Environmental RTDI Programme 2000–2006

NUTRIENT LEVELS AND THE ZEBRA MUSSEL POPULATION IN LOUGH KEY (2000-MS-5-M1)

Synthesis Report

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Prepared for the Environmental Protection Agency

by

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Executive Summary

The zebra mussel (*Dreissena polymorpha*) is an aquatic invasive species which spread to Lough Key, Co. Roscommon, from the lower Shannon in the late 1990s. The mussels have been monitored in this 9-km^2 lake each year since 1998. By 1999, the population estimate was 6 billion (6×10^9) with high cover of zebra mussels on stones in near-shore areas of the lake. This project was a 3-year study (2001–2003) on the impact of nutrients on the zebra mussel population in Lough Key (2000-MS-5-M1: ERTDI programme), which included some previous data from 2000.

Zebra mussels are effective filter feeders, with high individual clearance rates of phytoplankton, cyanobacteria and other particles. Successful colonisation of a lake results in increased transparency and decreased chlorophyll levels and often a consequent decrease in total phosphorus. Since 1999, these changes have been noted in Lough Key. Transparency and chlorophyll levels indicate an improvement in trophic status (to oligotrophic) but total phosphorus levels are still within the mesotrophic range and have not reached limiting levels. These direct impacts create problems in classifying lakes according to existing (OECD) and developing (Water Framework Directive 2000/60/EC) classification schemes.

The construction of the new Boyle Sewage Treatment Plant with a phosphorus removal system has reduced the loading of total phosphorus to Lough Key. It was believed that the reduction in phosphorus loadings could have a limiting effect on zebra mussels in Lough Key, due to a consequent reduced production of phytoplankton. It is not possible to separate the nutrient impact this species has had on lake water quality from that due to the new sewage treatment plant.

The project aimed to quantify the total number and biomass of zebra mussels and also to assess any changes to the population during the course of the study. Relevant water parameters and phytoplankton samples were analysed; direct ecological changes were also noted during the project.

Zebra mussels were studied at all stages of growth from larva/veliger stage, through juvenile settlement and most intensively in the juvenile and adult stage (0–3 years). The total number of adult zebra mussels in the lake was estimated at 34 billion (34×10^9) with a total biomass of 4.4×10^6 kg. This number is believed to relate to a more effective method of population estimate, rather than any real increase since 1999. This population is capable of filtering the entire volume of Lough Key in a 10-day period.

Biomass estimates taken in 2001 and 2003 were not significantly different – this indicates that changes in total phosphorus did not limit the zebra mussel population during the course of the study. Food availability appears to be the main density-dependent limiting factor in the lake, as many stony areas are not fully colonised.

Ecological changes noted during the study included the extirpation of the native duck mussel, *Anodonta anatina*, reduced usage of the common reed (*Phragmites australis*) as a substrate and increased growth of aquatic plants and benthic algae.

1 Introduction

1.1 Project Objectives

The main objective of this 3-year project was to develop a clear understanding of the role of the zebra mussel in lake ecosystems and in particular the relationship between phosphorus concentrations, zebra mussel populations and the trophic status of Lough Key. The objectives also aimed to:

- Contribute to a better environment by delivering applicable and relevant research data and information based on high quality science and technology
- Generate data, information and knowledge for improved management of the environment, and
- Develop new techniques, methods and systems for measuring, recording and predicting the quality of the environment. This is in line with the development aims of the Water Framework Directive (2000/60/EC), which has been transposed into national law (SI No. 722 of 2003).

1.2 Project Tasks

- Substrate and bathymetric mapping of Lough Key provided a depth (bathymetric) chart and a sediment map of the lake based on a hydro-acoustic RoxAnn™ survey. Underwater video survey work was also used to map shallow areas.
- Monitoring of zebra mussel populations (larval, juvenile and adult) in littoral, open water and benthic zones of Lough Key both before and after the commissioning of the new Boyle Sewage Treatment Plant (Boyle STP) (2000–2003). Total number of zebra mussels in Lough Key was assessed using a transect survey (2002).
- Measurement of light penetration and chlorophyll levels in the lake to assess the impact of the zebra mussel population on light penetration in the lake and on the composition and extent of algae (2000–2003).
- Collation and analysis of relative phytoplankton and cyanobacterial abundance from EPA data sets (2000–2003).
- Input and analysis of phosphorus data from (1) Boyle Sewage Treatment Plant (P loadings to lake) (Roscommon County Council), (2) Boyle River upstream and downstream of the treatment plant (Lough Ree–Lough Derg project data) and (3) Lough Key data (EPA monitoring programme) (2000–2003).
- Statistical testing of zebra mussel data sets for a possible response due to the commissioning of the new treatment plant.

Appendix 1 lists the personnel involved in each part of the research process and the timescale involved in their work.

Firstly, a brief overview of lake trophic status and classification scheme will be given, followed by a short introduction to the zebra mussel, its life cycle and arrival in Ireland (with consequent impacts).

1.3 Trophic Status in Lakes

Lake water quality is most commonly assessed by reference to a scheme proposed by the Organisation for Economic Cooperation and Development (OECD, 1982). This scheme (Table 1.1) defines trophic categories (water quality of lakes) by setting boundaries for annual average

Table 1.1. Trophic classification scheme for lake waters proposed by OECD (OECD, 1982).

Lake category	Total phosphorus (mg/m^3)	Chlorophyll (mg/m^3)		Transparency (m)	
	Mean	Mean	Max	Mean	Min
Oligotrophic	<10	<2.5	<8.0	>6.0	>3.0
Mesotrophic	10–35	2.5–8.0	8.0–25.0	3.0–6.0	1.5–3.0
Eutrophic	35–100	8.0–25.0	25.0–75.0	1.5–3.0	0.7–1.5
Hypertrophic	>100	>25.0	>75.0	<1.5	<0.7

values for total phosphorus, chlorophyll and water transparency. In Ireland, a modified version of this scheme is used, which is based on annual maxima results for chlorophyll. Lakes are categorised as oligotrophic (very low level of pollution), mesotrophic (low level of pollution), eutrophic (significant to high level of pollution) and hypertrophic (very high level of pollution) (McGarrigle *et al.*, 2002).

1.4 Invasion History and Impacts

The zebra mussel, *Dreissena polymorpha*, is a freshwater bivalve, which attaches to hard substrates (surfaces) by what are known as byssal threads. It is native to the Black Sea and Caspian Sea basins and spread through much of Europe almost 200 years ago with the development of canal systems. By 1830, the species had become established in Britain. In Ireland, the initial introduction of the zebra mussel is believed to have taken place in 1994 in the lower Shannon system (McCarthy *et al.*, 1998; Minchin and Moriarty, 1998). Imported second-hand leisure craft were the most likely vectors for their introduction. Live zebra mussels of English origin were found on the hulls of leisure craft on arrival in Ireland, over the period 1997–2001. Irish zebra mussels have also been genetically linked to English populations (Pollux *et al.*, 2003). Once established, significant zebra mussel settlement took place on native leisure craft and these mussels were carried to the upstream Shannon navigation via locks and swing bridges (Minchin et *al.*, 2002a). Large populations now exist in Loughs Derg, Ree, Bofin and Key. By 1996, zebra mussels had become established in Lower Lough Erne (Rosell *et al.*, 1999) and in the following year were present in Upper Lough Erne.

Further spread continued in the early years of the new millennium. At least 55 waterbodies are now known to be infested, including Loughs Sheelin, Gill and Derravaragh. Investigations in the summer of 2003 indicate a number of potential vectors in the spread of zebra mussels in Irish lakes; the primary vector is believed to be the overland movement of boats fouled by zebra mussels (Minchin *et al.*, 2003).

The growth and spread of the zebra mussel in Ireland has shown the species to be an aggressive competitor for substrate space. It is also an effective filter feeder with high individual clearance rates (Horgan and Mills, 1997), which has subsequent implications for both water quality and ecosystem processes. In addition to these impacts there is a financial cost to man, as this aquatic nuisance species is a very effective biofouler, capable of blocking up water abstraction pipes, damaging boat engines, sinking navigational buoys and creating other damage.

1.5 The Life Cycle of the Zebra Mussel *Dreissena polymorpha*

The zebra mussel life cycle consists of a relatively stationary adult phase and a planktonic, free-living larval stage. Sexes are separate, with mussels usually becoming sexually active in the summer season, at 1 year old. On the Shannon system in Lough Derg, gonads and gamete development were observed in mussels in all months and in all sizes of mussel from 6.0 mm up to 25.9 mm (Juhel *et al.*, 2003). In Europe, some survive as long as 9 years, but usually live from 3 to 5 years (Marsden, 1992). Many size distributions have been taken at different times of the year throughout the Shannon navigation system (Minchin *et al.*, 2002b). It would seem from the largest individuals found (38 mm) that the species may exceed a 3-year life cycle in Ireland, but that most of the population survive between 2 and 3 years and these spawn each summer from the 1+-year-old stage onwards.

