The Dynamics of Zebra Mussel (*Dreissena polymorpha*) Populations in Lough Key, Co. Roscommon, 1998-2003

by

Frances Lucy

Submitted to the Higher Education and Training Awards Council in fulfilment of the requirement for the degree of Doctor of Philosophy

June 2005

Supervisors: Mr. J.P. Timpson, Institute of Technology, Sligo
Dr. J.J. Bowman, Environmental Protection Agency

DECLARATION

I declare that this thesis is entirely my own work, except where otherwise stated and that it has not been previously submitted to any institute or university.

I also give permission to the library of the Institute of Technology, Sligo to lend or copy this thesis on request.

Frances Lucy

Frances Lucy

June, 2005

ACKNOWLEDGEMENTS

This thesis would not exist without the foresight, encouragement and hard work of a cohort of supporters. I wish to acknowledge the following.

The Environmental Protection Agency for research funding provided during 1999 and from 2001 to 2003. A special thanks to Jim Bowman for his initiative and enthusiasm in supporting zebra mussel research in Lough Key.

Pat Timpson, Head of School of Science, for supervising this PhD and gently guiding it towards the finishing line.

Dan Minchin for pushing me in the direction of this PhD. All your hard work and support is much appreciated, Navigator!

Monica - the finest partner in so many ways. Thank you so much for all the hard work, hugs and laughs. I couldn't ask for a better workmate or female friend. ESI is the best!

Pete Walsh and family, Lough Key Boats. It is wonderful to share a boat with someone who loves Lough Key with a passion! Keep those boats in the water.

My former students who were wonderfully patient with all the veliger samples and *Anodonta* work. Thanks to Elaine Ni Chonmhara, Noel Greaney, Anne Skelly, Sharon Duggan, Audrey Marshall, Karen O' Mahony and Justin Lohan.

A special thanks to Lyuba Burlakova for reviewing sections and for help in statistical analysis. Also thanks to Bruce Conn and Dianna Padilla for their suggestions.

Technical staff at the School of Science, Institute of Technology, Sligo and the laboratory staff at the EPA. Deirdre Cuffe for assistance with formatting.

Mr Ivor Marsh, Monterrey Software and Karen Delanty, Central Fisheries Board provided GIS maps of Lough Key.

John O' Gorman and John Casey, Roscommon County Council provided datasets relevant to the Boyle River and the Boyle sewage treatment plant.

Des Gillett, Tara Cruisers for allowing me to use their marina as a sampling site

David Dodd for all the hard slog on the Levitstown. I hope you've found somewhere more relaxing for your holidays!

Hugh Sullivan, mighty measurer of zebra mussels. I hope you can read this from up there!

Maria, Declan and Krys – for listening to me, when they really were not remotely interested in zebra mussels.

The Fisheries students, whose tenacity and concern inspired me on many a gloomy day. Thanks for the appreciation, hard work in class and all the laughs.

The international *Dreissena* family, it was a great boost to have you here last September. Here's to the next conference!

There are no words to express my thanks to Myles for all his love and support during this thesis. Also John, Adam and Darragh, wonderfully understanding sons – at least most of the time!

Finally thank you to Dr Alexander Karatayev and Dr Martin O'Grady for their dedication as external examiners for this thesis.

ABSTRACT

Dreissena polymorpha (Pallas), the zebra mussel, arrived in Ireland in the early 1990s. The species established itself in the lower Shannon River and was discovered in Lough Key (upper Shannon River catchment) in April 1998, two years following the estimated initial colonisation there. This research on zebra mussel populations began in 1998 and continued until 2003, utilising a variety of different techniques on larval (pelagic), juvenile (recently settled) and adult (benthic) life stages.

Variations were determined in seasonal larval densities, larval size distributions and juvenile settlement patterns among sampling weeks, years and monitoring sites from 1998 to 2003. High levels of settlement from 1998 to 2000, were typical for the early exponential growth phase of *Dreissena* invasions. The high level of successful recruitment in those years was evident from zebra mussel numbers, densities and biomass on the three main settlement substrates, stone, *Anodonta anatina* (live and shells) and aquatic plants. Snorkel survey results indicated that the population remained stable between 2001 and 2003 despite low settlement in 2002. High recruitment in 2003 was associated with warm water temperatures during that summer.

Total zebra mussel population in Lough Key was assessed in 2002 using a transect survey, combined with bathymetric data from hydroacoustic mapping (RoxAnn Tm). The total population was assessed as 3.3×10^9 *Dreissena,* with an estimated biomass of 4.4×10^6 kg.

The colonisation of *Anodonta* by *Dreissena* as a preferential substrate resulted in the extirpation of the native mussel from Lough Key by summer 2000. *Anodonta* shells continued to provide a substrate for zebra mussels but were less available by 2003 due to sinkage in soft substrates. Aquatic plants, particularly the perennial *Phragmites australis* were noted as settlement substrates for zebra mussels in the early years of invasion. By 2003 densities on reeds had reduced significantly, possibly linked to the reduction in overall recruitment of zebra mussels in 2002.

Transparency and chlorophyll *a* levels changed significantly between 1998 and 1999 (first year of significant population expansion), with an increase in the former and a decrease in the latter. This was due to a reduction in phytoplankton levels by zebra mussel filtration. Once water temperatures exceed 10°C, the Lough Key zebra mussel population is estimated to be capable of filtering the entire lake volume in 10 days. Total phosphorus levels in the lake have reduced significantly due to two drivers – the zebra mussel population and the new phosphorus removal system at Boyle sewage treatment plant. The lake remains within the mesotrophic status according to OECD classification. It is suggested that the impact of zebra mussel filtration should be built into a trophic model for the lake.

Summer algal blooms persist in the lake despite an overall annual reduction in phytoplankton. There is a possibility that zebra mussels may increase the density of Cyanobacteria, due to selective rejection during feeding. Careful monitoring should be carried out due to public health concerns associated with the presence of *Microcystis aeruginosa* toxic strains. Productivity in Lough Key has switched from the pelagic to a benthic zone, as typical for a *Dreissena* infested lake. This has resulted in increased *Cladophora,* blanket weed and emergent macrophytes in the lake.

The research carried out for this thesis, details the invasive success of *Dreissena polymorpha* in Lough Key from the early stage of colonisation, through an exponential growth phase, to a relatively stationery phase of growth. This intensive study highlights the fact that, even within a small lake, zebra mussel populations vary between sites and years. The extirpation of *Anodonta anatina* and the reduction in phytoplankton biomass by zebra mussels establish the position of *Dreissena* as a keystone species in Lough Key. Further survey work is required to determine long-term changes in population size and any associated ecological impacts.

CONTENTS

ABSTRACT **i**

ACKNOWLEDGEMENTS **iii**

CONTENTS **v**

CHAPTER 1: INTRODUCTION

1.1 Overview of Chapter **1**

1.2 Background to Thesis Research **1**

1.3 The Zebra Mussel (*Dreissena polymorpha*) **3**

1.3.1 Description, Invasion History, Impacts and Population Dynamics **3**

1.3.2 Life cycle **5**

1.3.3 Substrates for Zebra Mussel Settlement **13**

1.4 Zebra Mussel Impacts on Native Unionid Bivalves **14**

1.5 Zebra Mussel Impacts on Phytoplankton, Cyanobacteria and Water Quality **16**

1.6 Zebra Mussels and the Water Framework Directive **21**

1.7 Lough Key as a Study Area **22**

1.7.1 Lough Key – General Characteristics **23**

1.7.2 Lough Key Catchment – Topography and Landuse **23**

1.7.3 Geology and Soils of Lough Key Catchment **26**

1.7.4 Lake Water Quality **28**

1.7.5 Physico/chemical Factors Relevant to Zebra Mussel Colonisation **29**

1.7.6 Lough Key Zebra Mussel Populations and Nutrient Inputs 29

1.8 Suitability of Lough Key for Zebra Mussel Research 30

1.9 Aims and Objectives of Thesis 31

1.10 Tasks and Associated Methodologies 32

1.11 Lough Key Zebra Mussel Research Participants 33

CHAPTER 2: MATERIALS AND METHODS

2.1 Sampling Locations 34
- 2.1.1 General Monitoring Programme 34
- 2.1.2 Adult Zebra Mussel Sampling 36
- 2.1.3 Phytoplankton Sampling 38
- 2.1.4 Phosphorus Sampling 38

2.2 Sampling and Analytical Procedure 38
- 2.2.1 Transparency and Chlorophyll *a* 38
- 2.2.2 Temperature 39
- 2.2.3 Nutrients 39
- 2.2.4 Phytoplankton and Cyanobacteria 40
- 2.2.5 Zebra Mussel Life Stage Sampling 40
  - 2.2.5.1 Larval/Veliger Sampling and Analysis 40
  - 2.2.5.2 Settled Juvenile Sampling 41
  - 2.2.5.3 Adult Sampling 42
- 2.2.6 Estimation of Filtration Capacity of Zebra Mussel Populations in Lough Key 48

2.2.7 RoxannTm Survey, Computer Analysis, Ground-truthing and Video Surveys 48
2.2.8 Photographs 48

CHAPTER 3: DEVELOPMENT OF SUBSTRATE, DEPTH AND HABITAT MAPS FOR LOUGH KEY

3.1 Introduction **49**

3.2 Materials and Methods
3.2.1 Depth and Substrate Mapping – RoxAnn Tm Survey **51**
3.2.2 Groundtruthing of RoxannTm Survey **51**
3.2.3 Video Survey Work **52**
3.2.4 Substrate Analysis of Lake Transects **54**

3.3 Results
3.3.1 Depth and Substrate Mapping – RoxAnn Tm Survey **54**
3.3.2 Groundtruthing Results **57**
3.3.2.1 Category One: Muddy Substrates **57**
3.3.2.2 Category 2: Transitional Substrates **57**
3.3.2.3 Categories 3 and 4: Rock and Stone **58**
3.3.3 Video Survey Work **60**
3.3.4 Substrate Analysis of Lake Transects **60**
3.3.5 Habitat Map **62**

3.4 Discussion **62**

CHAPTER 4: EARLY LIFE STAGES OF LOUGH KEY ZEBRA MUSSELS – LARVAE AND JUVENILE SETTLEMENT

4.1 Introduction **64**

4.2 Materials and Methods **65**

4.3 Results

4.3.1 Seasonal appearance of larva in Lough Key **66**

4.3.2 Temperature **67**

4.3.3 Larval Density **69**

4.3.4 Larval Size Distributions **73**

4.3.5 Settlement **79**

4.3.5.1 Cumulative Settlement **79**

4.3.5.2 Individual Sites **82**

4.4 Discussion

4.4.1 Temperature **82**

4.4.2 Veliger Density **83**

4.4.3 Veliger Size Distribution **86**

4.4.4 Settlement **88**

4.4.5 Life Cycle Strategies **92**

CHAPTER 5: ZEBRA MUSSELS ON STONEY SUBSTRATES

5.1 Introduction **93**

5.2 Materials and Methods **94**

5.3 Results

5.3.1 Size Distributions 95

5.3.1.1 Size Distributions during the early Invasive Stage 95

5.3.1.2 Size Distributions at Different Sites 98

5.3.1.3 Bimonthly Size Distributions at Rockingham Site 100

5.3.1.4 Annual Comparison of Size Distributions at Rockingham Site 102

5.3.1.5 Size Distributions at Different Depths 103

5.3.2 Biomass 105

5.3.2.1 Snorkel Site Biomass 107

5.3.2.2 Transect Biomass and Total Number of Zebra Mussels 107

5.3.3 Ash-Free Dry Weight - Condition Index 109

5.4 Discussion

5.4.1 Size distributions 109

5.4.2 Biomass and Density 111

CHAPTER 6: ZEBRA MUSSELS ON *ANODONTA ANATINA* (L.)

