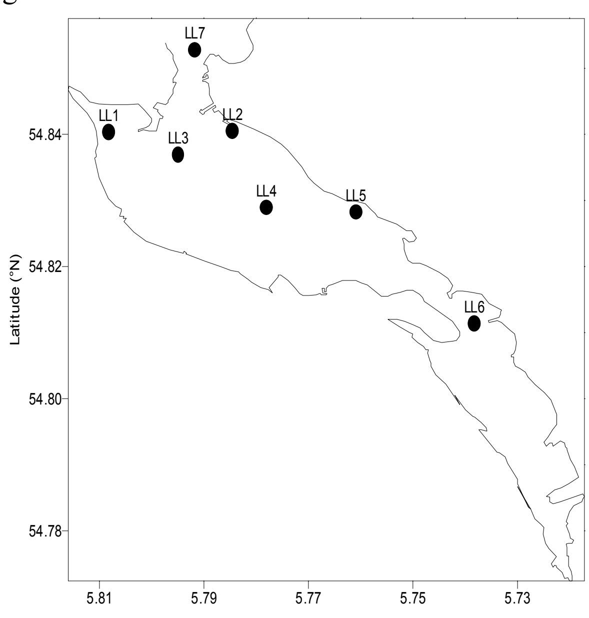


Figure 3.2.1. Marine monitoring sample sites in Larne Lough.

3.3. Results

The results are presented in graphs that show the temporal trends observed at each station and in 'box and whisker' format that gives a visual representation of the mean and spread of the data at each station over the complete sampling period. Explanation of the format of the box and whisker plots can be seen in Appendix 1.

3.3.1. Physical parameters.

Firstly, to investigate if there was any significant saline stratification in Larne Lough the surface water minus the bottom water salinity was plotted for each station (Figure 3.2).

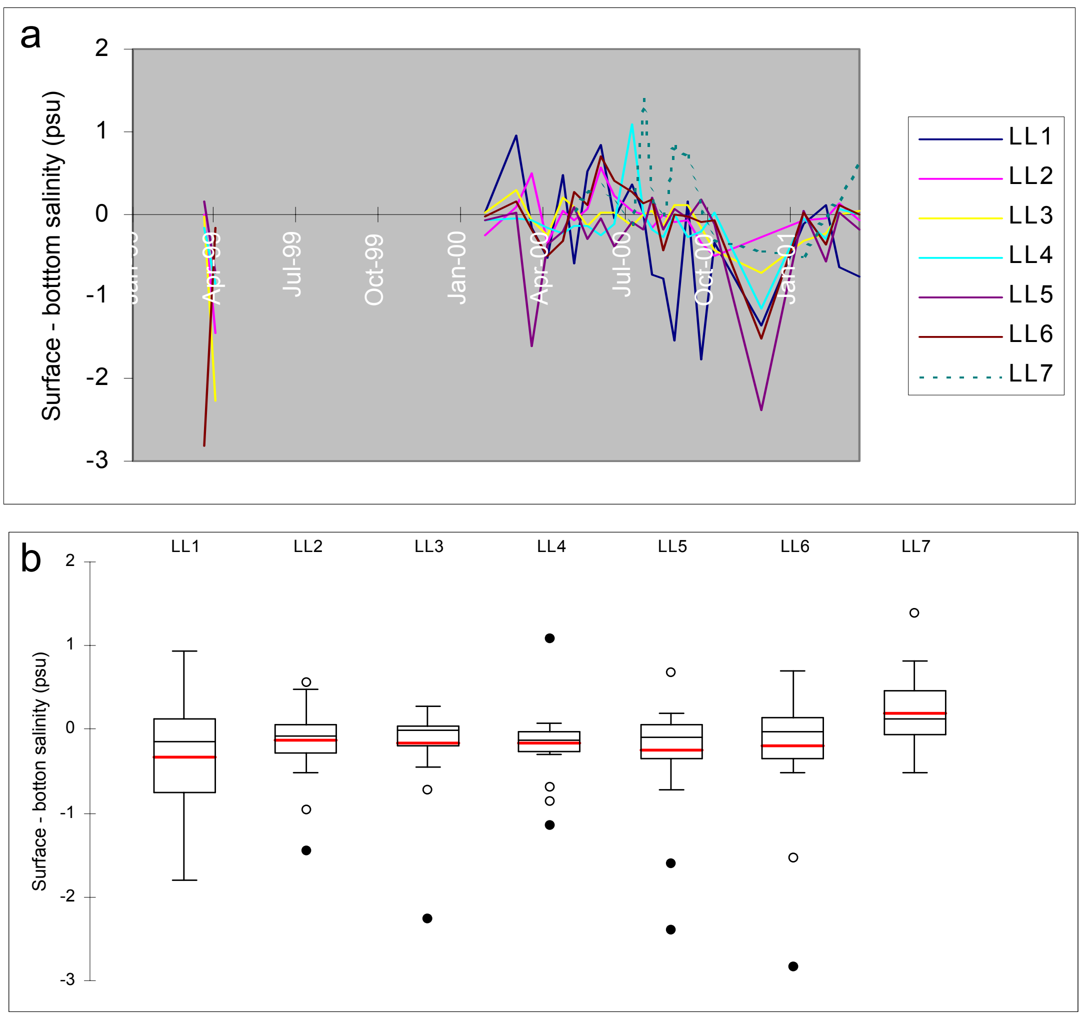


Figure 3.2. a) Surface – bottom salinity at all stations throughout sampling period; b) variation in surface – bottom salinity at each station.

In winter when freshwater inputs from the rivers are highest, negative values are generally observed due to the fresh less dense water floating on the surface of the more saline water beneath. In the summer positive values are often recorded which is probably due to the complex mixing between water bodies of different salinities. The box plot shows the mean and median values are mostly negative showing that freshwater inputs are the predominant influence in differences in the water column. However the difference between the salinity of the surface and bottom water is small suggesting a well mixed water column for most of the stations. An exception to this is LL1 which has predominantly negative values which is a reflection of its location close to the Inver River. LL7 is the only station with a positive mean and median value, which may be a result of complex tidal flow patterns at the mouth of Larne Lough. As most of the stations are well vertically mixed, the presentation of the other variables is an average of the surface and bottom water samples.

Figure 3.3 shows the salinity at all stations was lower during winter months as would be expected due to increased flows from freshwater sources. With the exception of LL1 which is influenced by inputs from the Inver River, stations towards the south of the Lough have lower salinities than in the north. This suggests significant freshwater inputs to the south of the Lough combined with a lower degree of mixing with fully marine water derived from the north.

Figure 3.3. a) temporal trend in salinity at all stations (average of surface and bottom readings); b) variation in salinity at each station.

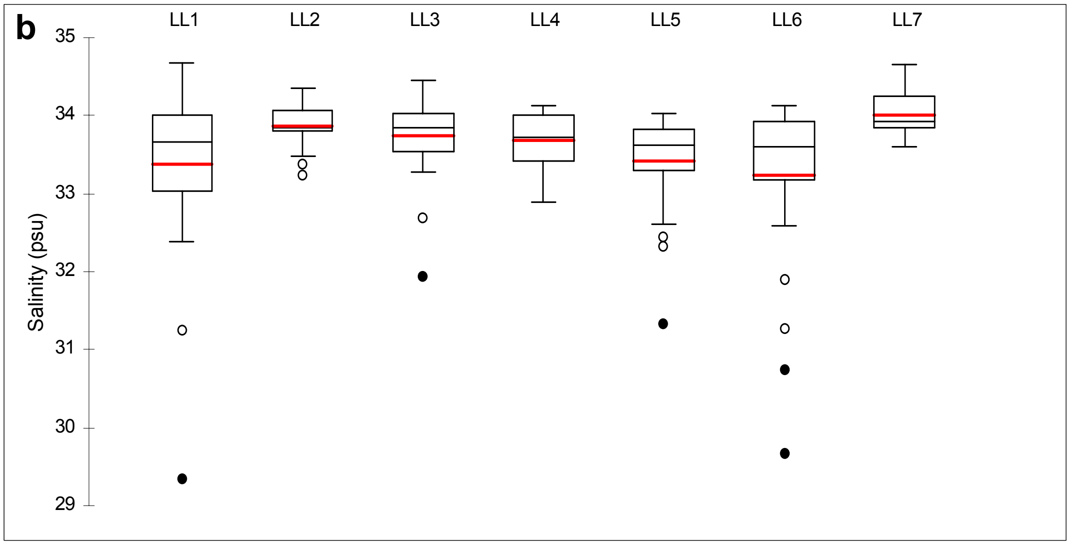


Figure 3.3. Continued.