Egg production estimates per mussel lifetime are over 1.5 million and fertilisation occurs externally (Nichols, 1996). Temperatures above 12°C have been reported as necessary for spawning but other factors may be involved, e.g. food availability, current patterns and other limnological variables (Haag and Garton, 1992). Embryological development follows the typical bivalve pattern. Relatively strong correlations have been found between temperature and food supply and the rate of growth in zebra mussels (Chase and Bailey, 1999). The developing juvenile acquires a mussel shape, with the distinctive banded pattern and begins to form its feeding apparatus at approximately 1 mm in size (Ackerman, 1995). The amount of time required for development of a fertilised egg to a juvenile varies inversely with water temperature and has been reported in the literature as typically 8–15 days in American waters (Marsden, 1992) and 7–10 days in Europe at favourable temperatures (Hillbricht-Ilkowska and Stanczykowska, 1969). Typical larval development time for Irish waters is between 2 and 3 weeks in the July/August period, with settling out occurring from 200 to 370 µm (Lucy and Sullivan, 2001). Mortality in larvae and newly settled individuals has been reported at levels from 20% up to 100%, most occurring late in the cycle during metamorphosis and settlement (Stanczykowska, 1977; Lewandowski, 1982; Sprung, 1989). The first year of significant spawning of zebra mussels in Lough Key was 1998.

1.6 Lough Key Zebra Mussel Populations and Nutrient Inputs

The zebra mussel population in Lough Key is supported by suspended material in the lake water. This material consists of organic matter, planktonic algae and cyanobacteria. The latter two components are sustained by phosphorus, believed to be chiefly derived from the waste discharge at Boyle STP. This STP was upgraded in March 2000 to include a phosphate removal system. When the new plant was commissioned there should have been a marked reduction in the nutrient loading on the lake, leading to depleted quantities of food available to the zebra mussels. This hypothesis provided a research opportunity in Lough Key to investigate the combined interactions between the reduced phosphorus input to the lake with the planktonic algae, the cyanobacteria standing crop and the zebra mussel populations.

There has been a considerable investment made in the River Shannon catchment for waste treatment facilities (including phosphorus removal), with the ultimate aim of reducing nuisance algal and plant growth in the lakes. It is therefore important that all the processes impacting on this growth are understood and quantified. There is a popular view that there may be no need to reduce phosphorus losses to waters in the River Shannon system as zebra mussels will take care of the ensuing algal growth. This misconception needed to be challenged with facts arising from a systematic study.

1.7 Substrates for Zebra Mussel Settlement

Primary settlement occurs on a wide range of substrates. North American and European research experience has shown that mussels can make byssal attachment to any firm surface material including:

- Natural substrates, e.g. stone, wood, aquatic plants and the shells of the native duck mussel, *Anodonta.* While it was initially believed that a firm substrate was critical for settlement, studies in Lake Erie have shown successful colonisation in areas where the actual substrate is a soft, muddy sediment (Berkman *et al.*, 1998).
- Other substrates usually introduced by man, e.g. concrete, plastic, fibreglass, metal, vinyl, glass and cloth. High settlement densities on man-made structures are financially costly, requiring strategic management and control strategies.

While initial primary settlement dominates the settlement patterns of the zebra mussel, secondary settlement may also occur in juvenile or adult zebra mussels. Translocation can take place to new locations via a number of mechanisms, including movement onto substrates and surface films, drifting using specially secreted threads, floating on air bubbles and rafting on aquatic plants and other flotsam (Martel, 1993; Ackerman, 1995). Probably the most important means of secondary settlement is by translocation on boats and barges.

1.8 Lough Key as a Study Area

Lough Key is situated in the Upper Shannon catchment (G830 060) and is located on the Boyle River, which flows into the Shannon above Carrick-on-Shannon. The Lough Key catchment is a mixture of sandstone, shale and limestone, resulting in a wide variation in ionic content of the waters of the inflowing streams. The lake water is of high ionic content, alkaline and strongly coloured, with low transparency. Lough Key is currently classified as mesotrophic, with reduced planktonic algal growth. It is believed that the presence of zebra mussels may be the principal factor in this reduction from eutrophic levels (McGarrigle *et al.*, 2002). This lake is uniquely suitable as a lake for zebra mussel sampling due to a number of factors:

- The lake is small (9 km^2), mean depth 4.5 m, with only one major inflow and outflow (the Boyle river).
- Zebra mussel population studies have been carried out since the early stages of invasion in 1998, the first year of population expansion in this lake.
- Water quality parameters associated with zebra mussels have also been monitored in conjunction with the above. These include chlorophyll *a*, transparency and different types of phosphorus.
- Significant changes in lake water quality can be directly associated with increasing zebra mussel populations between 1998 and late 2000. From 2001 onwards the new phosphate removal facilities in Boyle STP may also have contributed to such changes. EPA data sets for water quality prior to

zebra mussel invasion are available for baseline comparisons. Changing trends in water quality or in phytoplankton communities (e.g. *Microcystis*) can thus be monitored.

- Zebra mussel populations can be examined on a number of substrates – stony substrates, reed beds and *Anodonta* shells. In common with many Irish lakes, the littoral zone (near shore) substrate of Lough Key is often stony. Some of the perimeter of the mainland and islands is also fringed with reed beds. No living *Anodonta* have been found in the lake since 2000, due to extreme fouling of the shells by zebra mussels. Impacts of the zebra mussel on other native bivalves have been researched extensively both in Europe and North America (Lewandowski, 1976; Ricciardi *et al*., 1995; Schloesser *et al*., 1996; Karatayev *et al*., 1997). Negative impacts are believed to be due to smothering, prevention of opening and closure, and by interference with normal feeding patterns (Ricciardi *et al*., 1995).

1.9 Impact of Zebra Mussels on Water Quality and Phytoplankton

The key indicator in assessing the water quality or trophic status of a lake is the determination of the extent of plant growth, both planktonic (floating) and benthic (on the lake bottom), in the water. In the case of the planktonic forms, this assessment is most commonly expressed in terms of the concentration of the algal pigment chlorophyll. The extent of planktonic algae is a function of the nutrient levels, principally phosphorus, present in the lake and also of the extent of grazing by other organisms.

Up to relatively recently, zooplankton and fish were the only grazers of planktonic algae in Lough Key. A decade or so ago, a further and more significant grazer, the zebra mussel was introduced to the Shannon system. Zebra mussels are extremely efficient filter feeders and this has been well documented in both European and North American literature. Zebra mussels draw water through their mantle cavity but use only a portion of the seston particles for their digestion, while the rest is agglutinated as pseudo-faecal pellets and ejected (Stanczykowska and Planter, 1985). Many of the studies on zebra mussel ecology have concentrated on the types and size of phytoplankton consumed by zebra mussels (Sprung and Rose, 1988; Holland, 1993; Jack and Thorp, 2000; Wilson, 2003; Dionisio Pires *et al*., 2004). As zebra mussels can readily reject food particles as pseudo-faeces, research has also assessed whether this species is selective in its feeding habits (Ten Winkel and Davids, 1982; Vanderploeg *et al.,* 1996). One likely theory is the selection of more desirable algal species with rejection of less palatable cyanophytes (Nalepa *et al*., 1999). Observations using micro-cinematography show that zebra mussels reject the cyanophyte, *Microcystis*, which can have toxic strains, as pseudo-faeces (Vanderploeg *et al*., 1996). This could lead to toxic strain dominance in algal blooms with consequent public health issues (Chorus and Bartram, 1999 cited in Dionisio Pires *et al*., 2004).

Cyanobacteria were generally the dominant organisms in the plankton in Lough Key in 1998 and 1999, with *Microcystis* forming the most important constituents of this population (Bowman, 2000). *Microcystis* is associated with toxic blooms and thus has implications for water-based leisure activities and potable water supplies.

Zebra mussel adults are capable of filtering particles ranging in diameter from 0.7 µm (Sprung and Rose, 1988) to 1.5 mm (Horgan and Mills, 1997). Ingestion is selective and unsuitable particles are rejected as pseudo-faeces via the exhalent siphon (Ten Winkel and Davids, 1982). These particles include phytoplankton, cyanobacteria, zooplankton, microorganisms, detritus and inorganic suspended solids. Thus, the zebra mussel is capable of removing abiotic as well as biotic material from the water. By removing large amounts of suspended matter, populations of zebra mussels have the ability to alter transparency and plankton abundance (Holland, 1993). The increase in light penetration in the water column creates conditions favourable for benthic algal and other aquatic plant growth.

The filtering activity of zebra mussels has the direct effect of reducing nutrients, which are associated with particles and plankton. These are either assimilated into zebra mussel biomass or rejected and deposited on the substrate as faeces and pseudo-faeces. As a result, energy is shifted from the water to the lake bottom and changes occur in the normal pathways by which nutrients are utilised and cycled (Nalepa *et al*., 1999).

Ranges of the mean summer total phosphorus, chlorophyll *a* and transparency concentrations in Lough Key for 1976 are available in Toner (1979). Data for 1986 are available from AFF (An Foras Forbatha) and data from

1995 to 1997 are in Bowman (1998). These reports indicate a decline in trophic status between 1986 and 1997. There was a subsequent improvement in levels from 1998 onwards with total phosphorus concentrations in the summer of 1999 much reduced from 1996 and 1997 levels (Bowman, 2000).