6.1 Introduction **122**

6.2 Materials and Methods **124**

6.3 Results

6.3.1 Results for *A. anatina* in 1998 125

6.3.2 Results for *A. anatina* in 1999 127

6.3.3 *Anodonta anatina* shell as substrate, 2000-2003 131

6.4 Discussion **136**

CHAPTER 7: THE ASSOCIATION BETWEEN ZEBRA MUSSELS AND AQUATIC PLANTS

7.1 Introduction **145**

7.2 Materials and Methods **146**

7.3 Results

7.3.1 Distribution of Aquatic Plants in Lough Key **147**

7.3.2 Preliminary Results and Observations – 1999 **148**

7.3.3 Diversity of Aquatic plants settled by Zebra Mussels in Lough Key **150**

7.3.4 Reed-beds Video Survey Work (2001-2003) **151**

7.3.5 Zebra mussels on *Phragmites australis* **152**

7.3.5.1 Old *Phragmites australis* **152**

7.3.5.2 New *Phragmites australis* **155**

7.3.5.3 Zebra mussels on old *P. australis vs* other substrates **156**

7.3.6 Zebra mussels on *Schoenoplectus lacustris* **156**

7.3.7 Zebra mussels on other aquatic plants **157**

7.4 Discussion **157**

CHAPTER 8: ZEBRA MUSSELS AND TROPHIC STATUS IN LOUGH KEY

SECTION A: LAKE WATER QUALITY AND TROPHIC STATUS **163**

8.1.1 Introduction **163**

8.1.2 Methods **164**

8.1.3 Results

8.1.3.1 Transparency 165

8.1.3.2 Chlorophyll *a* 167

8.1.3.3 Phosphorus 172

8.1.4 Discussion

8.1.4.1 Transparency 175

8.1.4.2 Chlorophyll *a* 177

8.1.4.3 Phosphorus 178

8.1.4.4 Trophic Status of Lough Key 180

SECTION B: CYANOBACTERIA AND PHYTOPLANKTON **182**

8.2.1 Introduction 182

8.2.2 Methods 183

8.2.3 Results 184

8.2.4 Discussion 189

SECTION C: FILTRATION OF LAKE WATER BY ZEBRA MUSSELS **193**

8.3.1 Introduction 193

8.3.2 Methods 194

8.3.3 Results 194

8.3.4 Discussion 195

CHAPTER 9: CONCLUSIONS 197

REFERENCES 200

APPENDIX ONE: RoxAnn^{Tm} survey 224

APPENDIX TWO: Lough Key groundtruthing survey 231

APPENDIX THREE: Video substrate analysis 238

APPENDIX FOUR: Veliger densities 241

APPENDIX FIVE: Veliger size distributions 243

APPENDIX SIX: Zebra mussel settlement 248

APPENDIX SEVEN: Snorkel site results 2001, 2003 249

APPENDIX EIGHT: Transect results 264

APPENDIX NINE: *Anodonta* data 268

APPENDIX TEN: Chlorophyll *a* and transparency, Lough Key 1998-2003 294

APPENDIX ELEVEN: External water quality datasets 296

APPENDIX TWELVE: Aerial photos of Lough Key 302

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF CHAPTER

This introduction provides the background to this thesis titled 'The dynamics of zebra mussel (*Dreissena polymorpha*) populations in Lough Key, Co Roscommon, 1998-2003'. The chapter also provides an overview of the zebra mussel invasion history, life cycle and species impacts on water quality and aquatic communities. Also included is a review of Lough Key as a study area and the rationale for carrying out research on zebra mussel populations in this lake. The objectives of the thesis and the methodologies are outlined. The association with other researchers as a project team is also explained.

1.2 BACKGROUND TO THESIS RESEARCH

The monitoring of the zebra mussel populations in Lough Key commenced in 1998 subsequent to their first discovery there in April 1998. Summer research was carried out by Lucy (unpublished), with two undergraduate student projects carried out that autumn (Ni Chonmhara, 1999; Greaney, 1999). Research was supported during 1999 by the Irish Environmental Protection Agency (EPA) as a small-scale project. This established baseline information on the existing zebra mussel 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 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 provided by EPA funding at the end of 2000. A three-year project titled 'The impact of nutrients on the zebra mussel populations in Lough Key' (2000- MS-5-M1) officially commenced on December 1, 2000 as a three-year medium scale project for the EPA. It was funded by the Environmental RTDI sub-Measure of the Operational Programme for the Productive Sector (2000-2006) as part of the National Development Plan (2000-2006). This allowed continuity of sampling until the end of 2003. Monitoring was also continued during the summer of 2004. Between 1999 and 2003 various student BSc degree projects were carried out and supervised by Lucy (Skelly, 2000; Commons, 2000; Duggan, 2001; Marshall, 2002; O'Mahony, 2003; Lohan, 2004).

This thesis encompasses research elements from the years 1998–2003 and is an investigation into the dynamics of zebra mussel (*Dreissena polymorpha*) populations in Lough Key.

1.3 THE ZEBRA MUSSEL (*DREISSENA POLYMORPHA*)

Dreissena polymorpha (Pallas, 1771): Phylum: Mollusca; Class: Bivalvia; Order Cardiida (Ferussac, 1822); Family: Dreissenidae (Andrusov, 1897); Genus : *Dreissena*

1.3.1 Description, Invasion History, Impacts and Population Dynamics

The zebra mussel, *Dreissena polymorpha,* is a freshwater bivalve, which attaches to hard substrates by byssal threads. The species gets its name from the distinctive striped dark and pale colouration, although this is not seen on all specimens, especially older individuals (Minchin *et al.*, 2002b). Adult zebra mussels are either male or female, with a small percentage of hermaphrodites.

Dreissena polymorpha is native to the lakes, slow-moving rivers and low salinity areas of the Black Sea and Caspian Sea basins (reviewed in Minchin *et al.*, 2002). It was formerly present in the Aral Sea but due to increased salinity, it no longer exists there (reviewed in Karatayev *et al.*, 1998). Zebra mussels are members of the Caspian autochthonous faunal group (Orlova, 2002).

This species spread through much of Europe almost two hundred years ago with the development of canal systems. From 1775, connections between the waterways facilitated trade, initially in eastern Europe as water trade routes developed in a northern route on rivers and canals connecting the Black Sea with the Baltic (Panov *et al*., 1997; Bij de Vaate *et al*., 2001). The zebra mussel reached the Netherlands by 1826, being found in the Rhine and probably carried in with ships importing timber from the Baltic (Kerney and Morton, 1970).

By 1824 the species had become established in Britain (Kerney and Morton, 1970). In North America the first recording of the zebra mussel was in the Great Lakes in 1986 (Hebert *et al*., 1989). Within seven years it had spread to eighteen states in the USA and two provinces in Canada (Johnson and Padilla, 1996) and further colonisation is ongoing (New York Sea Grant, 2003).

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 vector for their introduction. Live zebra mussels of English origin, were found on the infested hulls of imported leisure craft on arrival in Ireland, over the period 1997 to 2001 and have also been genetically linked to English populations (Pollux *et al*., 2003, Astenei *et al*., 2005). 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*., 2002b). Large populations now exist in Loughs Derg, Ree, Bofin and Key. By 1996 zebra mussels had become established in Lower Lough Erne (Rosell, McCarthy and Maguire, 1999) and in the following year were discovered in Upper Lough Erne.

Further spread continued in the early years of the new millennium to include lakes outside the main Shannon-Erne waterway. At least fifty-five water bodies are now known to be infested including Loughs Sheelin, Gill, Arrow and Derravaragh.

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 also is 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 (reviewed in McMahon, 1992).

To date, *Dreissena polymorpha* has been one of the most aggressive freshwater invaders worldwide. Many Ponto-Caspian endemic species are characterized by wide environmental tolerances and high phenotypic variability (Reid and Orlova, 2002). The zebra mussel is considered to be an opportunistic successful invader and displays the most important qualities of an aquatic invasive species; a short life span, rapid growth, early sexual maturity, high fecundity, euryoecious, eurytopic, gregarious behaviour facilitated by byssal attachment, association with the activities of man, genetic variability and phylogenetic plasticity, suspension feeding, and an ability to repopulate previously recolonised habitats following recovery from population crashes (Lodge, 1993; Morton, 1997). High growth rates and short life spans allow zebra mussels to rapidly reach high densities in favourable habitats (Claudi and Mackie, 1993). Once introduced, populations can grow rapidly and the total biomass of a population can exceed ten times that of all other native benthic invertebrates (Dermott and Kerec, 1997). The zebra mussel is frequently competitively dominant over native benthic fauna, and can impact all components of the freshwater ecosystem, especially benthic animals (reviewed in Karatayev *et al.*, 1997, 2002). For this reason these species have been described as ecosystem engineers (Karatayev *et al.*, 2002); species which, 'directly or indirectly control the availability of resources to other organisms by causing physical state changes in biotic or abiotic materials' (Jones *et al.*, 1994, 1997).