In summer the Lough is marine in nature and typical of salinities found in outer Belfast Lough (Charlesworth and Service, 1999) suggesting that the influence of freshwater inputs on the Lough is minimal at this time of year.

Figure 3.4. shows the seasonal variation in temperature at all the stations. As would be expected temperatures start to increase in April from 8°c to a maximum of 16°c in August. Variations between stations can be accounted for by salinity, depth and residence time.

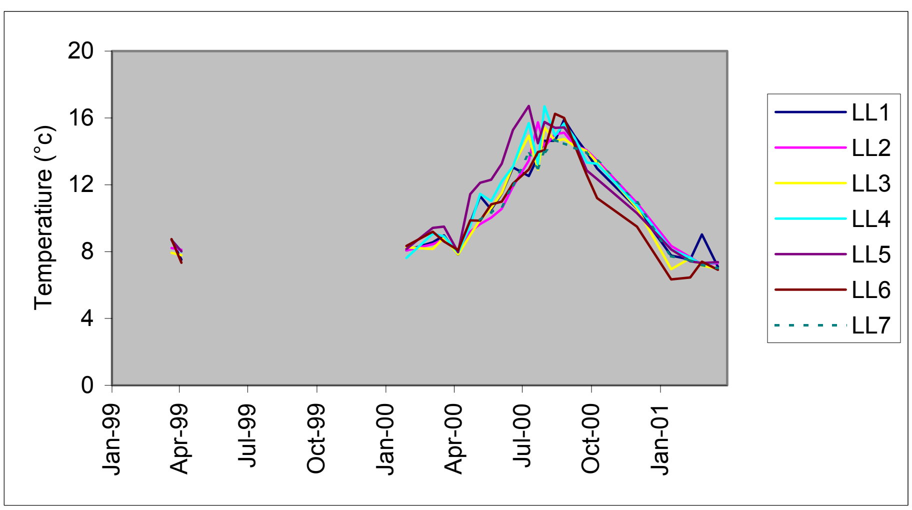


Figure 3.4. Seasonal variation in temperature.

Secchi depth gives an indication of water clarity and the variation throughout the sampling period is presented in Figure 3.5. The largest secchi depths are recorded at the stations with the greatest total depth showing that suspension of particulates from the sea bed is the predominant factor affecting water clarity. The compensation depth is used here to indicate at which point phytoplankton growth may be limited by irradience which may be estimated as three times the secchi depth (Parsons *et al.*, 1984). The total water depth is less than three times the secchi depth demonstrating that phytoplankton growth is generally not light limited throughout the Lough.

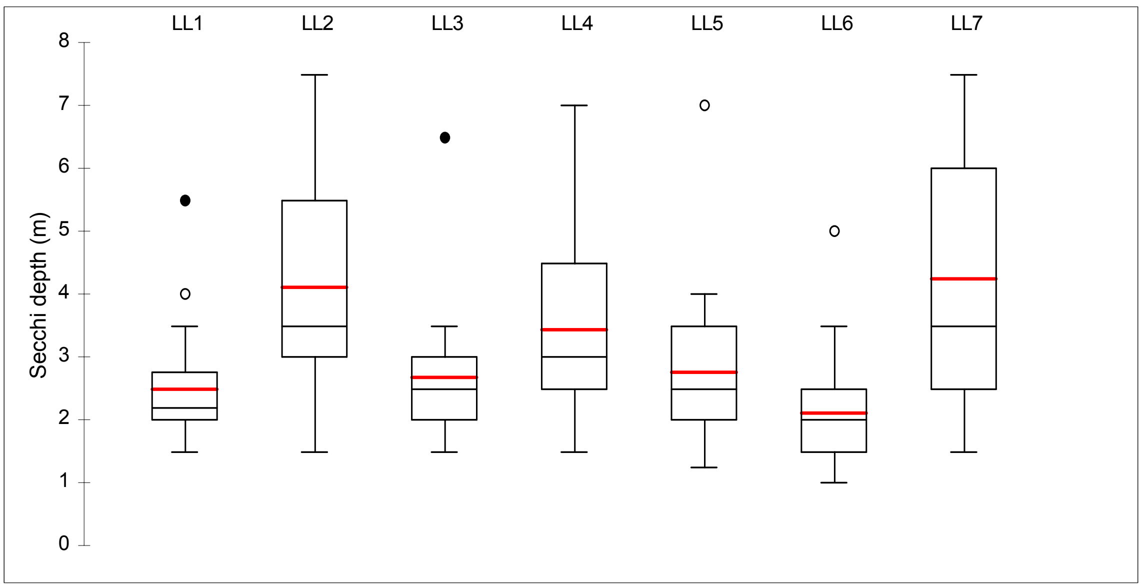


Figure 3.5. Variation in secchi depth.

3.3.2. Nutrients

TON shows a wide variation in concentrations throughout the year (Figure 3.6). With the exception of LL1, concentrations are lowest in spring and summer and highest in winter as would be expected considering that rivers contribute 98% of the input of TON to Larne Lough, and that N is taken up by phytoplankton in the spring and summer for growth. Peaks in TON on certain sampling dates are coincident with a decrease of salinity demonstrating further that freshwater sources are the predominant source of TON. The wider variation in TON concentrations at LL1 can be attributed to the influence of the Inver River. Minimum concentrations of < 1μM were observed in Aug-2000 at stations LL2-LL6.