A significant reduction in annual mean total phosphorus concentrations from 1998 levels was recorded in Lough Erne during 2000 and 2001 (Maguire *et al*., 2003). This trend in total phosphorus level was in line with results obtained in some North American (Johengen *et al*., 1995; Nalepa *et al*., 1999) and European studies (Stanczykowska and Planter, 1985).

The monitoring of the zebra mussel populations in Lough Key commenced in 1998 (Lucy, unpublished) and was supported through 1999 by the EPA with a small-scale project which established baseline information on the existing populations in the lake (Lucy and Sullivan, 2001). Simple maps were prepared of zebra mussel distribution in the lake as well as information on their adult and juvenile densities. An estimate was also made of the filtering capacity of the existing population. A further independent survey was carried out by the authors in the summer of 2000. This was considered vital as valuable information would be lost if there was a break in the continuity of the investigation. A research extension in terms of scale, technology and coverage was fortunately provided under the ERTDI programme (2000–2006).

2 Materials and Methods

Section 2.1 outlines project sampling locations and programmes while Section 2.2 details methodologies.

2.1 Monitoring Programme

An extensive monitoring programme was carried out for a range of physical and biological parameters. Water temperature, transparency and chlorophyll *a* samples were taken at the four sampling sites used in the 1998 and 1999 surveys (Lucy and Sullivan, 2001). An additional site was added to the survey at the northern end of the lake from 2000 onwards (summer only), as this had been noted for high populations during the 1999 survey. A monitoring programme for zebra mussel larvae and settlement also took place at the above sites. Figure 2.1 shows the five Lough Key monitoring stations (Sites A–E). Weekly sampling was implemented from July to mid-September. Fortnightly sampling was carried out from March to June each year and also from late September to the end of October in accordance with the scheduled sampling programme. Sampling for transparency and chlorophyll *a* was also carried out in summer 2000, *a priori* to this project. These results were included in this report.

2.1.1 *Adult zebra mussel sampling*

Eight sampling stations (Sites 1–8) were selected as snorkelling sites at the commencement of the project in 2000 and were re-surveyed in August 2001 and 2003 (Fig. 2.1). Video reed bed survey sites corresponded with these sites. Adult samples were taken along eight transects for an assessment of total population and biomass in the lake. Four standard axes were chosen in order to map the lake efficiently and avoid any bias.

2.1.2 *Phytoplankton sampling*

Phytoplankton samples were taken by the EPA at sampling Station C (G835 053) during the following periods: March 2000, 2002 and 2003; April 2001; July 2000–2003; September and October of 2000, 2001 and 2003. The data sets produced were used in this project.

2.1.3 *Phosphorus sampling*

- EPA data for the report are from the five Lough Key stations (A–E) used in annual surveys as selected by Toner (1979). The sampling schedule was the same as for phytoplankton sampling. An additional sample was analysed in November 2002.
- Roscommon County Council (RCC) monitoring focused on the effluent discharge point at Boyle STP.
- Boyle River data (RCC/ Lough Derg and Lough Ree Survey) were from two stations on the Boyle River. One was 0.5 km upstream (approx.) of Boyle STP at Boyle Abbey (G807 027) and the other was 1.1 km (approx.) downstream of the plant at Drum Bridge (G817 040). These sites were sampled on a monthly basis.

2.2 Sampling and Analysis Procedure

2.2.1 *Transparency and chlorophyll* a

Transparency: A standard 25-cm black and white Secchi disc was used to measure transparency.

Chlorophyll a *determination*: Two-litre water samples were removed from just below the water surface at each of the six sampling sites on each sample date, during the course of the field study. Replicate 1-l samples for each site were filtered through GF 50 glass fibre filter papers within 3 h of sampling, placed in individual bags, labelled and frozen. Subsequent laboratory analysis carried out regularly on sample batches included defrosting, followed by immediate chlorophyll *a* analysis according to standard EPA procedure.

2.2.2 *Temperature*

A temperature datalogger (Vemco minilog V3.04) was deployed at Tara Cruisers (monitoring station D) to record temperatures over the entire sampling programme. Temperature was also recorded with an alcohol thermometer at both Tara Cruisers and Bullock Island Buoy (monitoring station A) during the course of the survey.

2.2.3 *Nutrients*

Total phosphorus and orthophosphate were analysed in the EPA laboratory, Dublin, and in the RCC laboratory, using standard methods. Results were collated and relevant parameters were reviewed for the project.

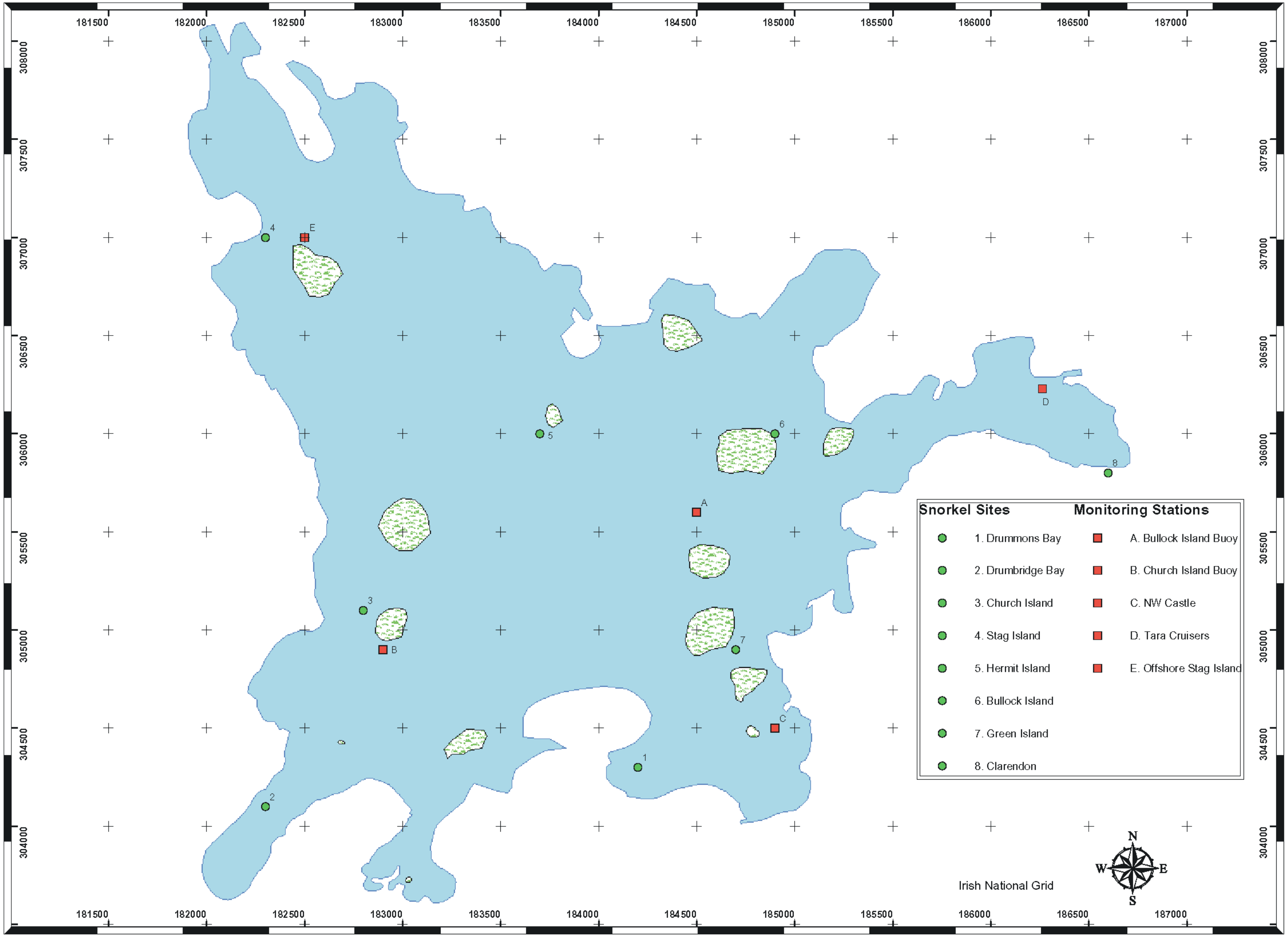


Figure 2.1. Sampling sites in Lough Key.

The Boyle STP flow and total phosphorus data were used to determine total annual phosphorus loadings (tonnes TP/year) to Lough Key. TP (total phosphorus) loadings/m^2 to Lough Key were calculated by dividing the annual Boyle STP loadings by the surface area of the lake.

The trophic status of a lake can be predicted using the relationship between mean depth, annual phosphorus loading (g P/m^2/year) and hydraulic retention time (τ_ω/year) (Vollenweider, 1975). This relationship was calculated for Lough Key in 1975 and 1976) (Toner, 1979) and was also used for this research to predict whether total phosphorus loadings should result in an oligotrophic or mesotrophic status in Lough Key during each year of the zebra mussel survey. Total phosphorus loads (g P/m^2/year) were estimated by multiplying the annual P load/g/year by the total lake area (9 km^2).