Recent research suggests that 'boom and bust' cycles may be a minor phenomenon in invasion biology (Simberloff and Gibbons 2004). Others have suggested the possibility of oscillatory behavior or dramatic spatial variation in population dynamics among invaders (reviewed in Parker *et al.*, 1999), both of which are observed in zebra mussel populations. Population densities are often not stable and can fluctuate widely (Ramcharan *et al.*, 1992; Stanczykowska and Lewandowski, 1993). Some invaded lakes have followed the typical 'boom and bust' pattern associated with the rapid exponential increase of the species. This has involved a rapid increase in the population followed by a significant decline just a few years after colonisation (Lake Constance, Walz, 1974; Saginaw Bay, Nalepa *et al.*, 1995; Hudson river estuary, Strayer *et al.*, 1996). Other long term studies have instead shown various fluctuations in population, most of which were attributed to environmental factors, e.g., substrate availability, water quality changes and predation (Stanczykowska and Lewandowski, 1993; Molloy *et al.*, 1997) larval recruitment (Lewandowski, 1977; MacIssac *et al.*, 1991) or food availability (Nalepa *et al.*, 1995). The type of dynamic most often observed is an irregular pattern of population increase and decrease. In some European lakes zebra mussel populations may vary no more than 15% among years over periods of 5-10 years. In other European lakes, populations can decline by two orders of magnitude within a few months and recover to their original levels in several years (Stanczykowska, 1977, Stanczykowska and Lewandowski, 1993; Cleven and Frenzel, 1993).

1.3.2 Life cycle

The zebra mussel life cycle consists of a relatively sessile adult phase and a planktonic, free-swimming larval stage. Oocyte production estimates per female mussel vary from 30,000 to 1.6 million per female (Mackie *et al.*, 1989; Borcheding, 1992) and fertilisation is external (Nichols, 1996).

Zebra mussels usually become sexually active in the summer season, at one year old. In Lough Derg however, a lake in the lower Shannon River, 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). Reproduction is annual in both European and North American waters, involving a gamete development phase in winter and early spring, spawning events in late spring and summer followed by a gonad rest phase (Lewandowski, 1982a; Sprung, 1989; Borcheding, 1991; Haag and Garton, 1982; Garton and Haag, 1993; Bachetta, 2001; Mantecca, 2003). Temperature is considered the main environmental factor which regulates both gametogenesis and spawning (Borcheding, 1991; Bacchetta *et al.*, 2001). Various temperatures from 12^{0}C upwards have been reported as thresholds for spawning. Fifteen degrees celcius has been cited as the temperature at which larvae were first observed in many European studies (Kachanova, 1966; Kirpichenko, 1964; Einsle, 1973; Stanczykowska, 1977; Karatayev, 1998), while temperatures in the 16-20^{o}C range have been reported in other studies (Hillbricht-Ilkowka and Stanczykowska, 1969; Walz, 1973; Fraleigh *et al.*, 1993). The time span in these studies when larvae were present in the water varied from May to October, depending on the water temperature regime.

Apart from water temperature, 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 progressing through swimming blastula, trochophore, straight-hinge (D) larva, umbonal (veliconcha), pediveliger (settling stage) and plantigrade (juvenile, postveliger, spat) stages (Conn *et al.*, 1993). Ackerman *et al.*, (1994) reviewed published sizes of the various developmental stages of *Dreissena polymorpha* and found that straight-hinge (D) larvae can range in height from 70 to 160µm, umbonal larvae from 120 to 280µm, pediveligers from 167 to 300µm and plantigrades from 158 to 500µm.

Zebra mussel larvae are distributed unevenly, both vertically and horizontally in the water column which results in a contiguous or patchy distribution of larvae. Maximum density of veligers occurs at depths of 3-7m (Mackie and Schloesser, 1996). Veliger densities as high as 400,000m^{-3} have been observed in Europe and 100,000m^{-3} in Lake Erie (Marsden, 1992). Pediveligers actively select substrates on which they settle by secreting byssal threads and undergoing metamorphosis to become plantigrade mussels.

The developing juvenile acquires a mussel shape, with the distinctive banded pattern and begins to form its feeding apparatus at approximately 1mm in length (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 was estimated at between two to three weeks in the July/August period, after which settling out occurring at a size range from 200-370μm (Lucy and Sullivan, 2001). Mortality in larvae and newly settled individuals has been reported at levels from 20% up to 100% (Stanczykowska, 1977; Lewandowski, 1982a; Sprung, 1989). Adult zebra mussels were found in Lough Key at low densities in April 1998 and that summer is believed to be the first year of significant spawning in Lough Key.

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

Following the settlement zebra mussels typically attach to each other often forming dense colonies, commonly 4-6cm thick, with several layers of zebra mussels attached to each other by byssal threads (Tuchman *et al.*, 2004). These three dimensional dense aggregations are often known as druses; and may be attached to a hard substrate, commonly stone on the benthos, or in the case of soft substrates form a loose conglomerate of zebra mussels, which originally settle on a small particle of sand or shell. Druses are found on many hard substrates including man-made navigational structures such as boat hulls, anchors and chains. In general oldest individuals occupy the centre of the druse, while towards the outermost regions the age decreases, due to the successive settlement of younger individuals on older ones (Stanczykowska, 1964).

Several studies have estimated the growth rate of zebra mussels during their life span. Distinguishing cohorts within zebra mussel populations can be very difficult, as there may be no distinct modes (Griffiths *et al.*, 1991). Growth rings caused by reduced growth during winter or other periods of stress are not reliable indicators of mussel age (Stanczykowska, 1977). This has led to conflicting estimates and uncertainty regarding the longevity and age structure of zebra mussel populations (Mackie and Schloesser, 1996). One way of overcoming this is to perform growth experiments on caged zebra mussels (Bij de Vaate, 1991; Smit *et al.*, 1992, 1993; Dorgelo, 1993; Neuman *et al.*, 1993; Allen *et al.*, 1998; Garton and Johnson, 2000). This exposes the animals to their natural environment, while still allowing the possibility of a controlled growth experiment. These experiments were carried out to determine the effects of a number of environmental factors on mussel growth including temperature, water currents and trophic status (food availability). Table 1.1 shows available estimated size at different year classes (1+ onwards) of zebra mussels in a number of studies from Europe and North America, all of which had 0+ starting lengths of <8mm.

Table 1.1 Size (mm) at different zebra mussel age classes in various studies

Location	**1+**	**2+**	**3+**	**4+**	**Reference**
Mazurian lakes, Poland	9	16	22	25	Stanczykowska, 1964
Walthamstow, England	22	29	35	41	Morton, 1969
Lake IJsselmeer, Netherlands	10	19	23	24	Bij de Vaate, 1991
Lake Maarsseveen, Netherlands	17	21	23	25	Bij de Vaate, 1991
Lake Markermeer, Netherlands	17	20	21	23	Bij de Vaate, 1991
Lake Wolderwijd, Netherlands	14	17	20	22	Bij de Vaate, 1991
River Rhine, Netherlands	19	24	28	nd	Smit *et al.*, 1992
Lower Mississippi, USA	13	22	nd	nd	Allen *et al.*, 1999
Lake Wawasee, USA	16	21	nd	nd	Garton and Johnson, 2000

nd = no data

In some cases there is no data for age cohorts greater than 2+. This may be due to the age cohorts chosen for the experimental setup (cage experiment). It also suggests that in some cases older cohorts may not be present. For example in Lake Wawasee, Indiana, shells rarely exceeded 25mm in length, suggesting a life span maximum of 3 years (Garton and Johnson, 2000). In North American studies, the life span has generally been estimated at a maximum of three years (Garton *et al.*, 1993; Mackie and Schloesser, 1996; Garton and Johnson, 2000). Chase and Bailey (1999) suggest a two year life span for Lake St. Clair (maximum size 29.5mm), a two to three year span for Lake Erie (maximum size 35.6mm) and up to four years in Lake Ontario (maximum size 24.8mm). Bij de Vaate (1991) found maximum shell length of 27mm in Lake Markmeer and 31-36mm in Lake IJsselmeer. Growth in these Dutch studies showed the typical trend of fast growth in year one, slowing down in following years. The largest known *Dreissena* was a 43mm individual found in Lake Gartov, Germany (Burlakova, 1998). In Europe zebra mussels usually live from three to four years (Morton, 1969; Bij de Vaate, 1991; Smit *et al.*, 1992, 1993). In the Polish Mazurian lakes, size at 1+ (9mm) is small relative to other studies. This diminutive size and the presence of cohorts up to ten years old indicates a slow growing population compared to other studies. In another Polish lake, Lake Rumian, over 80% of zebra mussels were between 0+ and 2+, with the remainder between 3 and 5 years of age (Stanczykowska, 1964).

In Ireland many size distributions have been taken at different times of the year throughout the Shannon navigation (Minchin *et al.*, 2002b). It would seem from the largest individuals found (38mm) that the species may exceed a three year life cycle in Ireland, but that since the vast proportion are <25mm (various studies), most of the population survive between two and three years and that these spawn in both their second (1+) and third summer (2+) of life. In this study size distributions in the early years of the invasion (1998 and 1999) could be used to distinguish age cohorts. This became more difficult as modes merged from 2000 onwards. This will be dealt with in detail in Chapter 5 of this thesis.

In the Great Lakes and mainland Europe, shell growth for all sizes of zebra mussel is positive throughout the summer and stops from Autumn to early Spring when temperatures are less than 10^0C (Walz 1978; Bij de Vaate, 1991; Smit *et al.*, 1992; Sprung, 1992; Dermott *et al.*, 1993; Neuman *et al.*, 1993).

Zebra mussels have been found growing at a range of depths from the shallowest waters of the littoral zone (less than 0.1m to 0.5m) depending on local water fluctuations and the probability of freezing (Stanczykowska, 1976; Stanczykowska and Lewandowski, 1993b; Burlakova, 1998) to depths of 50m in Garda Lake (Franchini, 1978), 55m in the Bodensee/ Lake Constance (Walz, 1973) and 60m on the profoundal sediments of Lake Erie (Dermot and Munawar, 1993).