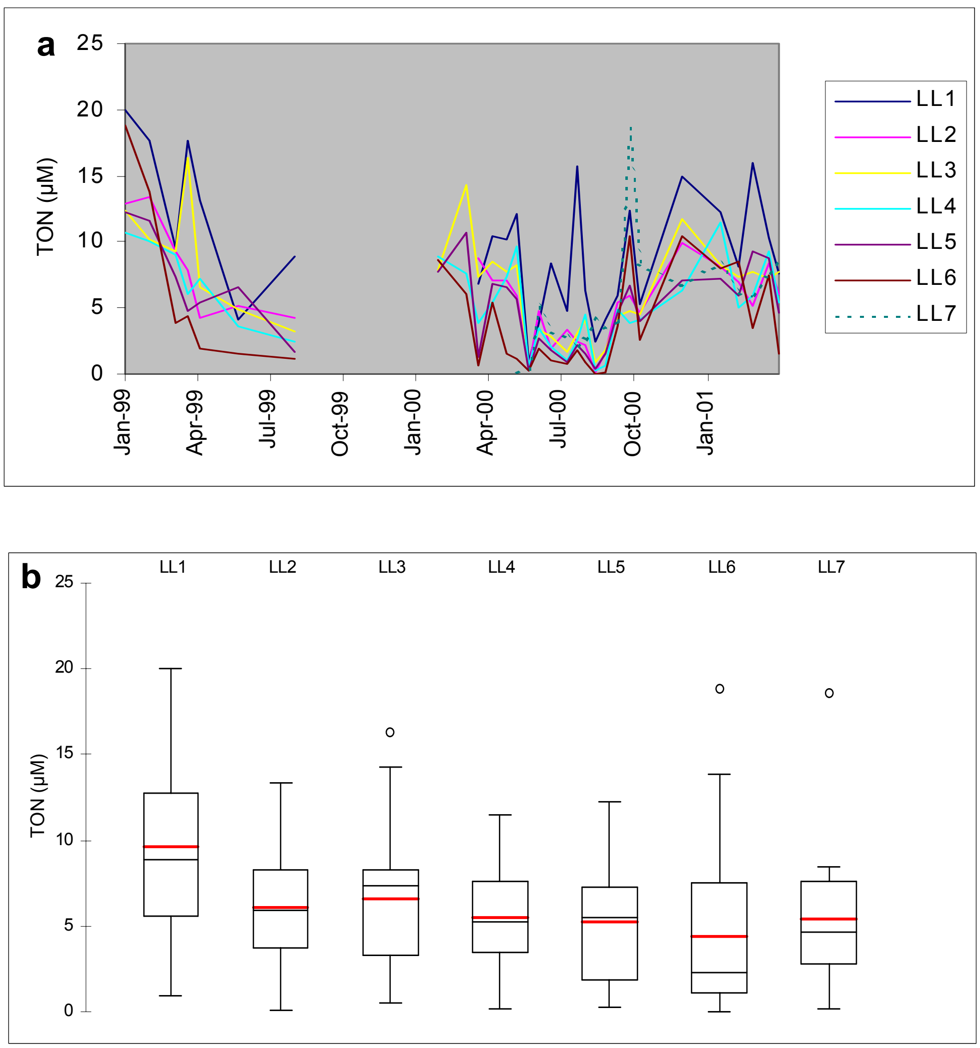
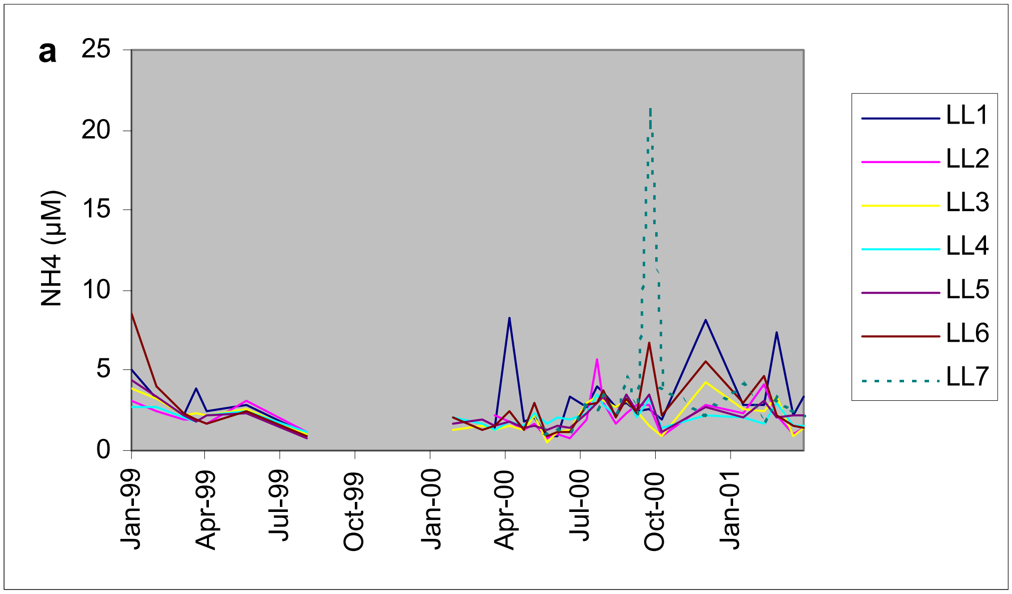


Figure 3.6. a) seasonal trends in TON (average of surface and bottom samples); b) variation of TON at stations.

Figure 3.7 shows the seasonal trends and variation in NH_4 concentrations. Highest concentrations are generally observed in winter when uptake by phytoplankton is at a minimum and there is an additional input from rivers. The peaks in concentration at LL1 are probably a reflection of the input from the Inver River and the CSO that drain into the River. The peak in concentration at LL7 in Oct 2000 is probably a direct impact from the sewage outfall from Larne STW in the main shipping channel.



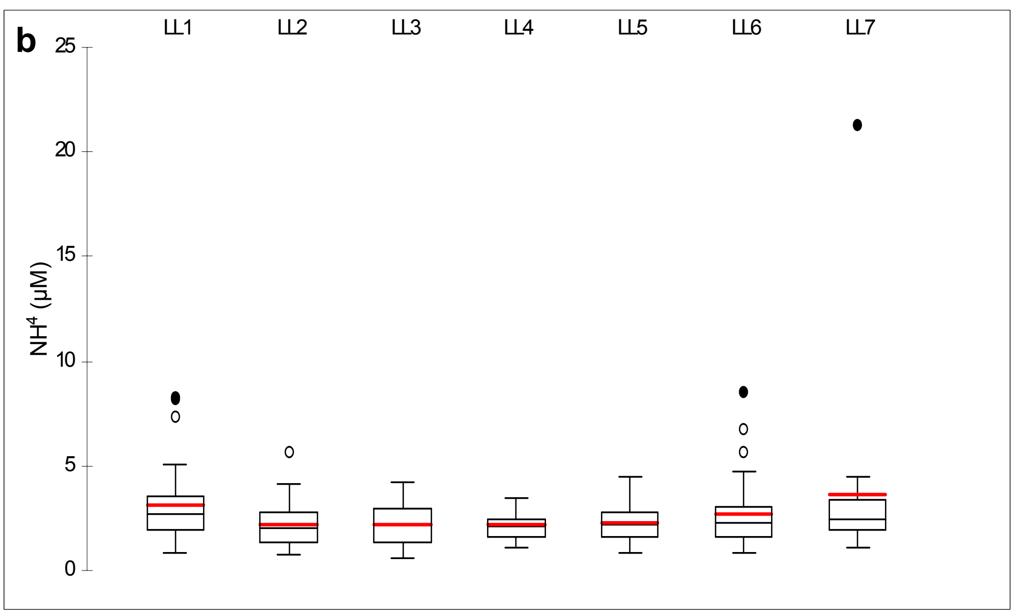


Figure 3.7. a) seasonal trends in NH_4 (average of surface and bottom samples); b) variation in NH_4 at stations.

Figure 3.8 shows the seasonal trend of DIN concentrations. Concentrations of DIN are highest in the winter and lowest in the summer due to higher inputs in the winter and biological uptake in the summer. During the months Dec- March DIN concentrations only exceeded 18µM on 5 occasions from 8 sample dates encompassing 7 stations (total of 56 samples). Four of these exceedences were observed at station 1 and can be related to the influence of freshwater at this site. DIN concentrations do not show good relationships with salinity, which is a result of a number of freshwater inputs to the Lough and the narrow range of salinities observed in the Lough.

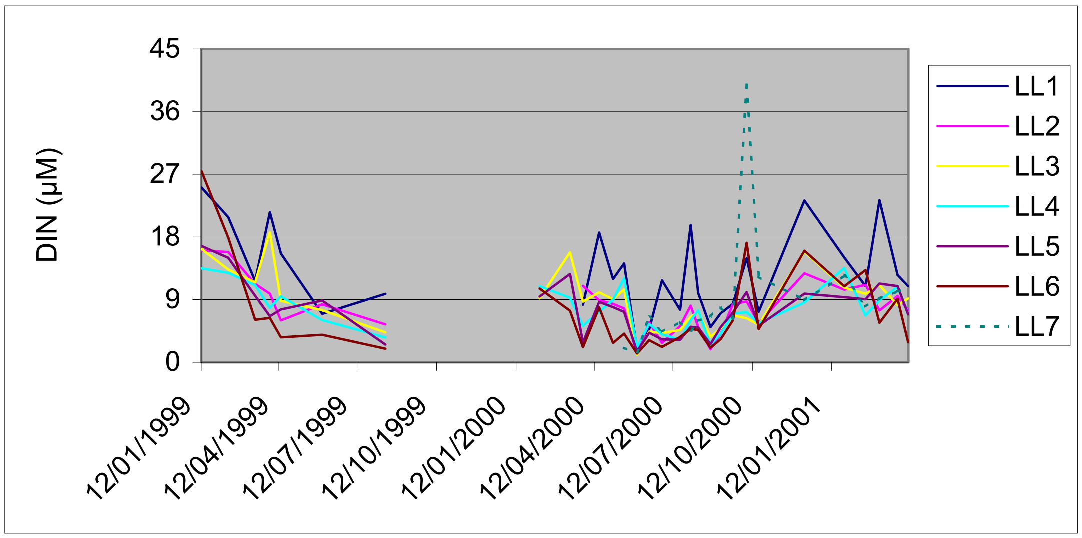


Figure 3.8. Seasonal trend of DIN concentrations (average of surface and bottom samples).