2.2.4 Phytoplankton and cyanobacteria

All samples were fixed in Lugol's solution and transported to the EPA laboratory, Dublin. A qualitative examination of the phytoplankton and cyanobacteria in each sample was carried out using an inverted microscope. Taxa were identified and an indication of relative abundance recorded.

2.2.5 Zebra mussel life stage sampling

Sampling of early zebra mussel life stages (larvae/veligers and settled juveniles) has been largely adapted from a monitoring programme designed by Marsden (1992). The adult zebra mussel sampling programme was devised by the research team. The transect survey methodology was adapted from Karatayev *et al.* (1990).

2.2.5.1 Veliger/larval sampling and analysis

(a) General monitoring programme: Vertical tows were carried out at the five monitoring sites (A–E). A 64-µm mesh plankton net with a 30-cm diameter opening was used for veliger sampling, allowing collection of all veligers >70 µm.

(b) Estimation of veliger/larval density and size distribution: For the monitoring programme each sample was examined under a high magnification (80–100×) microscope using 1-ml subsamples in a Sedwick–Rafter Counting cell. Three 1-ml subsamples were counted and the veliger density per ml of concentrated sample calculated from the mean as follows:

$$\frac{\text{Number of veligers/ml} \times 25^{a}}{\text{Volume of sample}^{b}}$$

[a]Volume in 25-ml tube

[b]$3 \times 3.14 \times (0.3)^2$ = length of tow x $\pi \times$ radius of net mouth^2 = 848 l.

2.2.5.2 Settled juvenile sampling

Settled juveniles were sampled using 15-cm^2 grey PVC plates with three plates deployed in series at each site as in Lucy and Sullivan (2001). The rope was tied at the top to a navigational buoy at Sites A, B, C and E and held in position from a jetty at Site D. The settlement plates were suspended from a concrete anchor weight, which held the plates firmly in mid-water (3 m depth approx). All plates were conditioned for 1 week to allow a biofilm to build up, thus encouraging settlement. The top plate at each site remained unchanged and was removed twice during the 2001 season (21 July and 21October) and once during the 2002 and 2003 seasons to estimate total seasonal settlement of juvenile zebra mussels. On each sampling date beginning early/mid-June, either the bottom or the middle plate was changed on a 2-week rotation. The mean of 30 × 1 cm^2 quadrats was obtained for each plate and an estimated density (m^2) calculated.

2.2.5.3 Adult sampling

Adult sampling was undertaken as part of snorkel surveys, prior to and during the project (August 2000, 2001, 2003), during the course of the transect survey (2002) or as part of ongoing monitoring.

(a) Snorkel surveys: In 2000, 2001 and 2003 eight sampling stations were surveyed by snorkelling (Fig. 2.1) to examine the biomass and size distributions of each zebra mussel population. Substrates examined included stony substrate, *Anodonta* shell, the common reed *Phragmites australis* (old and new), common club-rush *Schoenoplectus lacustris* and other plants, where present.

(b) Transect survey – sampling density and biomass of adult zebra mussels: Samples were taken along eight transects in order to study the density and biomass of adult zebra mussels in the lake. In order to acquire good, complete data sets, two methods of sampling analyses were used, namely grab sampling and scuba diving. A quadrat frame size 25 × 25 cm (sampling 0.0625 m^2) was used for sample collection by scuba diving. Since it was not feasible to dive the complete transects until they met

in the centre, a Van Veen grab was also used (1/40 m^2, i.e. 0.025 m^2). At each site/depth interval, a replicate of three samples was collected.

(c) Monitoring: Adults were also sampled periodically during the 3-year project from a jetty due east of Drummons Bay (Site 1). These were scraped from the vertical surface of the Rockingham jetty (G845 043) using a scraper attached to a 3-m pole (Minchin *et al.*, 2002b). A size distribution and biomass were taken for each sample.

2.2.6 Estimation of filtration capacity of zebra mussel populations in Lough Key

The transect survey provided the wet biomass of zebra mussels in the lake. A filtering rate of 44.4 ml/g wet tissue mass/h was obtained by taking the mean of five independent European surveys carried out at similar summer temperatures (Kondratiev, 1962; Stanczykowska, 1968; Lvova, 1977; Karatayev and Burlakova, 1993, 1995). The product of the biomass and the filtering rate was multiplied by 24 (hours) to give the daily filtration capacity of the zebra mussels in Lough Key. The lake volume (46×10^6 m^3) was divided by the filtration capacity to estimate how quickly the population could filter the entire lake during the summer period.

2.2.7 RoxAnn™ survey, computer analysis, groundtruthing and video surveys

The methodology for this survey is outlined in detail in Chapter 3 of the Main Report.

3 Results

3.1 Bathymetric Results

Table 3.1 gives the total area and percentage of depth zones in Lough Key; estimated by RoxAnn™ survey 58.9% of the lake is less than 5 m in depth. The mean depth of the lake is estimated at 4.5 m, slightly less than the 5 m result in Toner (1979); 84.7% of Lough Key is less than 10 m depth.

Table 3.1. Total area and percentage of depth zones in Lough Key, estimated by RoxAnn™.

Depth zone	Area m^2	% Lake
0–<2	673,124	8.0
2–<3	1,628,144	19.3
3–<4	1,809,059	21.5
4–<5	849,639	10.1
5–<6	506,684	6.0
6–<10	1,663,774	19.8
10–<14	805,490	9.6
14–<18	355,157	4.2
18–20	61,619	0.7
18–<22	46,297	0.5
>22	25,086	0.3

3.2 Habitat Map

Figure 3.1 shows the four main substrates found in Lough Key by the RoxAnn™ survey:

- Substrate 1: Mud – the main substrate in the lake
- Substrate 2: Transitional (mainly mud with various proportions of shell, sand and/ or gravel components)
- Substrate 3: Stone, *Anodonta*, gravel
- Substrate 4: Rock.

The map also includes depth contours at 3-m depth intervals. Figure 3.1 can also be viewed as a habitat map, with areas marked as substrate Categories 3 and 4 ideally suited to zebra mussel colonisation, Categories 2 and 1 as occasionally suited to zebra mussel colonisation. Shallow areas close to shorelines (shown as triangles in Fig. 3.1) mapped by video survey, are generally suitable for zebra mussel colonisation as most sites have a percentage of rock, stone, *Anodonta* or pebble present. Colonisation of shallow areas was corroborated by snorkel and dive work (for transect and snorkel site surveys) during the course of the project (2001–2003) and earlier (1999–2000). This habitat map provided a very important baseline for some of the investigative work on zebra mussel populations in the lake during the course of the project.

3.3 Transparency

Zebra mussels remove a wide range of particulate matter from the water column (Hebert *et al.*, 1991). The population began to increase rapidly in 1998 and a corresponding increased water transparency has been recorded since 1999 (Bowman, 2000; Lucy and Sullivan, 2001). Transparency continued to increase, at the beginning of the project, with a value of 3.4 m recorded in 2001. There was no significant increase in transparency in 2002. Water transparency was typically low during the early part of 2003 with levels increasing during June due to drier, calmer weather conditions.

Although there was no significant increase in overall transparency in 2003, transparency increased over the summer season and results in late October averaged 3.8 m, the highest recorded during the project period.

3.4 Chlorophyll *a*

The results for chlorophyll *a* are dealt with in chronological order, from 2000 to 2003.

3.4.1 2000 and 2001

Most individual values outside the summer period fall within the oligotrophic category (<8 mg/m^3). In general, levels between mid-June and late August 2000 and 2001 are mesotrophic (8–25 mg/m^3) (OECD, 1982) with elevated values corresponding to seasonal algal blooms.

3.4.2 2002

Chlorophyll *a* results for the sampling period were low, with a maximum level of 9.73 mg/m^3 recorded at Site A on 22 August 2002 during a slight algal bloom. These results indicate that Lough Key could almost be classified as oligotrophic during 2002 (OECD, 1982) although results were not significantly lower than in 2001 (Mann–Whitney test, P >0.05).