In Lakes Erie and Ontario higher densities were recorded at 6m than at 2m in three consecutive years from 1992 to 1994 (Chase and Bailey, 1999). In Lake Wawasee mussel shell growth declined 15% per metre increase in depth between 1 and 4m (Garton and Johnson, 2000). In Polish studies the Great Mazurian lakes had lowest densities near the shore (0.3-0.6m depth) with density increasing with depth, reaching a maximum at 2-4m depth. Generally in these lakes zebra mussels did not occur below 6-8m, but were found in a few lakes at depths as great as 12m (Stanczykowska and Lewandowski, 1993b). Size distributions may vary with depth. Investigations in Lakes Majcz Wielki and Tatowisko, Poland have shown that postveligers and young individuals live mostly in shallow waters near the shore whereas adult individuals were more numerous at depth (Stanczykowska and Lewandowski, 1993b). Availability of suitable hard substrate is the main limiting factor associated with colonisation at depth. Depth restricted colonisation can be also be caused by periods of low oxygen due to eutrophy (Stanczykowska and Lewandowski, 1993b) or the presence of a seasonal thermocline, factors which may vary among lakes and over years (Garton and Johnson, 2000). Many studies have found that in lakes and reservoirs zebra mussels have a maximum density at depths from 1 to 5m (reviewed in Karatayev *et al.*, 1998) but when suitable substrate and oxygen conditions are available, the maximum density has been found at greater depths (Franchini, 1978; Dermot and Munawar, 1993; Chase and Bailey, 1999).

In terms of densities of zebra mussels, many studies, particularly North American ones have concentrated on numbers of mussels per square metre. Others have included dry biomass (g/m^2) or wet biomass (g/m^2) and may also have included determination of seasonal variation of soft tissue weight, e.g ash free dry weight (AFDW) (Bij de Vaate, 1991; Smit and Dudok van Heel, 1992; Nalepa *et al.*, 1993, 1999). Wet biomass is very important as it can be used to estimate total biomass in a lake or on particular lake substrates, vital for estimating various ecological impacts. Number counts do not take into account varying age structures in population. Increase in biomass may be due to increased mussel density or to increased average mussel size (Dermott *et al.*, 1997). Therefore it is a good idea to carry out both in tandem, where possible. Table 1.2 shows relevant data on numbers/m^2 and biomass from a number of European and North American sources.

Table 1.2 Density of zebra mussels on different substrates from a number of international studies

Location	Year	Density (m²)	Dry biomass /g to shell length/mm	Wet biomass g/m²	g AFDW m⁻²	Substrate	Reference
Lake Majcz Wielki Poland	1978	1,700 455 61 13	nd	nd	nd	Characeae Zebra mussel Stones Sand, mud	Stanczykowska & Lewandowski, 1993
Lake Mikolajskie Poland	1966 1974	100 1,000	nd	nd	nd	Characeae Stone	Stanczykowska and Lewandowski, 1993
Lake Constance Switzerland	1982 1988 1989	21,000 60,000 5,000	nd	 9,900 350	nd	 Sand	Suter, 1982 Cleven & Frenzel, 1993 Cleven & Frenzel, 1993
Lake Garda, Italy		24,000	nd		nd	nd	Franchini, 1978
Naroch Lake Belorus	1997	2,400 200 1,100 3,100 100	nd	548 57 251 275 15	nd	Stones Sand Shells macrophytes Pure silt	Burlakova, 1998
Lake Dojran, Macedonia	1975	4,500	nd	nd	nd	Macrophytes (*Phragmites*)	Sapkarev, 1975
Szczecin Lagoon Poland	1963	114,000	nd	nd	nd	nd	Wiktor, 1963
Lake Huron Canada	1991 1992 1993 1994 1995	10,100 33,800 4,000 5,000 2,100	nd	nd	9.8 61.9 4.5 3.1 4.1	Sand, gravel, cobble	Nalepa *et al.*, 1999
Hudson River estuary USA	1993	17,000 80 4.4 50	nd	nd	nd	Rocks (>5m) Soft substrate Unionidae Rocky shore	Strayer *et al.*, 1996
Lake Wawasee, USA		70,000		nd	nd	Rock, macrophytes	Garton & Johnson, 2000
Lake St. Clair,USA	1994 1994 1997	10,300 2,247 1,237	2.44	nd	nd	Silt/clay, rock	Chase and Bailey, 1999 Nalepa *et al.*, 2001
Lake Erie (2m) Canada	1994	1,900	2.69	nd	nd	Fine sand, rock	Chase & Bailey, 1999
Lake Erie (6m) Canada	1994	7,100	2.67	nd	nd	Silt/clay, rock	Chase & Bailey, 1999
Lake Ontario (2m) Canada	1994	800	2.66	nd	nd	Fine sand, rock	Chase & Bailey, 1999
Lake Ontario (6m) Canada	1994	7,900	2.47	nd	nd	Rock, silt/clay	Chase & Bailey, 1999

nd = no data

1.3.2 Substrates for Zebra Mussel Settlement

Primary settlement occurs on a wide range of substrates (Table 1.2), some of which have already been mentioned. North American and European research experience has shown that mussels can make bysssal attachment to any firm surface material including:

- Natural substrates: Rock/ stone has been found in many international studies to be the main substrate for zebra mussels (Stanczykowska, 1964; Dorgelo, 1993; Mellina and Rasmussen, 1994; McIssac *et al.*, 1992; Nalepa *et al.*, 1999; Strayer *et al.*, 1996; Karatayev *et al.*, 1997; Burlakova, 1998). Growth on stone appears to relate to the availability of this substrate in the littoral zones of lakes (Stanczykowska, 1964; Nalepa *et al.*, 1995; Lucy and Sullivan, 2001). Zebra mussels have also been found on living unionids (Lewandowski, 1976; Mackie, 1991; Schloesser and Kovalak,1991; Hunter and Bailey, 1992; Nalepa, 1993; Haag *et al.*, 1993; Tucker *et al.*, 1993; Gillis and Mackie, 1994; Tucker, 1994; Schloesser *et al.*., 1996; Strayer and Smith, 1996; Karatayev *et al.*, 1997; Strayer *et al.*, 1999), on sand (Cleven and Frenzel, 1993; Burlakova, 1998; Nalepa *et al.*, 1999; Chase and Bailey, 1999; Berkman *et al.*, 2000), on shells including sometimes zebra mussels (Stanczykowska and Lewandowski, 1993b; Karatayev *et al.*, 1997; Burlakova, 1998), submerged and emergent macrophytes (Stanczykowska, 1964; Sapkarev and Angeloski, 1978; Stanczykowska and Lewandowski, 1980, 1993b; Lewandowski, 1982b; Horvath and Lamberti, 1996; Garton and Johnson, 2000), clay (Kovaleva, 1969; Chase and Bailey, 1999) and on silt (Burlakova, 1998; Chase and Bailey, 1999). Water motion may be a limiting factor for usage of finer substrates (sand and silt) as these may become dislodged and either bury zebra mussels or strand them above water (reviewed in Karatayev *et al.*, 1997). In North America, while it was initially believed that a hard substrate was critical for settlement, studies in Lake Erie have shown successful colonisation in areas where the actual substrate is soft, muddy sediment (Berkman *et al.*, 1998). This colonisation of soft sediments does however require an initial small hard 'seed', e.g. a shell fragment or a grain of hard substrate (Burlakova, pers. comm.)

- Manmade substrates: These include concrete, plastic, fibreglass, metal, vinyl, glass and cloth. Strategic management and control strategies due to high densities on manmade structures e.g. power-plant and drinking water abstraction pipes are financially costly (Claudi and Mackie, 1994).

1.4 ZEBRA MUSSEL IMPACTS ON NATIVE UNIONID BIVALVES

Prior to the arrival of zebra mussels, the only large bivalves in Irish freshwater benthic communities were unionids (Order Unionoida, Suborder Unionacea), which are presumed to be part of the native fauna. The first reference to their existence was made by Piers in 1682. There are only three species of unionids in Ireland, *Anodonta cygnea* (Linnaeus, 1758) the swan mussel, *Anodonta anatina* (Linnaeus, 1758), the duck mussel and *Margaritifera margaretifera* (Linnaeus, 1758), the pearl mussel. Indeed there may be only two species present as several workers have noted difficulties in distinguishing between *A. cygnea* and *anatina* due to similarities in structure and ecology (Ross 1984; Lucey, 1995). Only biochemical and genetic investigations could provide a conclusive result. Meanwhile it is recognised that *A. anatina* is distributed throughout the Shannon catchment (Kerney, 1999; Lucey, 1995). *A. anatina* populations in Lough Key were studied by Ross (1984, 1988), and is the only species recorded for this lake.

Spawning in the primarily dioecious *A. anatina* was observed in July, with up to 370,000 larvae per female, depending on size, from the second summer of life (Ross, 1988). The life span is variously described as between ten and fifteen years (Crowley, 1956; Okland, 1963; Negus, 1966; Lewandowski and Stanczykowska, 1975. The species has however, been recorded as reaching 27 years of age in Lough Key (Ross, 1984) which concurs with more recent literature from English fenland waters indicating a maximum age of 28 years (Aldridge, 1999). The striking feature of most age distributions in research work is the apparent absence or rarity of young mussels less than 5cm in length. This gap on the lower end of sampled size distributions, common to most freshwater Unionacean bivalves sampling surveys has been commented on by several authors (Lewandowski and Stanczykowska, 1975; Ellis, 1978; Ross, 1988). It may relate to their early life stages as glochidiial parasites of fish (Ellis, 1978), which may make it difficult to locate them when they fall off and become free-living (Lewandowski and Stanczykowska, 1975).

Impacts of the zebra mussel on native unionid bivalves has been researched extensively both in Europe and North America (including Lewandowski, 1976; Mackie, 1991; Schloesser and Kovalak, 1991; Hunter and Bailey, 1992; Haag *et al.*, 1993; Tucker *et al.*, 1993; Gillis and Mackie, 1994; Nalepa, 1994; Tucker, 1994; Schloesser *et al.*., 1996; Strayer and Smith, 1996; Karatayev *et al.*, 1997; Strayer *et al.*, 1999). Unionids can provide the most abundant source of hard substratum for the colonisation of *Dreissena polymorpha* in many lakes, reservoirs and rivers (reviewed in Karatayev *et al.*.,1997) particularly in the absence of stoney substrate. Evidence from many European and North American studies suggest that zebra mussels preferentially colonise living unionids as a substrate and can attach to them in very high numbers (Sebestyen, 1937; Morton, 1969; Lewandowki, 1976; Schloesser and Kovalak, 1991; Hunter and Bailey, 1992; Mackie, 1993; Nalepa, 1994; Karatayev *et al.*, 1997; Gillis and Mackie, 1996; Martel *et al.*, 2002) and this has rarely been refuted in the literature as merely providing an alternative substrate (Toczylowski and Hunter, 1996; Orlova and Panov, 2004).