Freshwater inputs are the predominant sources of silicate to near shore coastal waters, whereas biological uptake by diatoms act as a loss of silicate in the water column. The observed seasonal trend of silicate in Larne Lough with maximum concentrations in winter and lower concentrations in summer is a reflection of these processes (Figure 3.9). The large variation in silicate at LL1 is a reflection of the influence of the Inver River at this station. The variation in the remaining stations is relatively small with average concentrations of between 4.8 – 6.7 µM..

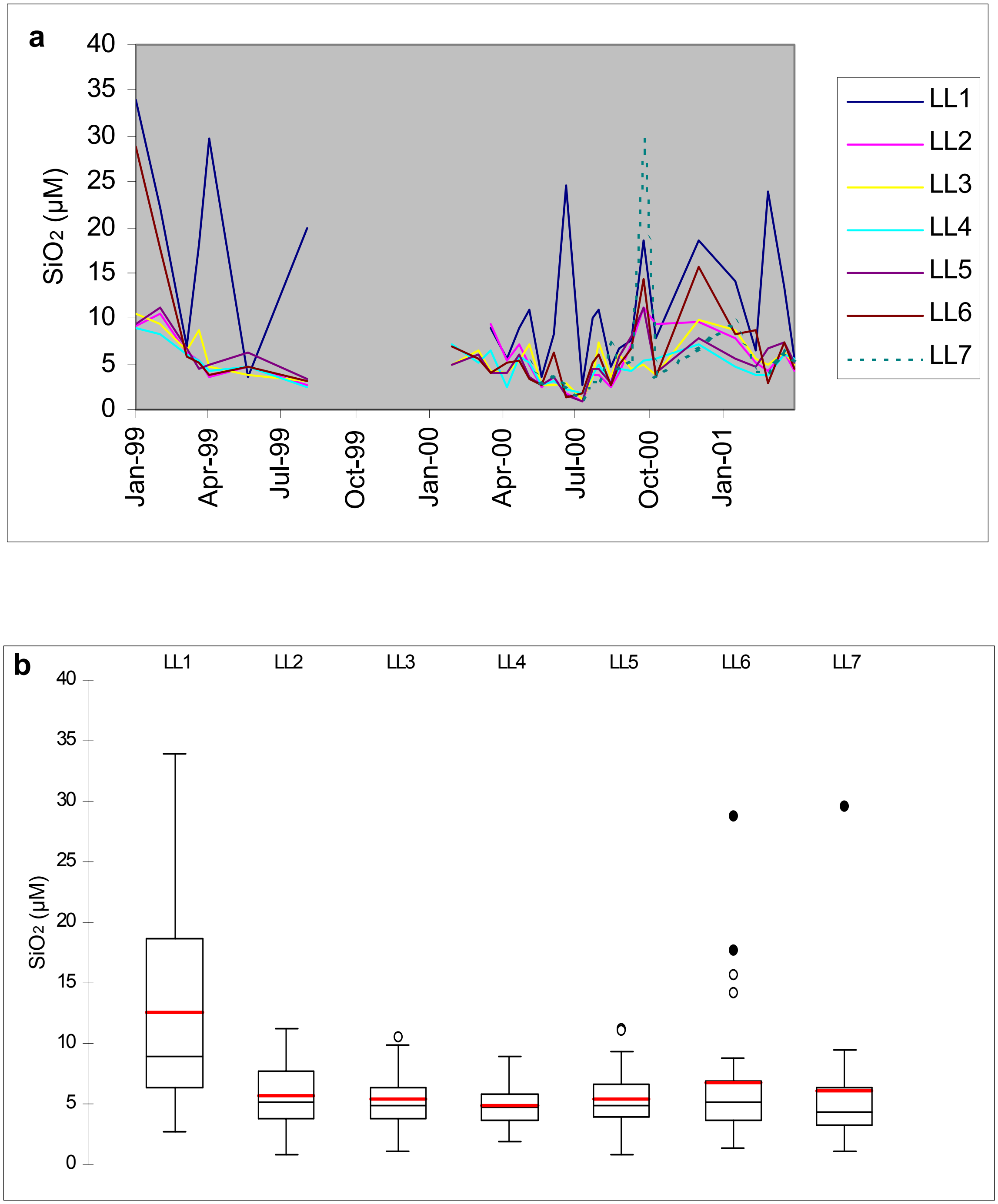


Figure 3.9. a) seasonal trends in silicate (average of surface and bottom samples); b) variation in silicate.

SRP shows a similar seasonal trend to silicate (Figure 3.10) with highest concentrations in winter due to inputs from the rivers and uptake by phytoplankton during the summer. The variation in SRP throughout the year is similar at all stations with mean concentrations between 0.46 – 0.67, and similar seasonal trends (with the possible exception of LL1). This suggests a common underlying mechanism controlling the concentration of SRP at all these sites, and may also reflect the importance of inputs from STWs that are relatively constant throughout the year (Chapter 2).