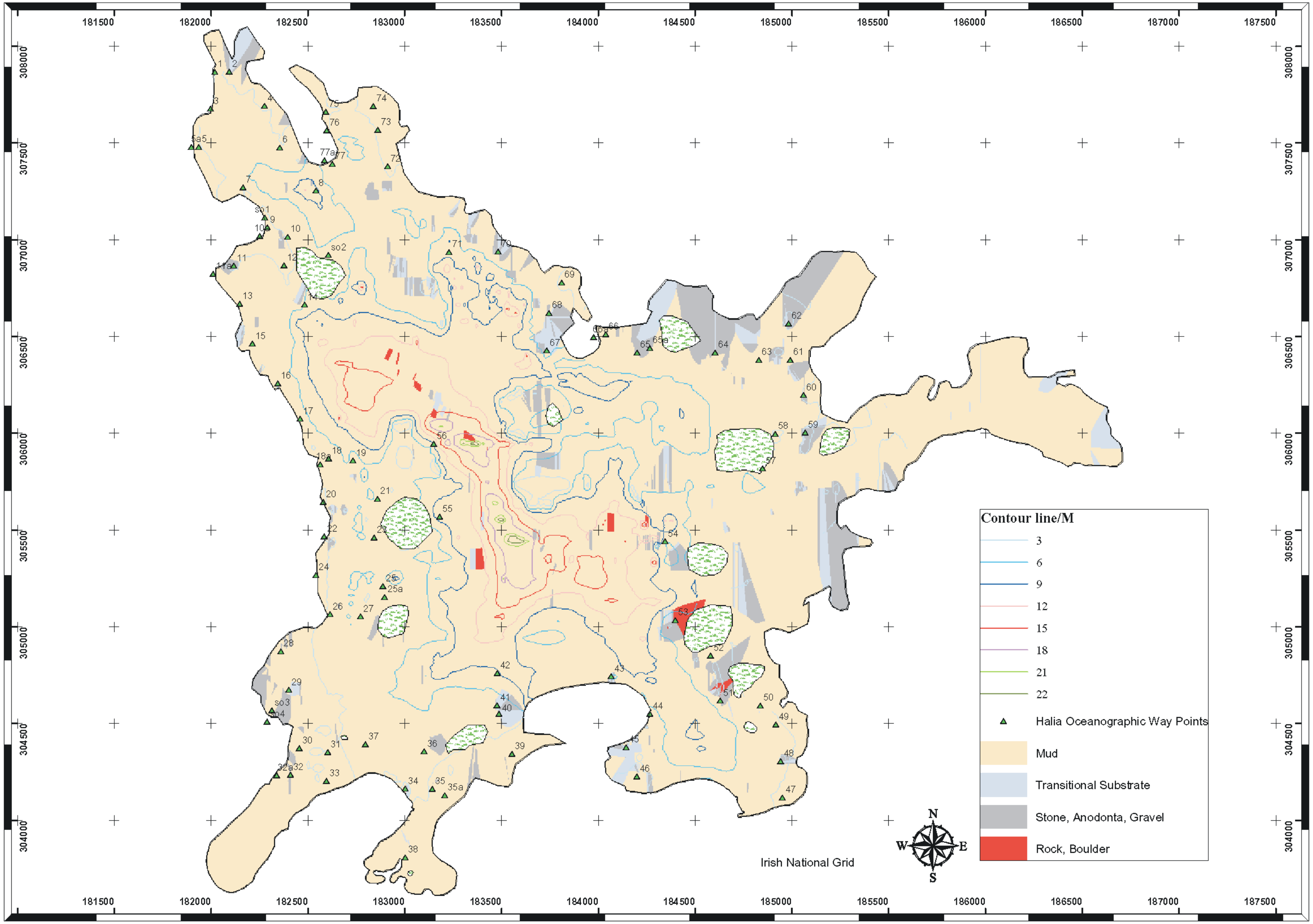


Figure 3.1. Map of Lough Key showing the four main substrates and depth at 3-m contour levels.

3.4.3 2003

March/April results for chlorophyll *a* were low as anticipated with a maximum level of 7.49 mg/m^3 recorded at Site B on 11 April 2003. June results were higher than those obtained in 2002, with mesotrophic levels recorded on 15 June 2003 at Sites C and D (11.18 and 10.99 mg/m^3, respectively). A level of 10.22 mg/m^3 was recorded at Site E on 30 June 2003. Chlorophyll *a* results for the 2003 sampling period were not significantly higher overall than in 2002 (Mann–Whitney test, $P > 0.05$) but reached a maximum level of 22.38 mg/m^3, recorded at Site C on 22 July 2003, during a slight bloom. From 54 samples taken over an 11-week period (31 May 2003–9 September 2003), 31 were <8 mg/m^3. Lough Key could be trophically classified as mesotrophic in terms of chlorophyll during 2003 (OECD, 1982).

3.5 Temperature

Annual and seasonal trends in water temperature were noted between November 2001 and December 2003 in the lake. Summer 2003 temperatures (maximum 22.4°C) were, on average, warmer than the previous summer. Weekly monitoring of temperatures also indicated that 2003 had higher water temperatures than any other year during the survey. Annual zebra mussel spawning in the lake corresponded to temperatures greater than 13°C, with larva detected from late May onwards depending on early-summer rising water temperatures.

3.6 Phosphorus Results

Table 3.2 shows range and mean total P (mg/l) concentrations in Lough Key from 2001 to 2003. The results are somewhat skewed due to occasional high values obtained in analysis. They do however show a significant decrease in mean total phosphorus levels over the 3 years. TP loadings/m^2 from Boyle STP for the project years 2001–2003 and TP loads in g P m^2/year to Lough Key are given in Table 3.3. Weighted total mean phosphate concentrations for Boyle STP treated effluent were 0.82 mg/l in 2001, 0.83 mg/l in 2002 and 1.22 mg/l in 2003. This is considered to be the main source of phosphorus in the lake catchment.

Figure 3.2 shows Vollenweider's relationship between annual phosphorus loading (g P/m^2/year) and ratio of mean depth (Z) to hydraulic residence time (τ_ω) for the 'permissible' and 'excessive' steady-state concentrations of phosphorus (0.01 and 0.02 mg P/m^3). Lough Key

Table 3.2. Mean and range of total P mg/l in Lough Key, 2001–2003.

Year	Mean TP mg/l	Range TP mg/l
2001	0.183	0.020–2.250
2002	0.04	0.020–0.182
2003	0.027	0.014–0.061

Table 3.3. Total phosphorus loads (Boyle STP) P g/year and total phosphorus loads to Lough Key g P/m^2/year.

Year	TP kg/year	TP g P/m^2/year
2001	2902	0.322
2002	745	0.083
2003	1011	0.112

phosphorus loadings for 2001, 2002 and 2003 are represented alongside the 1976 estimated phosphorus load for the lake (Toner, 1979).

This graph shows that the total P loadings in 2001 are within the mesotrophic range for Lough Key. In that year the results for total P levels within the lake were mostly either moderately mesotrophic or strongly eutrophic according to the OECD trophic classification (OECD, 1982). There was a highly significant difference in total phosphorus levels between 2001 and 2003 (Mann–Whitney test, $P < 0.01$). In 2003, most concentrations fell within oligotrophic levels (<10 TP mg/m^3). Figure 3.2 indicates that TP loadings for Lough Key are within the oligotrophic range for 2002 and 2003.

Lough Key's orthophosphate (PO_4) levels were particularly low in July and September 2003 (<5 µg/l), which probably reflects a high nutrient uptake by algae and plants due to a long, hot summer.

Monthly phosphorus sampling results from the Boyle River stations upstream and downstream of the STP were consistently relatively low throughout the duration of the project. Orthophosphate ranged from 1 to 26 µg/l P upstream (mean = 11 µg/l P) and from 2 to 25 µg/l P (mean = 15 µg/l P) downstream. According to the Phosphorus Regulations (SI 258 of 1998) both mean orthophosphate values fit into the unpolluted category for rivers. Total phosphorus varied from 16 to 45 µg/l P (mean = 32 µg/l P) upstream and from 18 to 62 µg/l P downstream (mean = 39 µg/l P). There were highly

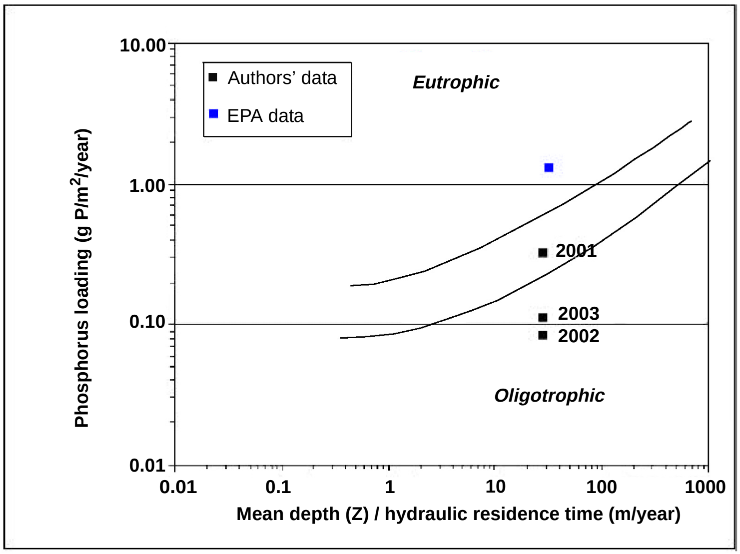


Figure 3.2. Vollenweider's relationship between annual phosphorus loading and ratio of mean depth (Z) to hydraulic residence time for mesotrophic state concentrations.

significant differences between both the total phosphorus levels and orthophosphate levels upstream and downstream of the sewage treatment plant during the project period (Mann–Whitney test, $P < 0.01$).

3.7 Phytoplankton and Cyanobacteria

There appears to have been no increase in *Microcystis* or any other cyanobacteria either during the course of the survey or relative to previous data (Bowman, 1998, 2000). The main species involved in Lough Key algal blooms are *Aphanizomenon flos-aquae* (recognisable by the bundles of trichomes visible in the water) and *Microcystis aeruginosa*.