In North America unionid mortality occurs when zebra mussels settle and attach in very high numbers hampering filter feeding, locomotion and reproduction. Mass mortality in Eastern European waters is usually characteristic of rapid population growth following invasion. Unlike the results from North American research, in these European studies unionids usually coexist and survive in ecosystems with zebra mussels maintaining varying densities without complete elimination of unionids (Burlakova *et al.*, 2000).

1.5 ZEBRA MUSSEL IMPACTS ON PHYTOPLANKTON, CYANOBACTERIA AND WATER QUALITY

Lake water quality is most commonly assessed by reference to a scheme proposed by the Organisation for Economic Cooperation and Development (O.E.C.D., 1982). This scheme (Table 1.3) defines trophic categories (water quality of lakes) by setting boundaries for annual average 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 these parameters. 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) (EPA, 2002).

Table 1.3 Trophic classification scheme for lake waters proposed by O.E.C.D. (O.E.C.D., 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	> 3
Mesotrophic	10-35	2.5-8	8-25	6-3	3.0-1.5
Eutrophic	35-100	8-25	25-75	3-1.5	1.5-0.7
Hypertrophic	> 100	> 25	> 75	< 1.5	< 0.7

The key indicator in assessing the water quality or trophic status of a lake is the determination of the extent of plant (algal, cyanobacterial and macrophytic) growth, both planktonic and benthic, in the lake. In the case of the planktonic forms, this assessment is most commonly expressed in terms of the concentration of the algal pigment chlorophyll *a*. The extent of planktonic algae present is a function of the aquatic nutrient levels in the lake, principally phosphorus, and also on 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 *Dreissena polymorpha*, 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 are agglutinated as pseudo faecal pellets and ejected (Stanczykowska and Planter, 1985). Ingestion is selective and unsuitable particles are rejected as pseudofaeces *via* the inhalent siphon (TenWinkle and Davids, 1982). These particles contain 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 macrophytic growth. Reduced phytoplankton levels lead to a reduction in chlorophyll *a* levels and increased transparency (Stanczykowska, 1968, 1977; Reeders and Bij de Vaate, 1990; Holland *et al.*, 1993; Fahnenstiel, 1995; Lucy and Sullivan, 2001). The filtering activity of zebra mussels also has the direct effect of reducing soluble 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 pseudofaeces. As a result energy is shifted from the pelagic to the benthic zone and changes occur in the normal pathways by which nutrients are utilized and cycled (Karatayev *et al.*, 1997; Nalepa *et al.*, 1999). Arnott and Vanni (1996) suggested that enhanced soluble nutrient mineralisation by zebra mussels may be detrimental in promoting a shift in phytoplankton dominance to noxious Cyanophytes. A significant reduction in annual mean total phosphorus concentrations was recorded in Lough Erne during 2000 and 2001, from 1998 levels (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, 1999) and European studies (Stanczykowska and Planter, 1985; Binelli *et al.*, 1997).

Many of the studies on zebra mussel ecology have concentrated on the size and type of phytoplankton consumed by zebra mussels (Sprung and Rose, 1998; Holland, 1993; Jack and Thorp, 2000; Wilson, 2003; Dionisio Pires *et al*., 2004). Larger particles are rejected either by production of pseudofaeces or by not incorporating them into the digestive diverticula. Sprung and Rose (1988) found that only particles > 0.7µm diameter were removed from the water, extending to at least 3µm. Smith *et al.* (1998) studies on the Hudson River found that declining algae tended to be small cells ranging from colonial to unicellular growth forms, which were in general comprised of non-diatom genera. Horgan and Mills (1997) observed clearance rates of up to 1.5mm diameter spherical particles in large zebra mussels (9-21mm). In their study, phytoplankton morphology did not hamper clearance rates, as zebra mussels were able to ingest uni-cells, filaments and globular colonies. This showed that most particles of natural seston in freshwater lakes, which are smaller than the incurrent siphons are subject to grazing by zebra mussels, consistent with findings in Lake Erie by Nicholls and Hopkins (1993).

As zebra mussels can readily reject food particles as pseudofaeces, research has also assessed whether this species is selective in its feeding habits (Ten Winkel and Davids, 1982; Vanderploeg *et al.,* 1996, 2001). In addition to decreasing phytoplankton biomass, it has been suggested that the zebra mussel can cause changes in the species composition of the phytoplankton (Smith *et al*., 1998). Changes in phytoplankton community composition following zebra mussel establishment have been observed in most systems but directions of the species shifts have varied. Some studies have investigated the composition of food selected by *Dreissena polymorpha*. Ten Winkel and Davids (1982) found negative selection of the large pennate diatoms, *Asterionella formosa*, while positive selection was shown for spherical forms of the diatom *Dynobryon divergens* with lengths and diameters of 15-45µm. Holland (1993) showed lower mean numbers of total planktonic diatoms following the invasion of zebra mussels in Hatchery Bay, Lake Erie. In addition to selection for grazing-resistant algae or Cyanobacteria, mussel filtering might promote selection of rapidly growing species that can grow faster than the mortality imposed by mussel clearance of the water column (Bastviken *et al*., 1998, Vanderploeg *et al*., 2001).

Microcystis and some other Cyanobacteria genera produce a potent class of hepatotoxins called microcystins that can poison aquatic organisms as well as wildlife, domestic animals and humans that drink or ingest algae in the water (Carmichael, 1994). Some strains of *Microcystis aeruginosa* in Irish lake blooms have been shown to be toxic in nature, producing the toxin microcystin. In some international studies, *Microcystis* was found to be readily ingested by zebra mussels (Smith *et al.* 1998; Dionisio Pires, 2004). A decrease was noted in the relative abundance of colonial Cyanobacteria in the Hudson River, mainly, *Microcystis* following the introduction of *Dreissena* (Bastviken *et al.*, 1998). Reeders and Bij de Vaate (1990) showed that filtration rate of zebra mussels was not affected by Cyanobacteria. Raikow *et al.* (2004) found that *Dreissena* has positive effects on the growth of *Microcystis aeruginosa* in low nutrient lakes (total phosphorus <25μg/L) but not in lakes with higher levels of total phosphorus. *Dreissena* has also been shown to reject *Microcystis* strains which produce microcystin; observations using micro cinematography filmed zebra mussels rejecting the cyanophyte, *Microcystis* as unconsolidated pseudofaeces (Vanderploeg *et al.*, 1996; Vanderploeg *et al.*, 2001). A study using Saginaw Bay lake water showed that zebra mussels had little effect on chlorophyll levels when cyanophytes were abundant (Fanslow *et al.*, 1995). As a result in some cases the colonial blue-green and other "unpalatable" algae may increase in abundance through selective rejection and availability of nutrients due to diminished demand from other grazed phytoplankton and from zebra mussel excretion (Arnott and Vanni, 1996; Vanderploeg *et al.*, 2001). In some systems, blooms of Cyanobacteria (blue green algae) have increased following the introduction of the zebra mussel. In Saginaw Bay, Lake Huron, a *Microcystis* bloom in 1995 was the first Cyanobacterial bloom on Lake Erie since phosphorus control measures had been implemented in the mid 1970s (Nicholls and Hopkins, 1993). Late summer blooms of the cyanophyte *Aphanizomenon* were recorded in Oneida Lake following the zebra mussel invasion (Horgan and Mills, 1997).

This rejection followed by successful resuspension of Cyanophytes in the water column could lead to strain dominance in algal blooms with consequent public health issues (Chorus and Bartram, 1999). The associated toxins can result in a range of human symptoms from skin rashes to vomiting and have given rise to anecdotal reports of dog deaths following the drinking of lake-water in various Irish lakes including the Shannon's Lough Ree.

Cyanobacteria were generally the dominant organisms in the plankton in Lough Key in the monitored summers of 1976, 1995-1999, with *Microcystis* forming the most important constituents of this population (Toner, 1979; Bowman 1998 and 2000). *Microcystis* is associated with toxic blooms and thus has implications for water-based leisure activities.

In contrast there can be a positive link between zebra mussels and public health, this species can be used to detect human waterborne parasites. Zebra mussels can be used to monitor freshwater reservoirs for pathogenic contamination (Graczyk *et al.*, 2001). A study carried out in Lough Key and other Shannon River sites recovered *Cryptosporidium parvum*, *Giardia lamblia*, *Encephalitozoon intestinalis*, *E.hellem* and *Enterocytozoon bieneusi* from zebra mussel samples; this strengthened the concept that zebra mussels can recover and concentrate environmentally derived pathogens and can be used for the sanitary assessment of water quality (Graczyk *et al.*, 2004)

Zebra mussels are capable of filtering large quantities of water in relatively short periods of time (Karatayev *et al.*, 1997). Studies on clearance rates and filtration rates have been mostly laboratory based, using different methodologies and using a range of food types from natural seston (Kondratiev, 1962; Stanczykowska, 1968; Lvova, 1977; Reeders and Bij de Vaate, 1990; Karatayev and Burlakova, 1993, 1995; Fanslow *et al.*, 1995; Roditi *et al.*, 1996; Horgan and Mills, 1997;) to specific algal cultures (Sprung and Rose, 1988; Bunt *et al.*, 1993; Aldridge *et al.*, 1995; Tuchman *et al.*, 2004), clay with adsorbed bacteria (Lei *et al.*, 1996) and inert microspheres (MacIssac *et al.*, 1992). The clearance rate of zebra mussels depends on the composition of phytoplankton (Ten Winkle and Davids 1982; Berg et al. 1996) and the overall grazing effect on plankton community may be different in different lakes (Wacker and von Elert 2003, Raikow *et al.*, 2004).

1.6 ZEBRA MUSSELS AND THE WATER FRAMEWORK DIRECTIVE

As part of a substantial restructuring of EU water policy, a Directive establishing a new framework for action in the field of water policy was agreed by the European parliament and Council in September 2000. The Directive (2000/60/EEC) generally known as the Water Framework Directive (WFD) was transposed into Irish law in December 2003 (Statutory Instrument (S.I.) No. 722 of 2003). The WFD utilises river basins as the natural unit for water management with each river basin within member states assigned to a river basin district (RBD). These form administrative areas as each has a river basin management plan. The island of Ireland has eight RBDs (www.wfdireland.ie) including the Shannon River Basin District, to which Lough Key belongs.