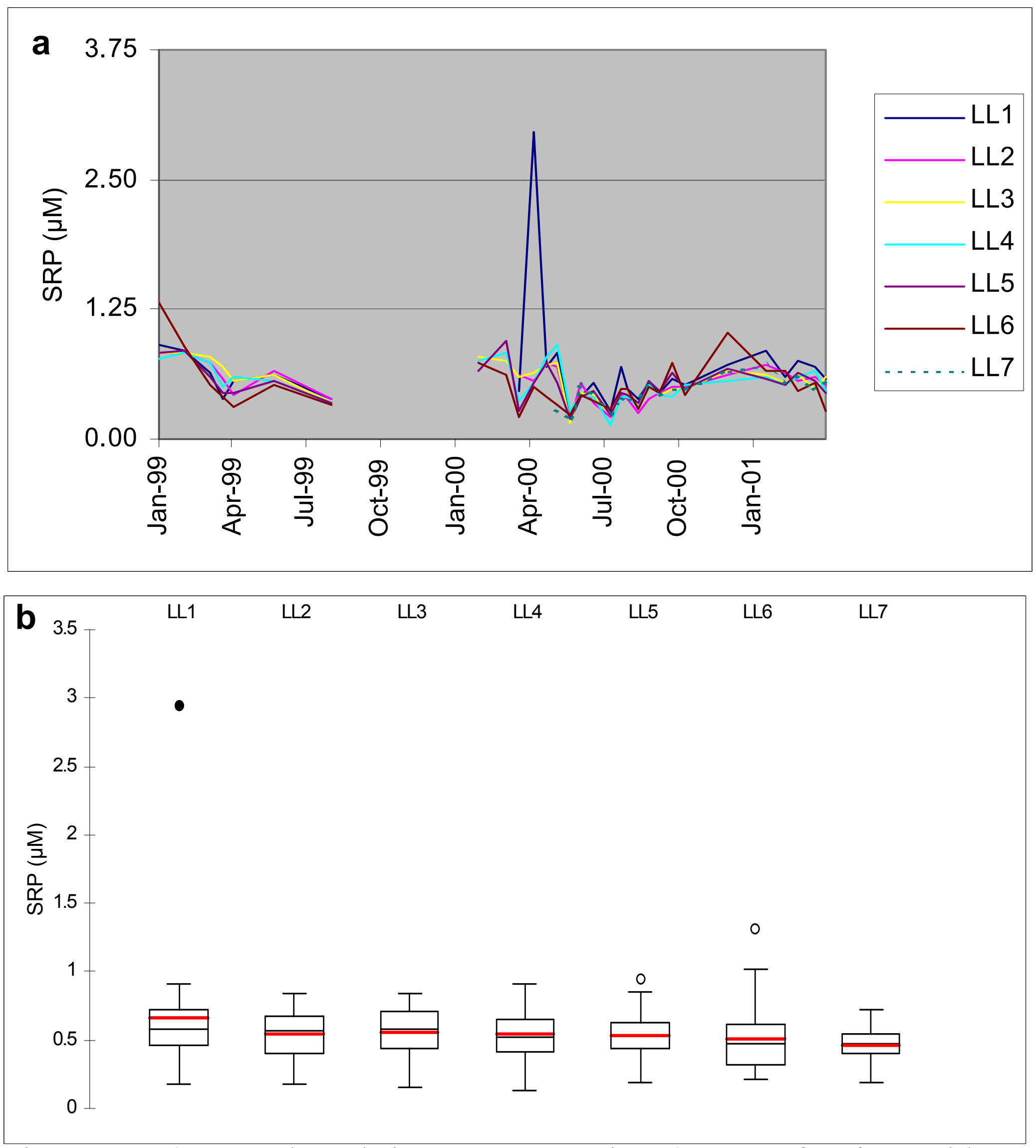
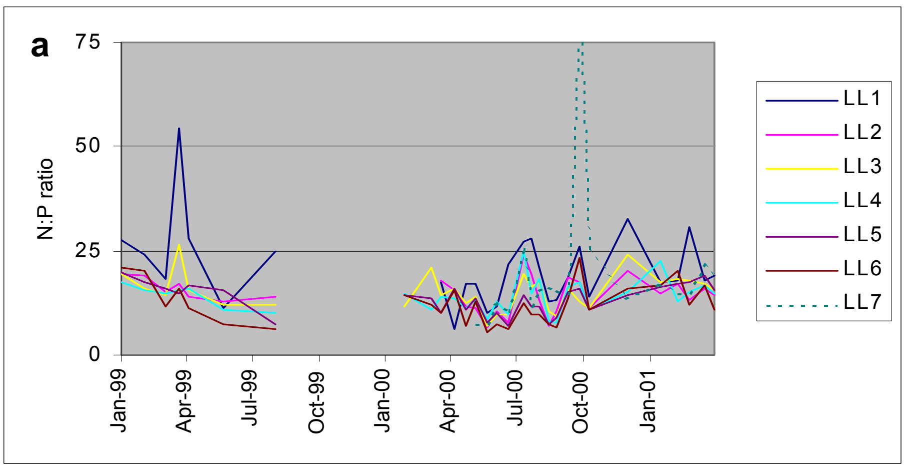


Figure 3.10. a) seasonal trends in SRP concentrations (average of surface and bottom samples); b) variation in concentrations.

The N:P ratio is important in determining if the system is nitrogen or phosphorous limited if low concentrations of nutrients exist. The N:P ratio (DIN/SRP) is generally lower in the spring and summer probably as a result of the lower inputs of DIN from the rivers during this season, whereas the predominant source of SRP is from STWs which remains constant throughout the year (Figure 3.11). Biological modification also may account for changes in the N:P ratio. From April to September the mean N:P ratio is LL1 and LL7 is 18 and 14.1 respectively (Table 3.1). The ratio at the remaining stations is < 13.4 which decreases in a southerly direction in the spring and summer. Winter N:P ratios only exceed 25 at station 1 on 3 occasions which can be related to the freshwater influence at this site (Table 3.2). The N:P ratio will be discussed further in section 3.4. in relation to algal growth. Winter N:Si ratios only exceed 2.5 on one occasion at station LL4 (Table 3.3).



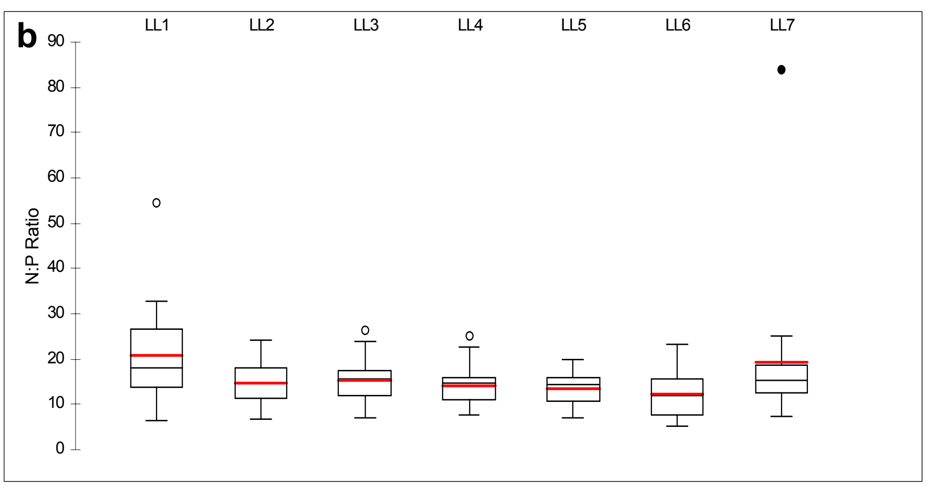


Figure 3.11. a) Seasonal trend in N:P ratios (DIN/SRP); b) variation in N:P ratios at each station.

Table 3.1. Mean N:P ratio from April to September.

	LL1	LL2	LL3	LL4	LL5	LL6	LL7
Mean N:P ratio	18	13	13.3	13.2	11.9	9.4	14.1

Table 3.2. Statistics of winter (Dec-March) N:P ratios.

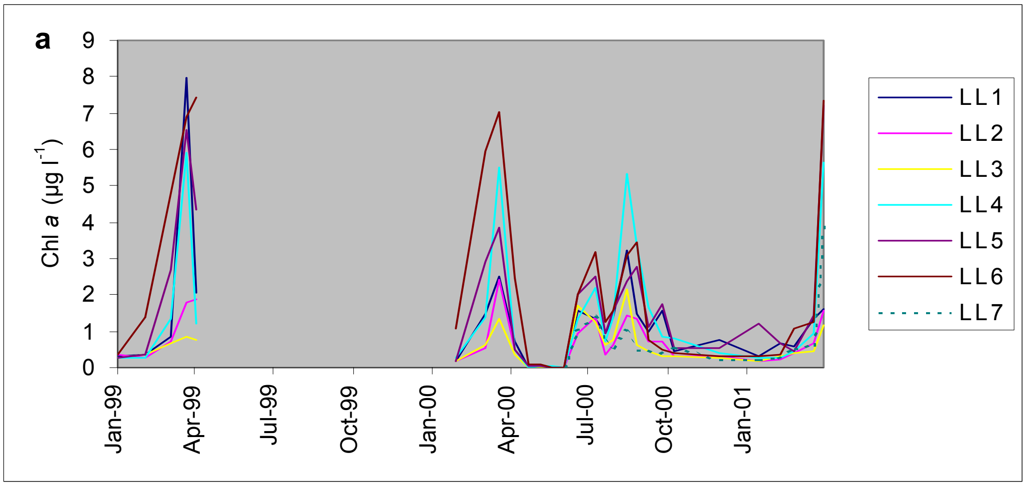
	min	max	mean
LL1	17.5	32.8	23.7
LL2	13.1	20.4	16.8
LL3	14.5	24.0	18.3
LL4	13.0	22.6	16.6
LL5	14.5	19.9	17.2
LL6	11.5	20.9	16.7
LL7	13.7	21.3	16.7

Table 3.3. Statistics of winter N:Si ratios.