3.8 Zebra Mussel Life Stage Sampling

Early zebra mussel spawning was detected from the middle to the end of May each year and corresponded to water temperatures >13°C. Peak densities occurred between the start of July and the middle of August (max = 45 larvae/l). Larval numbers dropped off when spawning ended in September. Only occasional larvae were detected in October samples.

3.8.1 Estimation of veliger/larval size distribution

Size distributions from the veliger samples in all years, measured D veligers (early development) ranging from 70 µm (lower limit of mesh size, 64 µm) to pediveligers of 260 µm. Juveniles as large as 840 µm were occasionally recovered. At the start of the annual sampling period (late June/early July), the samples were dominated by early stage D veligers and umbonal larvae (70–110 µm). As the season progressed larger pediveligers were seen to peak in samples before settling out. Few larvae >260 µm were found in samples indicating that settlement had taken place by that size.

3.8.2 Settled juvenile sampling

Figure 3.3 shows the mean total juvenile settlement for the intensive spawning periods over the 4 years at three of the monitoring sites. The year 2002 had the least successful settlement, whilst 2000 and 2003 showed the greatest. Settlement decreased by 54% from 2000 to 2001 and again by a further 23% in 2002. In 2003, there was an increase in settlement at all three sites relative to the previous 2 years.

3.9 Adult Sampling

3.9.1 Snorkel surveys

In 2001 and 2003, the percentage cover of zebra mussels on stone at snorkel sites varied from 40 to 100%. Plate 3.1 shows 100% zebra mussel cover on stone at Site 8 in 2003.

Individual sizes of zebra mussels measured during the project varied from <1 mm to 34 mm, which reflects the presence of at least three main year classes (0+, 1+ and 2+ age cohorts). Figure 3.4 shows the size distribution of zebra mussels on stones from Sites 2, 6 and 7 in early

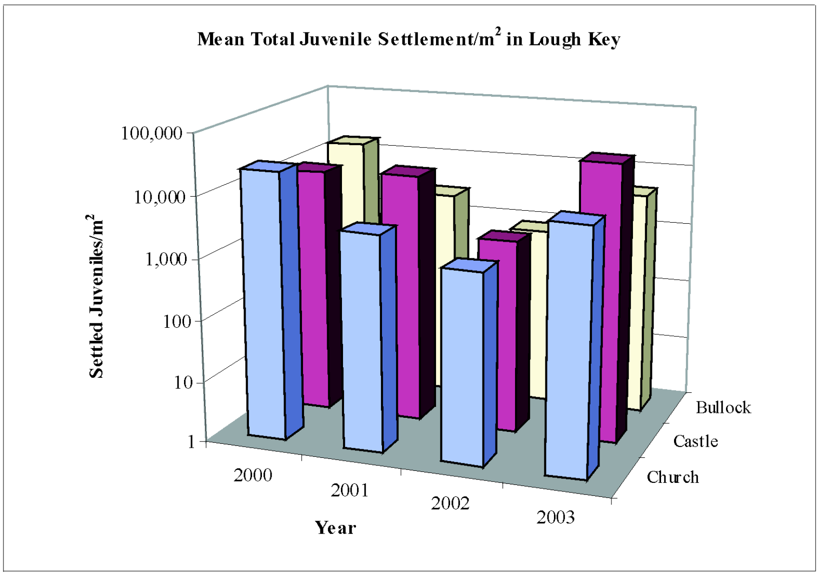


Figure 3.3. Total mean juvenile settlement for July and August in Lough Key, 2000–2003.

Plate 3.1. Intensive zebra mussel cover on stone (Site 8), 2003.

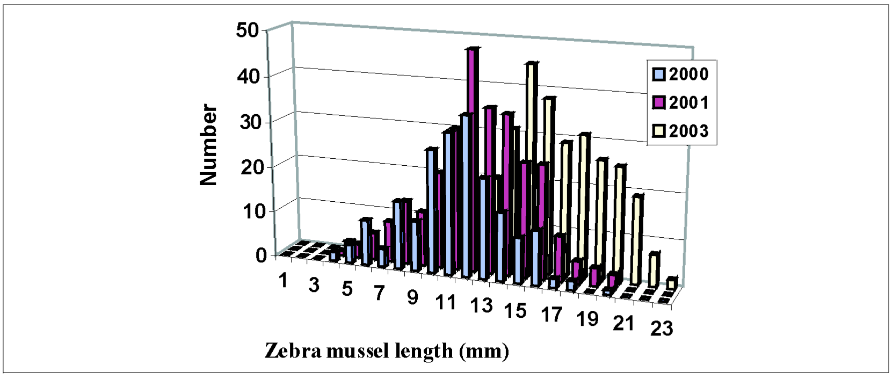
August 2000, 2001 and 2003. New settlement of zebra mussels was taking place at the time of sampling in each of those years. Only zebra mussels of 1 mm or more were measured in samples. It is difficult to separate age cohorts present due to merging of modes, but Fig. 3.4 indicates the presence of at least two modes. The 3- to 9-mm (approx.) category represents settlement from the previous summer and autumn and is categorised as the 1+ cohort. Zebra mussels greater than 10 mm were considered to be 2+ individuals. The 2000 and 2001 samples are well represented by 1+ and 2+ modes. The 2003 samples appear to have low numbers of 1+ individuals, which correlates with the poor settlement in 2002. Individuals of 2+ attained a larger size in 2003 than in other years (23 *vs* 20 mm) due to the increased summer water temperatures. October 2003 and January 2004 samples showed high numbers of 1 mm zebra mussels, representing high rates of successful settlement in late summer 2003.

Statistical analyses indicate that there was no significant difference in zebra mussel size distributions from different depth ranges in the lake, i.e. 0–1, 1–2, 2–3, 5–6 and 12–13 metres (Mann–Whitney test, $P > 0.05$).

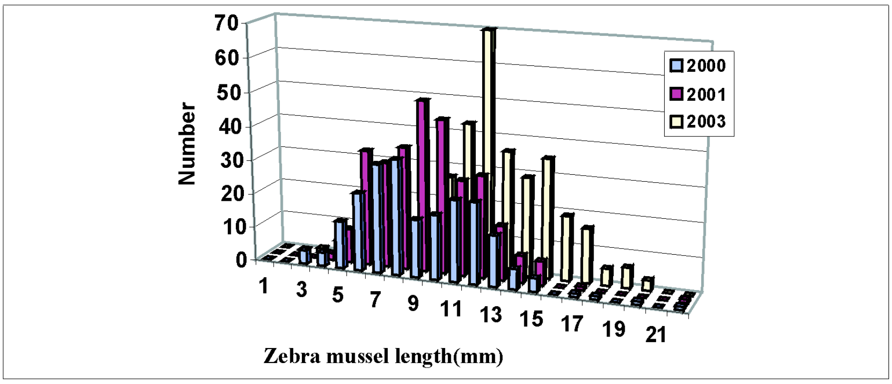
ANOVA analyses on various snorkel-sampled sites also showed no significant difference in size distributions ($P > 0.05$) on the three settlement substrates (stone, *Phragmites australis* and *Anodonta* shells) in 2001 or 2003. There was also no overall significant difference in zebra mussel biomass in the snorkel sites between those years (ANOVA, $P > 0.05$). The mean biomass for adult zebra mussels in 2001 was 4.75 kg/m^2 while the mean for 2003 was 4.64 kg/m^2. This is interesting in that there appeared to be fall-off in settlement in the two previous years, yet the biomass of the adults present maintained the overall biomass.

3.9.2 *Zebra mussels on reeds, rushes and other aquatic plants*

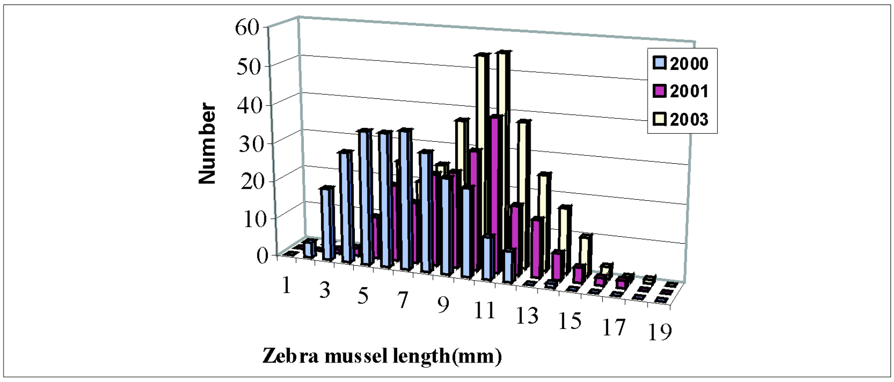
Many aquatic plants were noted as zebra mussel settlement surfaces in Lough Key including the algae *Cladophora*, the moss *Fontinalis antipyretica* and annual and perennial vascular plants. Submerged tree roots of alder *Alnus glutinosa* and branches of ash *Fraxinus*



Site 2



Site 6



Site 7

Figure 3.4. Size distributions of adult zebra mussels at Sites 2, 6 and 7 for 2000, 2001 and 2003.

excelsior were also found with zebra mussels attached. All plants within the lake showed varying degrees of colonisation by zebra mussels. Table 3.4 outlines the most important plants to which zebra mussels were found attached in Lough Key.