In the EU document Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive (2003) the introduction of alien species is given as an example of a biological pressure. Therefore, the threats to water bodies, from alien species have to be assessed. The main pressure is determined as competition with indigenous species. Substitution of populations, destruction of habitats and competition for food are seen as the main impacts. Eight aquatic alien species, including *Dreissena polymorpha* have been selected as key organisms for the development of an Irish Risk Assessment Model (EPA, 2004b).

1.7 LOUGH KEY AS A STUDY AREA

Lough Key, Co Roscommon is situated in the Upper Shannon catchment (Irish Grid G840 057) and is located on the Boyle River, which flows into the Shannon River, 8km downstream of Lough Key, at a point 2km above Carrick-on-Shannon, Co Leitrim. (Fig 1.1).

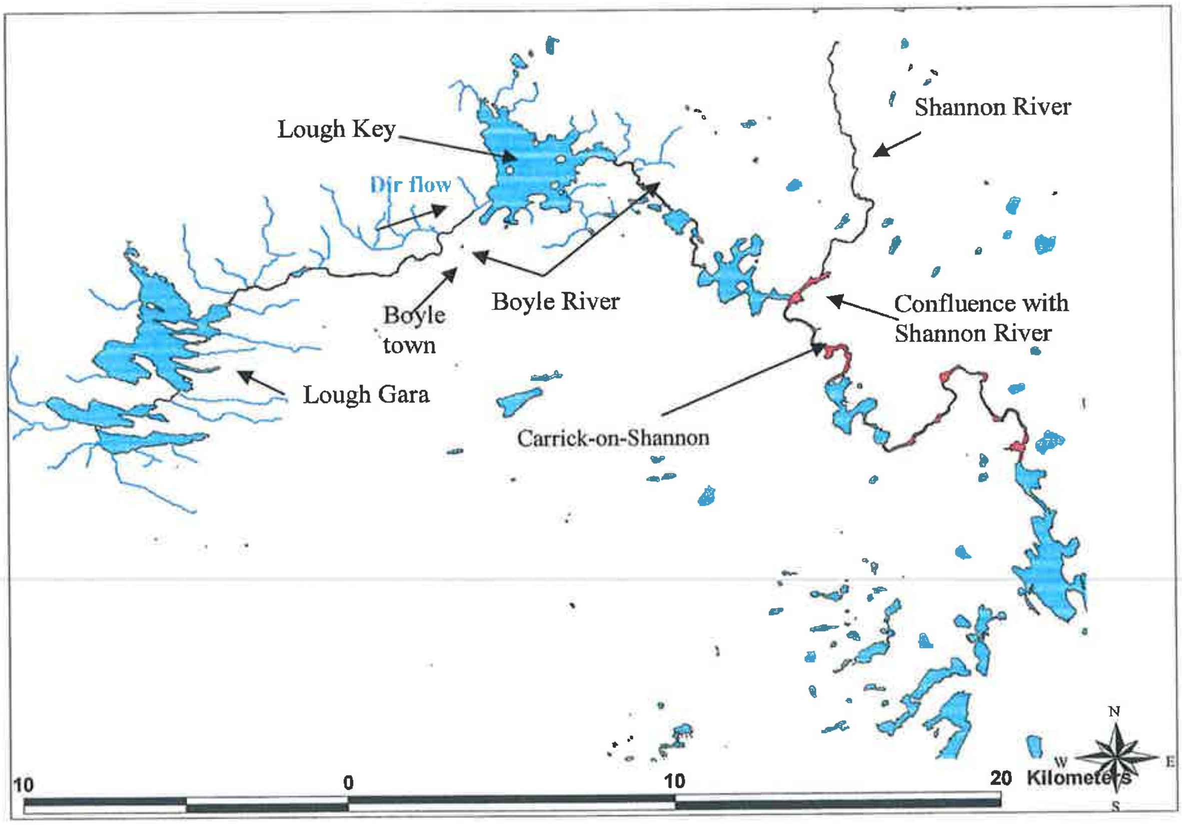


Figure 1.1 Lough Key and Upper Shannon Catchment

1.7.1 Lough Key – General Characteristics

Lough Key is $9km^2$ in size, is located at an altitude of 45m O.D., and is relatively square in shape with a maximum length of 4.2km and a maximum width of 4km. It has an estimated volume of 45.97 m^3 x 10^6 and a maximum depth of 23.5m (Toner, 1979). The lake is relatively shallow with a mean depth of 4.5m (this study). Most near shore areas of the lake have a stoney substrate. Lough Key has a well-indented shoreline, approximately 28km in length. Lake substrates will be dealt with in detail in Chapter 3. There are 13 islands on the lake, with a total island shoreline of 8km. Three of these islands are designated as Natural Heritage Areas by the Department of the Environment, Heritage and Local Government.

1.7.2 Lough Key Catchment – Topography and Landuse

The lake is bordered on the west and northwest by steep slopes rising up to the Curlew Mountains (Fig 1.2). Rolling landscape occurs to the north of Lough Key, with gentle slopes found around the remainder of the land surrounding the lake in eastern and southern parts.

The immediate catchment of the lake is very confined and the majority of inflowing streams are small. These have low flows and are sometimes dry during summer months (Bowman, 1998). The only substantial inflowing stream to the lake is the Boyle River, which drains the greater portion (93%) of the catchment west of the lake (Fig 1.1). A larger lake, Lough Gara ($11km^2$) lies 4km upstream of Lough Key (Fig 1.1). The entire catchment size of the lake is estimated at 587 km^2 (Toner, 1979).

An amenity area, Cilín (also known locally as the Doon shore) on the west side of the lake is used for bathing. Near shore areas have a high component of mature deciduous woodland. This dominates the southern end of the lake where mature trees, planted in an old country estate (Rockingham, 19^{th} and early 20^{th} century) are a major component of Lough Key Forest Park. This park is owned and managed by Coillte Teoranta, an Irish semi-state owned forestry company (www.coillte.ie). This provides a walking amenity for local families and also a camping facility. Boating facilities are also available on the lake. Lough Key is part of the Shannon-Erne navigation and leisure craft enter the lake *via* Clarnedon Lock travelling within the lake or upstream to the Boyle canal (Appendix 12). The main use for land in the Lough Key catchment is for small scale agricultural usage; pasture and meadow for low–intensity cattle and sheep farms. There is very little tillage in the catchment. Fig 1.2 (Central Fisheries Board, GIS map) shows land usage patterns in the catchment area.

In general population density is relatively low with only two towns in the catchment, Ballaghadereen (population estimate, 2,000) and Boyle (population estimate, 2,200) (CSO, 2002). A food industry in Boyle discharges a population equivalent (pe) of 2,650 to the town sewer. Boyle Sewage Treatment Plant (Boyle STP) discharges to the Boyle River at a point source approx 2km upstream of the lake.

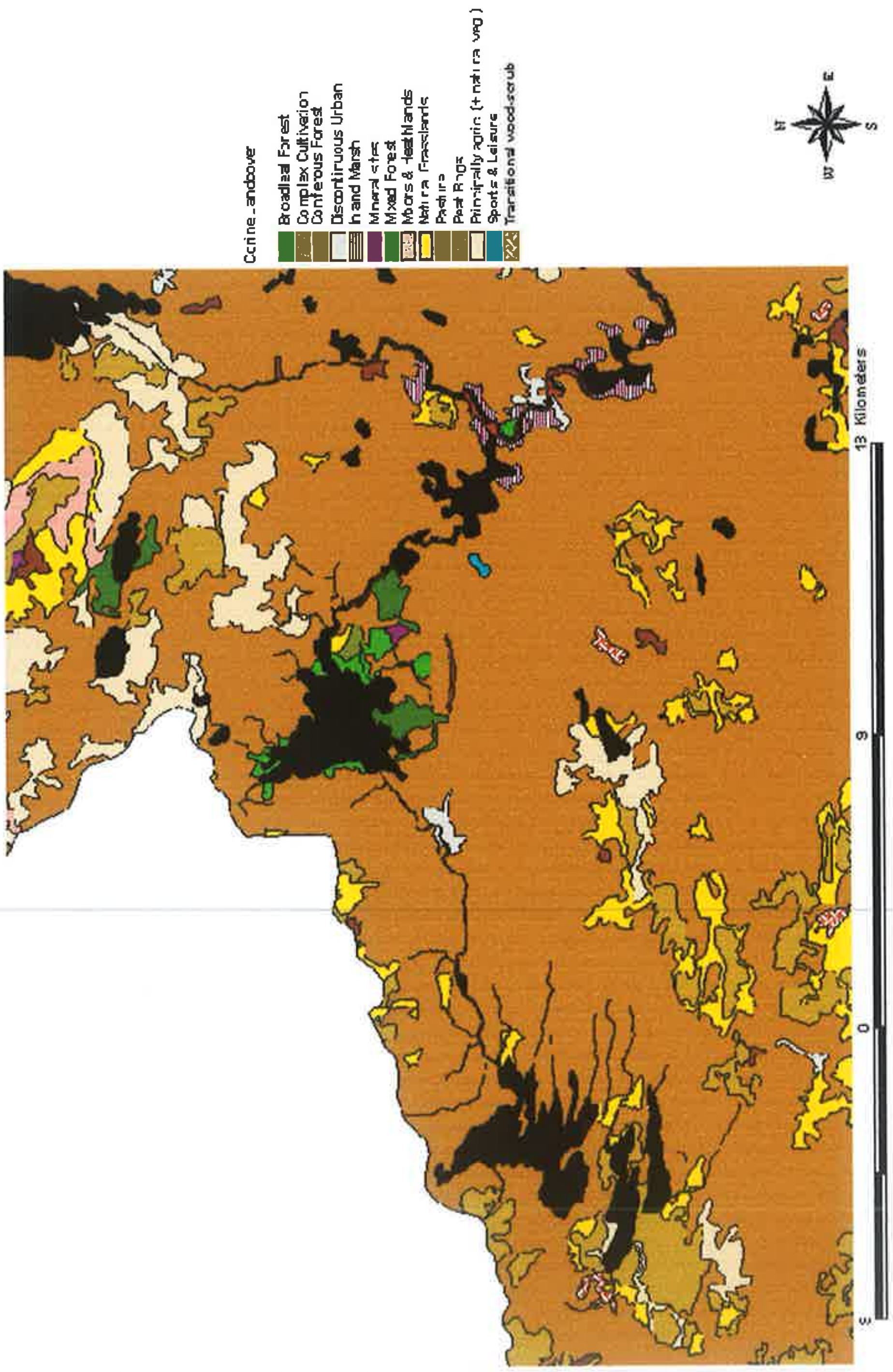


Fig 1.2 Land-use map of Lough Key and Upper Shannon catchment area (CFB, GIS map)

1.7.3 Geology and Soils of Lough Key Catchment

The geology of Lough Key and its catchment is outlined in Toner (1979), McDermot, Long and Harney (1996) and Hepworth Holland (2001). The geology of the catchment area shows two main divisions (Fig 1.3, Central Fisheries Board, GIS map). The bedrock of the more extensive part of the catchment, south and south east of the River Boyle channel, is composed of carboniferous limestone while the rising ground to the north is bedded on shales and sandstones.