	Min	Max	Mean
LL1	0.7	1.7	1.2
LL2	1.3	2.2	1.8
LL3	1.2	2.3	1.8
LL4	1.2	2.9	2.0
LL5	1.3	1.9	1.6
LL6	1.0	2.0	1.5
LL7	1.3	2.3	1.8

3.3.3. Biological

Chl *a* is a measure of the standing crop of phytoplankton and is shown in Figure 3.12. The spring bloom starts at the end of March/ beginning of April in each of the three years studied. After the spring bloom in 2000 concentrations decrease to below 0.1 μg l^{-1} at the beginning of May and subsequently increase at the end of June. Concentrations finally decrease to winter levels in October (< 1 μg l^{-1}). This seasonal trend is generally observed in nearshore coastal waters and reflects the spring and autumn cycle of phytoplankton growth. Concentrations never reach above 10 μg l^{-1}. The concentration of chl *a* clearly increases in a southerly direction in the Lough with highest concentrations at LL6.



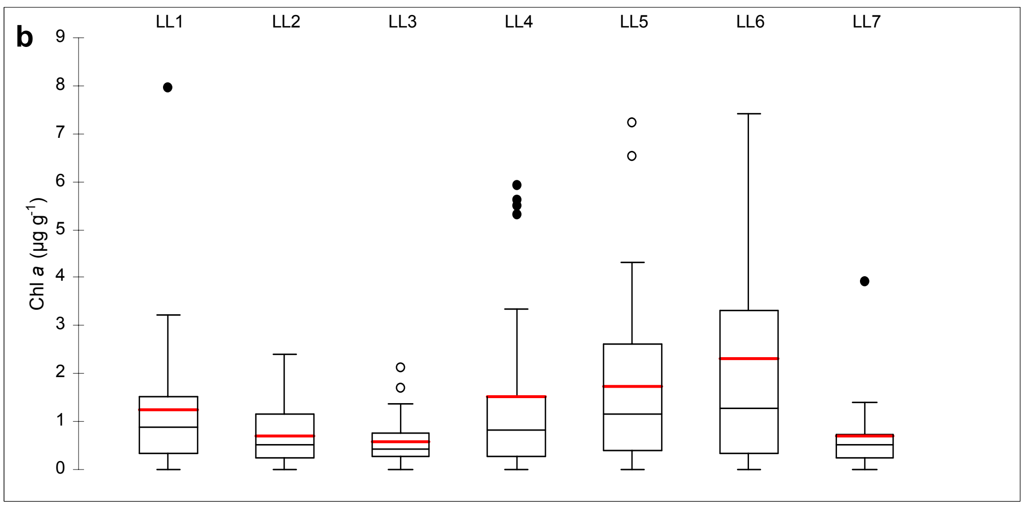


Figure 3.12. a) Seasonal trend in chl *a* (average of surface and bottom samples); b) variation in chl *a* at each station.

Identification of toxic phytoplankton species has been undertaken at 3 sites situated close to the shellfish beds between the narrow channel between the north and south of the Lough (Mill Bay, Shingle Bay and White Bay) every 2 weeks from April 2000 to Sept 2002 under the Shellfish Hygiene Directive. Data taken for this purpose is shown on the attached disk under '*phyto.xls*' (A. McKinney, pers comm). Maximum concentrations of toxic phytoplankton identified over this period are shown in Table 3.4.

Table 3.4. Maximum concentrations (cells l^{-1}) of phytoplankton identified for the Shellfish Hygiene Directive April-2000 to Sept-2002.

Species	Millbay	Single Bay	White Quay	Category
Dinophysis acuminata	20	40	0	Dinoflagellate
Dinophysis acuta	80	20	40	Dinoflagellate
Dictyocha speculum	40	120	20	Silica flagellate
Gyrodinium aureolum	20	20	0	Dinoflagellate
Gymnodinium spp.	240	480	300	Dinoflagellate
Pseudo-nitzschia spp.	9280	10540	1040	Diatom
Phaeocystis spp.	0	1400	0	Haptophyte

Pseudo-nitzschia spp. was the species recorded at highest concentrations and has the potential to cause ASP. High concentrations were often observed at more than one sampling site on a sampling date (Figure 3.12). Over the period of sampling, concentrations of all toxic species did not exceed target levels. Concentrations were greatest during the spring and summer due to the seasonal cycle of phytoplankton growth. Maximum concentrations were rarely maintained between sampling dates.

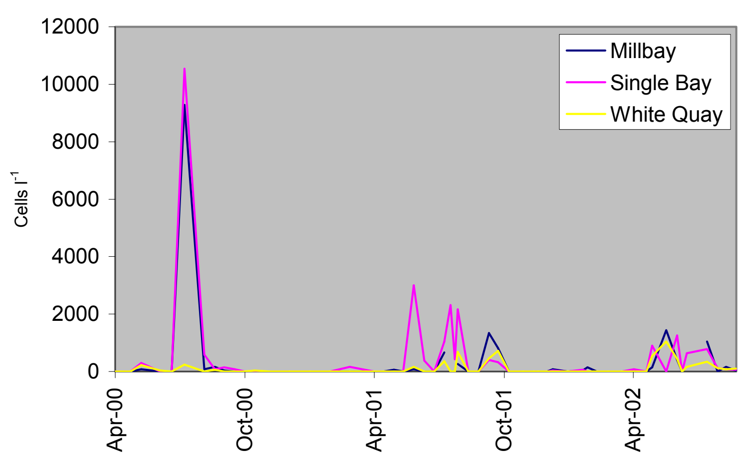


Figure 3.12. Concentration of *Pseudo-nitzschia spp* over sampling period.

The OSPAR common assessment criteria give information with regard to phytoplankton indicator species and the levels at which they may have a detrimental effect. These are shown in Table 3.5. A comparison of Table 3.4 to 3.5. shows that the levels of phytoplankton recorded do not exceed the levels at which they may have a detrimental effect. *Pseudo-nitzschia spp* is not identified as a phytoplankton indicator species by OSPAR however the levels observed fall below the target level set for the Shellfish Waters Directive.

Table 3.5. OSPAR phytoplankton indicator species and levels atwhcih they may have detrimental effects.

Species	Concentration of cells which may cause detrimental effects (cells l^{-1}).
Phaeocyctis spp	10^6
Noctiluca scintillans	10^3
Chrysochromulina polylepis	10^6
Gymnodinium mikimotoi	10^3-10^6
(formally *Gyrodinium aureolum*)	
Alexandrium spp	10^2
Dinophysis spp	10^2
Fibrocapsa japonica	$4 * 10^6$

Chapter
4

Mathematical Modelling

4.1. Introduction

From a study of the movement, transformations and inputs of nutrient to the study area, future trends and the effectiveness of certain management options may be predicted. It may also be used to assess the relative influence of external inputs and internal processes on observed concentrations, and be used to calculate residence times and the susceptibility to extensive algal growth.

4.2. Methods

The volume of Larne Lough at high and low spring and neap tides was calculated and is shown in Table 4.1. As can be seen the volume of water entering the Lough on a flood tide is almost 1-2 times the volume of water present at low tide. The tide is therefore the dominant control on water movement and exchange rather than freshwater inflow. A single box model has been applied to the Lough to investigate the exchange of water and the relative importance of nutrient inputs from the tide, rivers and STWs.

Table 4.1. Volume of Larne Lough (million m^3)

Tide	Volume (million m^3)
MLWS	14.9
MHWS	41.3
MLWN	17.6
MHWN	37.6

The model follows that given by Comprehensive Studies Task Team (CSTT) (1994).