The old stems of the common reed *P. australis* had the greatest biomass of *D. polymorpha*. Mean biomass per plant (random ten plants) in 2000 was 478 g and 551 g in 2001. T-tests indicate that there was no significant increase in biomass on the plants between these years ($P > 0.05$). There was also no difference in size distribution between 2000 and 2001.

New *P. australis* plants showed a biomass of <1 g on individual plants (Plate 3.2), while plants in their second year or older showed a biomass up to 580 g/individual.

In 2003, results from three of the snorkel sites (Sites 1, 4 and 7) showed a very highly significantly lower cumulative

Table 3.4. List of plants with zebra mussels attached, in order of importance, Lough Key.

Phragmites australis	Common reed
Schoenoplectus lacustris	Common club-rush
Nuphar lutea	Yellow water lily
Equisetum fluviatile	Water horsetail
Elodea canadensis	Canadian waterweed
Potamogeton perfoliatus, P. lucens, P. natans	Pondweed species
Sparganium emersum	Unbranched bur-reed
Lemna triscula	Ivy-leaved duckweed
Cladophora	Filamentous alga

Table 3.5. Biomass of zebra mussels (g) on ten old *P. australis* stems at Sites 1, 4 and 7 in 2001 and 2003.

Year	Site 1 biomass (g)	Site 4 biomass (g)	Site 7 biomass (g)
2001	3506	939	806
2003	48	23	31

Plate 3.2. Transverse section of *Phragmites* stems, showing extensive fouling by zebra mussels on old stem (right) and <1 g fouling of new stem (left).

biomass for the ten stems sampled in 2003 than in 2001 (ANOVA, $P < 0.001$) (Table 3.5).

Throughout the survey the common club-rush, *Schoenoplectus lacustris* showed a low density of settlement; in 2001, the biomass was significantly lower than old *Phragmites australis* ($P < 0.01$) and not significantly different to new *P. australis* (ANOVA, $P > 0.05$). Video reedbed work in 2001 recorded >95% of *S. lacustris* with no zebra mussels attached.

3.9.3 *Zebra mussels on* Anodonta

In the year 2000, all *Anodonta* shells sampled were fouled with zebra mussels (mean fouling = 30.5 g/shell). The 2000 snorkel sampling recorded only one recently dead *Anodonta*, all other specimens were dead. *Anodonta* specimens sampled in subsequent years, 2001 and 2003 (n = 719) were all dead. No *Anodonta* shell sampled in 2003 was without attached zebra mussels. Zebra mussel cover of exposed parts of *Anodonta* shells was 100% at most sites in 2001 and 2003.

3.9.4 *Transect survey results*

The total number of zebra mussels in Lough Key was estimated in this project at 34 billion with a rounded total biomass of 4.4×10^6 kg. The greatest numbers of zebra mussels occurred in the first 3 m of depth relating directly to availability of suitable substrate (Categories 3 and 4). Transitional substrates (Category 2: areas of predominantly fine-grade material with occasional shell, pebble, sand, i.e. matter with some mass) began to show evidence of providing substrate for the zebra mussel. The total number of zebra mussels is a useful tool in the explanation of how an invasive species can multiply exponentially in a short period of time. In terms of biological impacts, biomass is a more meaningful parameter which can be used to assess filtration and consequently relate it to the trophic status in the lake.

3.10 Filtration Capacity of Zebra Mussels in Lough Key

The filtration capacity of zebra mussels in Lough Key can be summarised as follows:

Biomass of zebra mussels in Lough Key = 4.4×10^6 kg

Filtration rate = 44.4 ml/g zebra mussel/h

Filtration rate/h Lough Key = 19.5×10^6 l

Filtration rate/day = 4.7×10^9 l which is = 4.7×10^6 m^3

Lake volume = 46×10^6 m^3

Therefore, the zebra mussel population in Lough Key filter a volume of water equivalent to the entire volume of Lough Key approximately every 10 days, once water temperature exceeds 10°C (Reeders and Bij de Vaate, 1990).

4 Discussion

4.1 Trophic Status of Lough Key

From the data available (Bowman, 1998, 2000; Lucy (unpublished), Lucy and Sullivan, 2001; this work) it would appear that from July 1998 onwards, during the summer months at least, concentrations of total phosphorus and chlorophyll *a* have remained low while transparency initially increased in 1999 and has remained relatively high. The change in these values coincides with the expansion of the zebra mussel population in Lough Key during the late 1990s (Lucy and Sullivan, 2001). These changes occurred 2 years before the commissioning of the new Boyle STP.

In terms of trophic status (OECD, 1982) during the project period, some transparency levels exceeded 3 m (oligotrophic minimum, obtained during late summer/autumn 2003) while most were in the mesotrophic range; chlorophyll *a* levels fit within the oligotrophic range (<8 mg/m^3), except during seasonal blooms. Total phosphorus levels were within the mesotrophic range (10–35 mg/m^3) in 2001 and 2002, but were often within the oligotrophic range in 2003 samples.

4.2 Transparency

Zebra mussels remove a wide range of particulate matter from the water column and, since shortly after their mature establishment in the lake (1999), there has been a corresponding increased water transparency recorded. Phytoplankton levels appear to have been kept in check by the zebra mussel population from 1998 onwards.

4.3 Chlorophyll *a*

Low chlorophyll *a* levels obtained during 2000–2003 cannot be attributed to limiting nutrients. The OECD (1982) model for eutrophication assumes that productivity predominantly occurs in the water column, i.e. the lake system functions via food and energy transfer through a pelagic food web. Once the zebra mussel became widely established in Lough Key, however, the system changed to a benthic (bottom) dominated system in which most of the productivity occurs in the benthic regime. The zebra mussels strip food resources from the water column, which are then reintroduced as organic detritus directly to the benthic area. This involves extensive grazing on phytoplankton particles from 5 to 150 µm; some large mussels have been known to remove particles as large as 1.2 mm (Horgan and Mills, 1997). In many studies, high densities of mussels with high individual clearance rates (Fanslow *et al*., 1995; Horgan and Mills, 1997; Karatayev *et al*., 1997; Kotta *et al*, 1998) have been attributed to the removal of phytoplankton and the subsequent reduction of chlorophyll *a* from various waterbodies. As the Lough Key chlorophyll levels remain consistently low, it appears that, with the exception of periodic seasonal blooms, the zebra mussel population is able to filter at a rate comparable to phytoplankton growth.

One major ecosystem impact of the increased transparency has been the increase in the growth of blanket weed *Cladophora* and benthic aquatic plants in response to greater light availability. Since the phytoplankton are being stripped from the water column by the zebra mussels, sampling of benthic algae and aquatic plants rather than chlorophyll could provide an alternative solution to assessing trophic status in zebra mussel infested lakes.

4.4 Phosphorus

As mentioned previously, the total phosphorus levels in Lough Key are not in tandem with the low chlorophyll *a* levels despite the filtering activity of the zebra mussel population, which removes total phosphorus both directly from the water column and also from the biomass of plankton consumed. Lough Key levels were consistently mesotrophic according to the OECD classification and suggest a constant input of phosphorus from the catchment area. It is presumed that a high percentage of this is entering *via* the Boyle River and that the major point source is Boyle STP. Statistical analysis of Boyle River total phosphorus and orthophosphate data upstream and downstream of the plant indicates that this indeed was the case.

The reassessment of the Toner (1979) Vollenweider model is useful in showing specific loadings for Lough Key because it incorporates mean depth, flushing rate and lake area. The model was slightly changed from the original because, in this study, a new mean depth (4.5 m) had been calculated from the bathymetric survey. Plotting the 2001–2003 annual loadings from Boyle STP suggested that the phosphorus load in the first year of commissioning led to a mesotrophic status in the lake, while for the latter 2 years it was within oligotrophic levels. This should lead to long-term improvement in lake water quality, if levels are kept within this margin.

Orthophosphate results for the project period were generally at their highest at spring sampling of each year, before algal/plant growth. The orthophosphate results for summer 2003 were very low (<5 µg/l). This is probably due to increased uptake by phytoplankton and aquatic plants during the extremely good summer, as indicated by temperature data sets.

There is always the possibility that phosphorus may be released from resuspended sediment in the shallow and wind-exposed areas of Lough key, where zebra mussels are at their highest densities. Wind-induced sediment resuspension occurs frequently in shallow areas (Sondergaard *et al.*, 1992). It is considered however, that this phosphorus would not be in a form readily available for use by phytoplankton (Nalepa *et al.*, 1999).

4.5 Phytoplankton

The drop in the level of chlorophyll *a* concentrations in the late 1990s is a clear indicator of the decline in levels of phytoplankton. This has been an international experience in waters where zebra mussels have been introduced (MacIssac *et al.*, 1995; Karatayev *et al.*, 1997; Nalepa *et al.*, 1995; Maguire *et al.*, 2003).

As stated in the results section, in terms of relative abundance of various taxa, there appears to have been no increase in *Microcystis* or any other cyanobacteria either during the course of the survey or relative to previous data (Bowman, 1998, 2000). These data sets also suggest that there are no definite trends in either increase or decrease of the relative densities of phytoplankton taxa during or before the project.