Lough Key lies on three main strata; quartz rich sandstone and mudstone (KW-Keadew formation) in the north end of the lake; sandstone and red green conglomerates (BO-Boyle sandstone formation) in the south end of the lake and dark nodular calcerenites (KL- Kilbryan limestone formation) in the south-east lake corner. The Keadew formation was laid down during the Devonian period (410-355 million years ago). The sheets of quartz-rich sandstone generally have a thin veneer of mud-cracked or ripple-marked mudstone.

Both the Boyle sandstone and the Kilbryan limestone formations were formed in the Carboniferous period (355-310 million years ago). The topmost part of the BO is the Rockingham sandstone member, a pale grey, bioturbated sandstone overlain by calcareous sandstone with shelly fragments. This formation is 130m thick in the Lough Key area. The Kilbryan limestone formation (KL) consists of bioturbated, nodular-bedded limestones interbedded with calcareous, often fossiliferous shales and strongly argillaceous limestone with a lime:mud ratio of between 80:20 and 50:50. The south-eastern section of Lough Gara (11km^2), 4 km upstream, is also situated on limestone and this drains into Lough Key. The Kilbryan limestone formation has a major influence on the water chemistry of Lough Key.

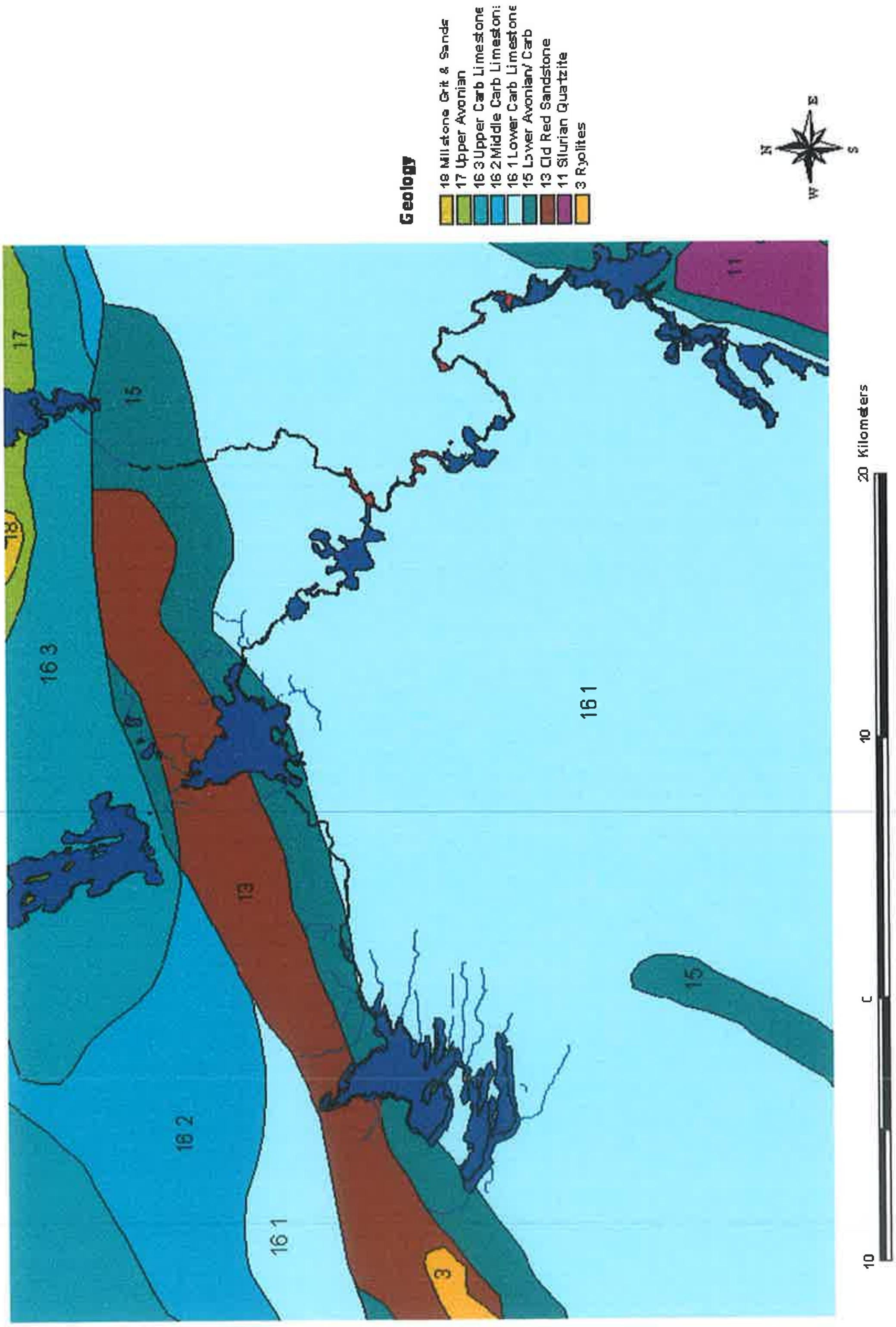


Figure 1.3 Geology of Lough Key and Upper Shannon catchment (CFB, GIS)

The soil types immediately surrounding Lough Key are chiefly gleys with peaty gleys, acid brown earths and some inter-drumlin peat. In the area to the south of Lough Key and east of Lough Gara grey-brown podzolics dominate with gleys of minor importance but in large areas south of the latter lake gleys are again the major soil type with some grey-brown podzolics (Toner, 1979). West of Lough Gara, there is an extensive area of peatland (Fig 1.3).

1.7.4 Lake Water Quality

Due to limestone influence, Lough Key water is of high ionic content (270-340 μscm^{-1}) and high pH (8.04-8.59) (Bowman, 2000). This provides buffering against humic acid inputs. The lake water is strongly coloured, ranging from $20\text{-}100^{0}$ Hazen with similar ranges in the mid-1970s and late 1990s through to 2003 (1976-1977, Toner, 1979; EPA datasets 1995-2003). The upper high colouration levels reflect the input of humic acids from peaty soils in the catchment. Total hardness in the lake has been recorded at levels of 155 mg/L $CaCO_3$ (Flanagan, 1975).

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 was provided by AFF, An Foras Forbatha and data from 1995-1997 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 (Bowman, 2000).

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 (EPA, 2002).

1.7.5 Physico/chemical Factors Relevant to Zebra Mussel Colonisation

Environmental factors considered important in terms of colonisation potential of zebra mussels include the physico/chemical factors of water temperature, dissolved oxygen, water hardness and pH.

The annual temperature regime in Lough Key is suitable for zebra mussel colonisation. The temperate climate means that the lake is above 10^0C for seven months of the year, rarely freezes in winter and the highest temperature recorded in recent years (23^0C, this study) is well below the thermal tolerance of $>30^0$C recorded by Karatayev (1998) and others in the former Soviet Union (FSU). Summer lake temperature regimes ($>15^0$C) in Lough Key are suitable for prolonged spawning over the summer season.

Dissolved oxygen levels recorded in the lake between 1995 and 1999 range between 88 and 130%, which provides sufficient oxygen for zebra mussels to respire. Although slight thermal stratification was recorded in 1998 and 1999, this occurred only in the deepest part of the lake (Bowman, 2000). Dissolved oxygen levels recorded in the hypolimnion were recorded at 83%, well in excess of the 25% critical threshold minimum for *Dreissena* recorded by Spiridonov (1971) reviewed in Karatayev *et al.* (1998).

The limestone influence in the lake ensures that total hardness and pH levels are within high colonisation potential levels for zebra mussels (O' Neill, 1995 and Ramcharan *et al.*, 1992). The presence of calcium ions (from dissolved limestone) is required by these bivalves to secrete the mineral portion of their shells (McMahon, 1992).

1.7.6 Link Between 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 and planktonic algal and Cyanobacterial organisms. The latter two components are sustained by phosphorus.

While it is recognized that some diffuse pollution occurs from farming activity in the catchment, many datasets indicate that phosphorus is chiefly derived from the waste discharge at Boyle Sewage Treatment Plant (Boyle STP) (Toner, 1979; Bowman, 1998; Roscommon County Council data). High levels of phosphorus contributions from sewage have been observed in other Irish lakes including Lough Ennell, Co.Westmeath, where up to 97% of the orthophosphate entering the lake could be attributed to a sewage point source (Lennox, 1984). Boyle 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 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, *Dreissena polymorpha*, 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 including zebra mussels are understood and quantified. There is a popular view that there may be no need to reduce phosphorus input 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.

1.8 SUITABILITY OF LOUGH KEY FOR ZEBRA MUSSEL RESEARCH

This lake is uniquely suitable as a lake for zebra mussel sampling due to a number of factors:

1. The lake is small ($9km^2$) and therefore relatively easy to comprehensively survey, with the Boyle River as the only major inflow and outflow.
2. 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.

3. Water quality parameters associated with zebra mussels have also been monitored in conjunction with the above. These include chlorophyll *a*, transparency, molybdate reactive phosphorus and total phosphorous.

4. 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 datasets 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.

5. Zebra mussel populations can be examined on a number of substrates - stoney substrates, reed beds and *Anodonta* shells. In common with many Irish lakes the littoral zone substrate of Lough Key is often stoney. 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 but shell persisted as a substrate from 2000 to 2003.