The exchange ratio (**E**) of water within the box (i.e. Larne Lough) and that outside (i.e. North Channel) is given by:

$$\mathbf{E = P/(P + V)}$$

where **P** is the intertidal volume (tidal prism) and **V** is the low tide volume. The flushing time in tidal cycles is then 1/E. From the above potential, steady state, nutrient concentrations can then be estimated by:

$$\mathbf{S = S_0 + ((s_i)/(E.V))}$$

where:
S is the concentration of DIN in the box
$\mathbf{S_o}$ is the concentration of DIN in the adjacent water
$\mathbf{s_i}$ is the total of inputs to the box
E is the exchange rate with adjacent water
V is the volume of the box under consideration

The concentration of nutrients in seawater entering the Lough on the flood tide is required to be representative to accurately calculate nutrient concentrations within the Lough. Monitoring station LL7 was chosen for this purpose as all samples were collected at high tide and therefore this site at the mouth of the Lough is probably representative of North Channel. The high salinity (~34 psu) and the low TON concentrations at this site support this view. Outflow from the Larne STW occurs close to this site which may have an influence on concentrations, but the monitoring data suggest that it does not except for the high concentration of NH_4 in October 2000 which has been excluded from any calculations.

Observed and predicted concentrations have been calculated for summer and winter for a mid spring and neap tide. Inputs are an average from April to September 2000 (summer) and

October to March 2001 (winter). Observed concentrations within the Lough have been averaged from all sites on available dates for the above periods.

4.3. Results and Discussion

4.3.1. Tidal flushing and exchange rate

The exchange ratio and flushing time for Larne Lough in different tidal conditions in shown in Table 4.1. The flushing time of the Lough varies between 1.6-1.9 tidal cycles (i.e. less than 1 day) which is rapid in comparison to other sea Loughs in Northern Ireland (Charlesworth and Service, 1999; Charlesworth *et al.*, 1999, Taylor *et al.*, 1999). This calculation should be considered a minimum as it implicitly assumes complete mixing of water within the Lough over a tidal cycle, and that water exported on the ebb tide does not return on the following flood tide.

Table 4.1. Tidal flushing and exchange rate of Larne Lough.

	Low water	High water	Tidal Prism	Exchange ratio (E)	Flushing time (tides)
Spring	14.9	41.3	26.4	0.64	1.57
Neap	17.6	37.6	20.0	0.53	1.88
Mid	16.3	39.5	23.2	0.59	1.70

4.3.2. Nutrient Concentrations

Table 4.2 details the observed and predicted concentrations of DIN and SRP in the Lough at present discharge levels, and inputs 50% greater than and less than at present. There is good agreement between the observed and predicted concentrations. Small differences between the observed and predicted values may be a result of internal process such as biological uptake and denitrification, or due to small inaccuracies in the estimation of nutrient concentrations in the North Channel. Since the differences between the observed and predicted nutrient concentrations are small it shows that the internal processes are not sufficient to mediate concentrations on time scales greater than the flushing of the Lough by water derived from the North Channel.

Table 4.2. Observed and predicted concentrations of DIN and SRP.

	Winter DIN	Summer DIN	Winter SRP	Summer SRP
Observed (μM)	10.6	6.1	0.58	0.48
Predicted (μM)	13.5	6.4	0.65	0.43
Predicted + 50% (μM)	15.2	7.0	0.69	0.45
Predicted – 50% (μM)	11.9	5.7	0.62	0.40

Since the flushing of Larne Lough is rapid, the dominant control of nutrient concentrations within the Lough is the nutrient concentrations in the North Channel. Thus a predicted 50% increase or decrease in inputs derived from rivers and STWs does not significantly increase or decrease the concentration of nutrients in the Lough.

4.3.3. Algal biomass.

Relationships between algal biomass and nutrient concentrations are explored so that effect of changing nutrient concentrations on the trophic status can be predicted. A significant negative relationship between Chl *a* and DIN is only observed throughout the sampling sites on 15/03/1999 and 29/03/2000. If data is combined for spring and summer there is not a significant relationship. This shows that there are other factors that are important in determining the Chl *a* concentration other than nutrient concentrations. It is therefore difficult to accurately predict the change in Chl *a* concentrations following a change in the nutrient status of the Lough. However, using the median value of 1.05 μg chl l^{-1} produced from 1 μM of NO_3 (Gowen *et al.*, 1992), a 50% increase in DIN inputs to Larne Lough during the summer would be expected to elevate Chl *a* concentrations by 1.8 μg chl l^{-1}.

4.4. Summary

The flushing time of Larne Lough is very rapid which results in the concentrations of nutrients in the North Channel being the main determining factor of nutrient concentrations within the Lough. Thus, unless there are major changes to inputs from the rivers and STWs into the Lough, nutrient concentrations will not significantly change. There is generally no relationship between Chl *a* and DIN suggesting that other factors within Larne Lough are more important in determining algal biomass.

Chapter

5

General Discussion

5.1. Limitations to phytoplankton growth

DIN and SiO_2 did not fall below 0.5 µM throughout the Lough during the survey period, and SRP did not reach concentrations < 0.05 µM. This demonstrates that levels of nutrients within the Lough were sufficient to maintain algal growth, suggesting that other factors are important. The N:P ratio fell below the Redfield ratio of 16:1 during the spring and summer particularly for stations in the south of the Lough. Since nutrients were not at concentrations that are considered to be limiting this does not suggest that the system is P limited, but is likely to reflect inputs and biological mediation.

The total water depth of the Lough is less than 3 times the compensation depth which demonstrates that light does not limit algal growth in the Lough. To investigate if algal growth within the Lough is limited by physical exchange with the North Channel flushing times are compared to the mean intrinsic growth rate. Assuming a mean intrinsic phytoplankton growth rate of 0.27 day^{-1}, (Gowen *et al*., 1993) and the concentration of Chl *a* in the North Channel of 0.55 µg l^{-1} (calculated by average spring summer concentrations at LL7), and a flushing time of 1 day, phytoplankton growth would not be sufficient to result in Chl *a* concentrations > 5 µg l^{-1}. This clearly suggests that phytoplankton growth within Larne Lough is limited by physical exchange.

As previously discussed the calculation of the flushing time assumes complete mixing within the Lough over a tidal cycle. This is a simplification of mixing processes in coastal waters and common sense suggests that the exchange of water towards the south of the Lough is likely to be less than in the north close to the mouth. This would result in longer residence times towards the south of the Lough resulting in the greater potential for phytoplankton growth. This is reflected in greater Chl *a* concentrations towards the south of the Lough which was observed during this survey (Figure 3.11).

5.2. Trophic status and compliance with EC Directives.

Classification of criteria used to indicate the trophic status as defined by DEFRA (2002) are discussed below.

Trends and source apportionment of nutrient inputs.

Chapter 2 shows that DIN inputs are predominantly from rivers flowing into the Lough, and that DIP sources are dominated by riverine sources in the winter and STWs in the spring and summer. Temporal trends in inputs can not be determined over the time scale studied for the purposes of this report.

Winter nutrient concentrations and ratios significantly enhanced relative to background.

Winter nutrient concentrations are compared to the background values of 12µM DIN and 0.8µM DIP given for the Irish Sea. Concentrations of 50% above this value (18µM DIN and 1.25µM DIP) are considered elevated. Winter DIN and DIP at all stations in the Lough rarely exceed 18µM DIN and 1.25µM DIP. Exceedences can be related to freshwater inputs in the vicinity of the stations. Winter N:P and N:Si ratios are rarely >25 and >2 respectfully.

Planktonic algal biomass and duration of blooms.

Concentrations of Chl *a* did not exceed 10 µg l^{-1} throughout the study period. Concentrations > 5 µg l^{-1} were rarely sustained between sampling dates.

Occurrence of exceptional or unusual algal blooms

Phytoplankton that have the potential to cause toxicity were identified in the Lough but at concentrations less than the target level set for the Shellfish Hygiene Directive.