4.6 Zebra Mussel Larval Stages

In Lough Key, spawning of zebra mussels commenced in May when temperatures reached 13°C, with peak densities during the last 2 weeks of July and the first week of August, coinciding with periods of prolonged highest water temperatures and chlorophyll *a* levels.

Zebra mussel larvae have a patchy distribution within the lake. Even when densities are at their highest at one site, results may be very different for other sites within the lake. This emphasises the need for multiple site analysis, even within a small lake like Lough Key. Prevailing winds and currents have been suggested in other studies as explanations for this patchy distribution (Lewandowski, 1976; Hunter and Bailey, 1992; Martel, 1993).

4.7 Assessment of Habitat for Adult Zebra Mussels in Lough Key

Earlier survey work on Lough Key had established that in common with other Irish lakes, stony substrates and *Anodonta* were the main substrates for adult zebra mussels in Lough Key (Lucy and Sullivan, 2001; Minchin *et al.*, 2002a; Maguire *et al.*, 2003). Aquatic plants were also found to be a substrate (Sullivan *et al.*, 2002).

The discovery of zebra mussel clusters/druses on mud in transitional substrates is believed to be significant. Transitional substrate areas are important for zebra mussel colonisation as they grade from densely colonised stony substrate into mud. Transition zones are apparently acting as a stepping-stone for zebra mussel colonisation of Lough Key muddy substrates.

4.7.1 Lake substrates for adult zebra mussels

The 1999 survey indicated that the three main substrates used for settlement by zebra mussels in Lough Key were stone, *Anodonta* and aquatic plants in order of decreasing importance (Lucy and Sullivan, 2001). This formed the basis for the snorkel survey work in the current project, which made it possible to examine zebra mussel biomass and size distributions at eight separate sites around the lake in both 2001 and 2003.

It might seem logical to assume that the poor settlement in 2002 and low numbers of 1+ individuals in size distributions recorded in summer 2003 might indicate a decline in the zebra mussel population. Visual analysis of percentage cover on stone had decreased at some sites. Analysis of the zebra mussel biomass (on stone) at the seven stony snorkel sites indicated, however, that that there was no significant difference between 2001 and 2003. It thus appears that any decline in numbers of the 1+ cohort was made up for by the biomass of the larger 2+ cohort. As zebra mussel filtration is gauged by biomass, this measurement is considered to be more significant than examining actual numbers.

Density-dependent processes, etc., may balance the successful recruitment and survival of the species and may cause fluctuations in populations (Ramcharan *et al.*, 1992; Karatayev *et al.*, 1998). During the time period of this project the zebra mussel population appeared to be stable in terms of biomass; the lake appears to be maintaining an equilibrium carrying capacity for this species. The degree to which populations irregularly fluctuate varies widely among European lakes; in some it varies by no more than 15% over periods of 5–10 years (Ramcharan *et al.*, 1992) and this may be the case for Lough Key.

In common with many other lakes elsewhere, the two main density-dependent factors involved in the abundance of zebra mussels in Lough Key are availability of suitable substrate and sufficient food source (Lucy and Sullivan, 2001). As camera work and snorkel surveys indicated that stone substrate throughout the lake was not fully colonised by zebra mussels (<100%) it seems likely that food availability is the major limiting factor to population increases in Lough Key.

The very high initial rate of settlement on *Anodonta* is a widespread phenomenon as the unionid family forms a preferential substrate for zebra mussels (Lewandowski, 1976; Mackie and Schloesser, 1996) and often provides the only suitable substrate in soft sediments. This has led to their extinction in Lough Key as *Anodonta* has no evolutionary burying mechanism to deal with zebra mussel colonisation. The weight of zebra mussel burden on the exposed anterior end impedes movement and feeding, resulting in eventual death. As noted in the introduction, this type of mass mortality is well documented in the literature. The complete demise of this native bivalve mollusc is the most direct ecological impact caused by zebra mussels in Lough Key. Shannon surveys indicate that the extirpation of *Anodonta* is widespread throughout the Shannon navigation (Minchin *et al.*, 2002b). This is a clear-cut example of how an invasive species can impact on native biodiversity and there may be a case for *Anodonta* joining the pearl mussel (*Margaritifera margaritifera*) on the list of protected species in Ireland (EPA, 2004).

4.8 Filtration Capacity of Zebra Mussels in Lough Key

The filtration rate as calculated assumes maximum filtration rates and may be over-estimated for periods of low water temperature. It should be noted that the 10-day lake filtration time calculated is considerably shorter than the overturn rate of 58 days (0.16 year), i.e. the total natural replacement of the lake water volume.

4.9 Potential Links Between Zebra Mussel Populations and Nutrient Levels in Lough Key

The total phosphorus results show that loadings to the lake from Boyle STP had been reduced between 2001 and 2003. There was also a corresponding drop in total phosphorus levels in Lough Key. It is not possible however to separate the nutrient impact of the new sewage treatment plant from that due to zebra mussel filtering. The Vollenweider model shows that since 2002 total phosphorus loadings have been within acceptable levels, without even taking zebra mussels into account. The dual reduction of the sewage treatment plant and the zebra mussels has not as yet resulted in phosphorus levels becoming limited. This is evident from the increase in benthic algae and aquatic plants. As the zebra mussel population in Lough Key remained significantly similar during the project period, it suggests that phytoplankton were still being produced in abundance, but are immediately stripped from the water column by filtering activity.

As of 2004, seasonal algal blooms were still occurring in Lough Key either because the algae are inaccessible (due to size or flotation) or because the zebra mussels are unable to process the phytoplankton during intense periods of algal growth. This emphasises the need for regular monitoring of waters, during the spring to autumn period to assess statistically valid means rather than occasional maximum levels. Determination of species in blooms is also important, in case an abundance of *Microcystis* (possibly toxic strains) occurs, which is an important public health issue.

As zebra mussels are an introduced species and have been noted to cause changes to the biology, physico–chemistry and hydromorphology of Lough Key, it is very difficult to consider whether the lake can achieve good ecological quality status according to the Water Framework Directive (WFD). There may also be significant changes to the lake between this survey period and 2015, by which time good quality should be achieved according to the WFD.

5 Conclusions

- Lough Key remains firmly within mesotrophic levels as total phosphorus concentrations are within 10–35 mg/m^3. Neither the decrease in loading from Boyle STP nor impacts caused by the zebra mussel population in the lake have reduced these levels sufficiently to achieve oligotrophic status.

- Low chlorophyll *a* levels and high transparency are directly related to the filtration capacity of the zebra mussel population, which can filter the entire lake in an estimated 10 days. Seasonal algal blooms persist, but have not shown any consequent increase in *Microcystis* abundance. Increased benthic aquatic plants and algae are a direct response to resultant increased transparency and continued bioavailability of nutrients for growth.

- Zebra mussels are mainly found on stone and rock, in shallow waters (3 m or less), with small numbers found on occasional rocky areas at greater depths. Hard substrate was sometimes less than 100% colonised, implying that food and not space is the density-dependent limiting factor for zebra mussels in Lough Key.

- The most direct impact of zebra mussel colonisation in Lough Key has been the extirpation of the native duck mussel *Anodonta.* By 2003, the heavily burdened, sinking *Anodonta* shells were becoming less available as zebra mussel substrates.

- Old *Phragmites* stems were well utilised as a substrate in the early stage of colonisation (late 1990s). This use was still evident in 2001, but had decreased significantly by 2003.

- The population of zebra mussels in the lake is estimated at 34 billion with a total biomass of 4.4×10^6 kg. Biomass remained statistically similar between 2001 and 2003. Variation in spawning and settlement patterns did occur, with some years showing more successful recruitment than others. As most zebra mussels survive and spawn over two summers, the data suggest that such imbalances may be evened out over several age cohorts resulting in a similar biomass.

- Zebra mussels create problems in classifying lakes according to the WFD for two reasons. Firstly, they are aquatic aliens and thus regarded as a biological pressure and impact and, secondly, they are known to cause direct changes to biological, physical/chemical and hydromorphological elements relating to this Directive.

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Appendix I Project Participants, Roles and Associated Timescales

Project participant	Role	Timescale
Mr Pat Timpson	Project Coordinator	2000–2003
Dr Frances Lucy	Lead researcher. Intensive and extensive lake-water and zebra mussel monitoring, laboratory analysis, project co-ordination, report writing. BSc Supervisor of student projects on larval/veliger stage.	2000–2003
Dr Monica Sullivan	Intensive zebra mussel monitoring, snorkeling, diving, report writing and spreadsheet management	2000–2003
Dr Dan Minchin	Intensive zebra mussel monitoring, navigator of research vessel	2000–2003
Seabed Surveys Ltd	RoxAnn^{Tm} Survey of lake substrates	2001
Mr Ivor Manning Monterrey Software	Digitised Mapping of RoxAnn^{Tm} and other project data	2001–2002
Mr Martin Manning Halia Oceanographic	Underwater video for substrate mapping of the shallow areas of the lake and reed bed survey work	2001–2003
Mr Peter Walsh Lough Key Boats	Boat-handling for routine lake monitoring	2001–2003