Changes in macrophyte/macroalgal growth.

Macrophytes were not studied during the course of this research.

Oxygen deficiency.

Previous studies have shown no evidence of oxygen depletion (IRTU, 1995).

Changes in fauna.

Not studied

Formation of algal scums.

There were no reported observations of algal scums over this period.

Occurrence of PSP.

PSP toxins have not been detected at the sampling sites over the sampling period covered by this report.

The above shows that Larne Lough is not eutrophic at present or likely to become eutrophic in the future. Since the flushing time of the Lough is the primary mechanism of limitation to phytoplankton growth, only a significant change to the hydrological regime would result in Larne Lough having the potential to become eutrophic. The southern part of the Lough has a longer residence time and particular attention should be applied in this region.

Chapter
6

Conclusions

- Salinity within the Lough is generally greater than 33 psu demonstrating the predominantly marine nature of the Lough.

- SRP, SiO_2, NO_3 and NH_4 concentrations are highest in the winter and lowest in the summer due to greater loads during the winter and biological uptake during the summer.

- The load of DIN to Larne Lough is dominated by contributions by rivers. STWs contributed an average of 18% to the total load of DIN to the Lough during the spring and summer months.

- Winter concentrations of DIN and DIP show that they are not elevated above background levels. Winter N:P and N:Si ratios are not elevated.

- Chl *a* concentrations do not exceed > 10 $\mu g\ l^{-1}$. Higher concentrations are generally observed towards the southern part of the Lough.

- Mathematical modelling shows that the flushing time of the Lough is less than 1 day, and therefore nutrient concentrations within the Lough are predominantly a reflection of concentrations in the North Channel. Predicted nutrient concentrations within the Lough were close to observed values, suggesting that the effect of internal processes on nutrient concentrations is small relative to the flushing time of the Lough.

- Significant negative relationships between Chl *a* and DIN were only observed on 2 sampling dates. This in combination with sufficient nutrient concentrations to maintain algal growth suggest that physical exchange is the predominant limitation to phytoplankton production in Larne Lough. It is suggested that the residence time is greater in the southern part of the Lough which gives rise to higher Chl *a* concentrations observed in this region.

- Classification of the Lough under criteria to assess trophic status show that the Lough is presently not eutrophic or likely to become eutrophic in the future.

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Glossary

The following definitions are for use with this report only and have not been accredited by any statutory organisation. For definitions of these terms used outside of this report, the reader should refer to published literature. These terms may only be quoted in any literature after permission is given by the authors.

8.1. Hydrographic and General

Stratified - water bodies that have a sharp vertical interface, above and below which is water of different physical and/or chemical properties.

Entrainment – The shearing effect at the halocline which precipitates the formation of internal waves between the two water masses, therefore creating turbulence. During this process salt water is transfused through the halocline into the lower salinity water.

Halocline – the sharp vertical gradient of salinity in stratified waters.

Anthropogenic – derived from human activities.

Eutrophication – 'the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorous, causing an accelerated growth of algae and higher plant life to produce an undesirable disturbance to the balance of organisms in the water and to the quality of the water concerned' (EEC, 1991a).

Chemical Precipitation – the formation of an insoluble solid by a reaction that occurs in solution.

Hypernutrified – winter concentrations of nutrients exceed 12 μM DIN and 0.2 μM SRP (CSTT, 1997).

Conservative/non-conservative behaviour – a chemical species whose concentration relative to salinity is controlled solely by it's concentration in the contributory sources (fresh and marine water) is conservative (i.e. by plotting concentration verses salinity, across a salinity gradient a straight line is obtained). Any *in situ* process which alters the concentration of a constituent relative to the total salt content imparts non-conservative behaviour.

8.2. Biological

Algae – simple plants, usually aquatic. May be unicellular or filamentous.

Phytoplankton – aquatic unicellular algae suspended in the water column.

Dinoflagellates – A taxonomic class of phytoplankton that have two flagella and therefore have some control upon their movements within a water column.

Diatoms – A taxonomic class of phytoplankton that have a silica frustule. i.e. require silica for growth.

Primary producers – autotrophic organisms able to manufacture complex organic substances from simple inorganic compounds.

Primary production – a scientific measure of the above process.

Nutrient – a substance that provides nourishment for living organisms, and therefore is essential for growth.

Limitation of phytoplankton production – The standing crop of phytoplankton may only increase if conditions are favourable to do so. Such conditions include temperature, light, water column stability, and nutrients (C, N, P, Si). Growth will only be achieved if these conditions are favourable. If one of these conditions is not met and is therefore restricting an increase in phytoplankton biomass it is said to be 'limiting'. Also of importance are losses via grazing by primary consumers, sedimentation, and hydrographic movements out of the area of consideration.

8.3. Chemical

Nitrogen – The major inorganic forms of nitrogen in seawater are

N_2 (dinitrogen)

NO_3^- (nitrate)

NO_2^- (nitrite)

NH_4^+ (ammonium)

NH_3 (ammonia)

The first and last of these are gases and not available to algae for growth, whereas the remainder are available for primary production and are thus to an extent biologically mediated.

In this report nitrogen species are further grouped as follows:

TON (Total Oxidised Nitrogen) = $NO_3^- + NO_2^-$

DIN (Dissolved Inorganic Nitrogen) = TON + NH_4^+

In natural marine waters > 80 % of the DIN is NO_3^- and > 90 % of the TON is NO_3^-. The balance between ammonia and ammonium is predominantly dependent on pH although in natural marine waters ammonium is present in far greater concentrations.

Phosphorus –Inorganic species of phosphorus in marine waters are present as phosphates as follows:

PO_4^{3-}

HPO_4^{2-}

$H_2PO_4^-$

H_3PO_4

The extent of protonation is dependent on pH. Seawater has a pH of ~ 8.2 and therefore ~ 80 % of phosphates are present as the monoprotonated form. Polyphosphates are mainly derived from organic detergents and are long chained oxidised phosphorus molecules.

SRP (Soluble Reactive Phosphorus) is the soluble (operationally defined) proportion that is reactive with molybdate. This is proportional to the concentration of phosphorus present in seawater as orthophosphate. This is also the phosphorus that is available for uptake by primary producers.

Silicate – The vast majority of dissolved silicon in seawater is present as SiO_2 (Silicate), which is available for uptake by diatoms, and is the proportion measured by spectroscopy after complexing with molybdate.

Chlorophyll 'a' – chlorophyll's are the principle photosynthetic pigments in phytoplankton of which chlorophyll 'a' is the most common. Therefore the concentration of chlorophyll 'a' may be used as an indicator of phytoplankton biomass.

Salinity – a measure of salt in seawater measured in p.s.u. (practical salinity units) which is a dimensionless number.

Appendix 1

A box plot is a chart that indicates the central tendency of the values, their variability, the symmetry of the distribution, and the presence of outliers (values very different from the others). Box plots are often used to compare several sets of data.
There are several ways to display a box plot. XLSTAT uses the following format:

- the lower edge of the box represents the first quartile Q1,
- a black line represents the median Q2 ,
- a red line represents the average,
- the upper edge of the box represents the third quartile Q3

Two intervals are defined on either side of the first and third quartiles:

$IQ1 = [Q1 - 1.5 \times (Q3 - Q1) , Q1]$
$IQ3 = [Q3 , Q3 + 1.5 \times (Q3 - Q1)]$

- the lower part of the box plot reaches from Q1 to the value nearest to the lower bound of IQ1, while remaining within IQ1,
- the upper part of the box plot reaches from Q3 to the value nearest to the upper bound of IQ3, while remaining within IQ3,
- the values underneath the lower part and above the upper part are represented individually by circles. These circles are filled in when the values are more than 3 times the distance between the quartiles (Q3 – Q1), and are empty if they are within that interval,

- the minimum and maximum values are shown in the box plot.