1.9 AIMS AND OBJECTIVES OF THESIS

The main objective of this project was to develop a clear understanding of the dynamic role of the zebra mussel in the Lough Key ecosystem. This included research in the following areas

- Population dynamics at different stages of the life cycle in different years
- Estimation of total number and biomass in the lake associated with different substrata and depth zones
- Impacts on the native *Anodonta* population
- Association of zebra mussels with aquatic plants
- Impacts on chlorophyll *a* and transparency (trophic status) and phytoplankton
- Relationship between phosphorus concentration and zebra mussel populations (trophic status)
- Filtration rate estimate of lake water volume by zebra mussels

1.10 TASKS AND ASSOCIATED METHODOLOGIES

There were many tasks and associated methodologies involved in Lough Key zebra mussel research. These included the following:

- Monitoring of zebra mussel populations (larval, juvenile and adult) in littoral, open water and benthic zones of Lough Key between 1998 and 2003. This involved the use of plankton nets, settlement plates, grabs, quadrats, an underwater video camera, snorkel and dive surveys. Adult zebra mussels were monitored for biomass and total number on identified lake substrates, aquatic plants and on unionid shells. Total number and biomass of zebra mussels in Lough Key were assessed using a transect survey (2002).

- Substrate and bathymetric mapping of Lough Key (2001). This provided a depth (bathymetric) chart and a sediment map of the lake based on an acoustic Roxann^{Tm} survey (Seabed Surveys Ltd). This survey provided information on the different consistencies of the lake sediments and the extent of substrate types suitable for zebra mussel colonisation in Lough Key. The different substrate areas were then further investigated, by grab sampling, snorkelling or diving, to confirm their composition and the extent of their suitability. The lake area at different depth intervals was estimated using this data. Underwater video survey work was also used to map shallow areas. A zebra mussel habitat map of Lough Key was determined based on different substrate types.

- Measurement of light penetration and chlorophyll *a* levels in the lake. This was to assess the impact of the zebra mussel population on light penetration in the lake and on the extent of alga (1998-2003). These were monitored using Secchi disc and standard EPA chlorophyll *a* methods, respectively. Temperature was measured using an alcohol thermometer and also with a data-logger.

- Collation and analysis of relative phytoplankton and cyanobacterial abundance from EPA datasets (1995-2003). Data were examined to see whether there were any changes in frequency of varying taxa to assess the impact of a possible reduction in the Lough Key phosphorus loading on the planktonic algal and Cyanobacterial biomass in the lake.

- Input and analysis of phosphorus data from (a) Boyle Sewage treatment Plant (P loadings to lake) (Roscommon County Council), (b) Boyle River upstream and downstream of the treatment plant (Roscommon County Council, 2000-2003) and (c) Lough Key data (EPA monitoring programme) (2000-2003). These data were analysed to determine changes in water quality due to the new phosphate removal system at Boyle.
- Statistical analysis of zebra mussel and water quality datasets where appropriate.

1.11 LOUGH KEY ZEBRA MUSSEL RESEARCH PARTICIPANTS

Table 1.4 outlines the Lough Key research structure in terms of project tasks and deliverables, giving a timescale for each participant's role.

Table 1.4 Project participants, roles and associated timescales

Project Participant	Role	Timescale
Ms Frances Lucy	Lead researcher. Intensive and extensive lake-water and zebra mussel monitoring, snorkeling, video research, laboratory analysis, projectco-ordination.. BSc Superviso student projects on larval/veliger stage.	1998- 2003
Dr Monica Sullivan	Intensive 2 week zebra mussel monitoring, EPA Spreadsheets, video research	1999-2003
Dr Dan Minchin	Intensive 2 week zebra mussel monitoring, navigator of research vessel	2000-2003
E. Ni Chonmhara, N. Greaney, A. Skelly, E. Commons, S. Duggan, A. Marshall, K. O' Mahony, J. Lohan	BSc projects on early *Dreissena* life stages and *Anodonta*	1998-2003
Seabed Surveys	Roxann^{Tm} Survey of lake substrates	2001
Monterrey Software	Digitised Mapping of Roxann^{Tm} and other project data	2001-2002
Mr Martin Manning	Underwater video for substrate mapping of the shallow areas of the lake and reed bed survey work	2001-2003
Mr Peter Walsh	Boat-handling for routine lake monitoring	1998-2003

CHAPTER 2

MATERIALS AND METHODS

Materials and methods are divided into two sections in this chapter. Section 2.1 outlines project sampling locations. Section 2.2 details the sampling and analysis procedures. Further details of sampling and analysis are also included in subsequent chapters of this thesis.

2.1 SAMPLING LOCATIONS

This section outlines the Lough Key and Boyle River sites selected for various parameters including water temperature, transparency, chlorophyll *a*, zebra mussel sampling (larva, juveniles and adults), phytoplankton and phosphorus. The sampling schedule for each parameter and zebra mussel life stage is also included.

2.1.1 General Monitoring Programme

An extensive monitoring programme was carried out for a range of physical and biological parameters. Fig 2.1 shows the five Lough Key monitoring stations (Sites A-E). Water temperature, transparency and chlorophyll *a* samples were taken at four sampling sites (A-D) in 1998 and 1999 surveys (Lucy and Sullivan, 2001). An additional site (E) at the northern end of the lake was added to the survey from 2000 onwards (summer only), as this had been noted for high populations during the 1999 research. A monitoring programme for zebra mussel larva and settlement also took place at the above sites. The scheduled sampling programme was designed to maximize sampling during the summer season. Weekly sampling was implemented from July to the start of September. During 2001-2003 occasional sampling was also carried out earlier and later in the year.

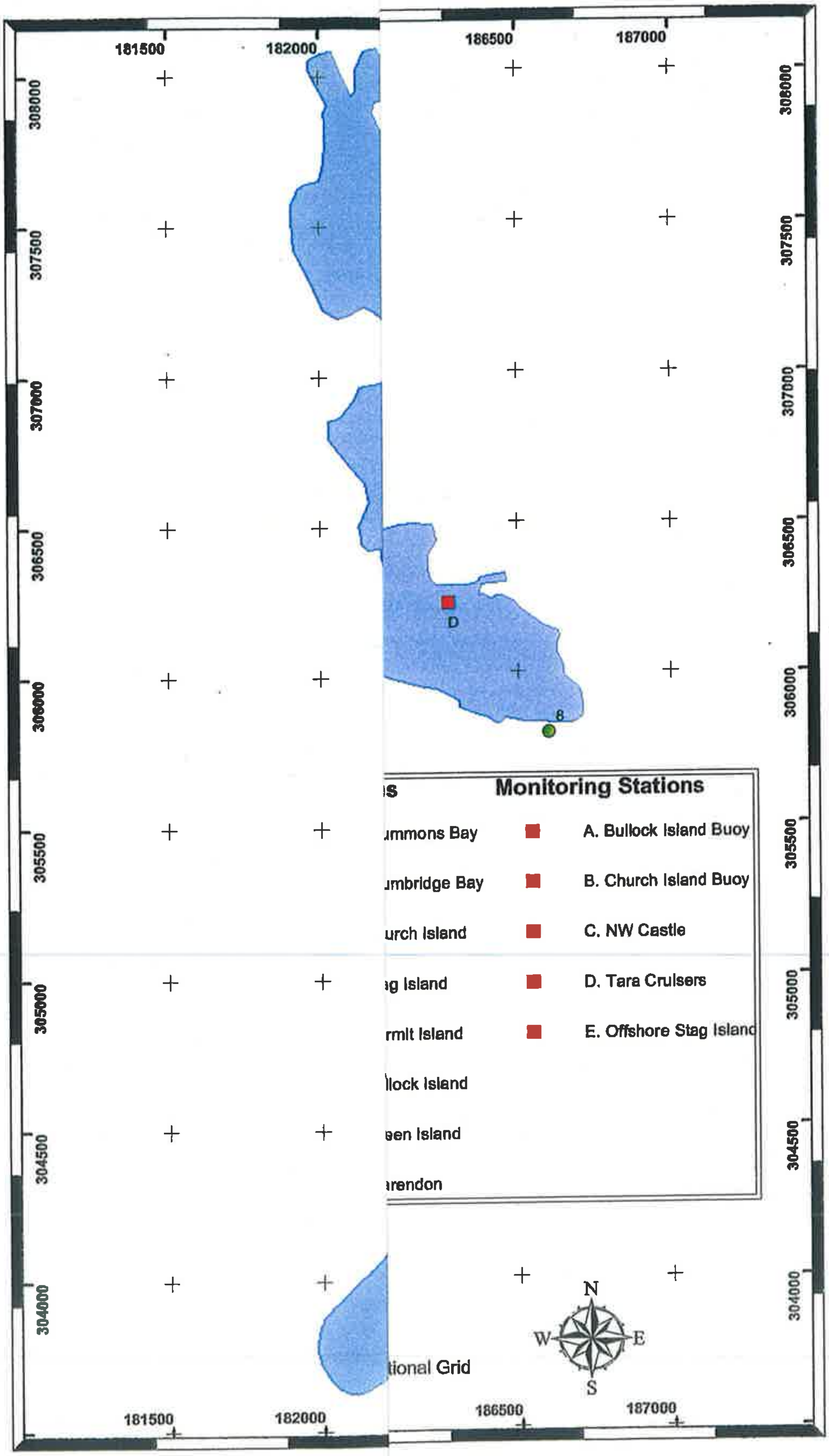


Fig 2.1 Monitoring stations and s

2.1.2 Adult Zebra Mussel Sampling

Eight sampling stations (Sites 1-8) were selected as snorkel sites in August 2000 and were resurveyed in August 2001 and 2003 (Fig 2.1). Adult sampling was carried out on the mainland shore west of Site 3, Church Island (G 825 055) in 1998 and at various lake sites during 1999. Adults were also sampled periodically during 2001 to 2003, from a jetty due east of Site 1, Drummons Bay (G 845 043)

Samples were taken along 8 transects for the transect survey. These transects ran from a lakeshore point across the centre of the lake to the opposite shore (Fig 2.2). Four standard axes were chosen in order to map the lake efficiently and avoid any bias. The transect lines were:

i) N->S
ii) E->W
iii) NE->SW
iv) NW->SE

Each transect line made up two transects.

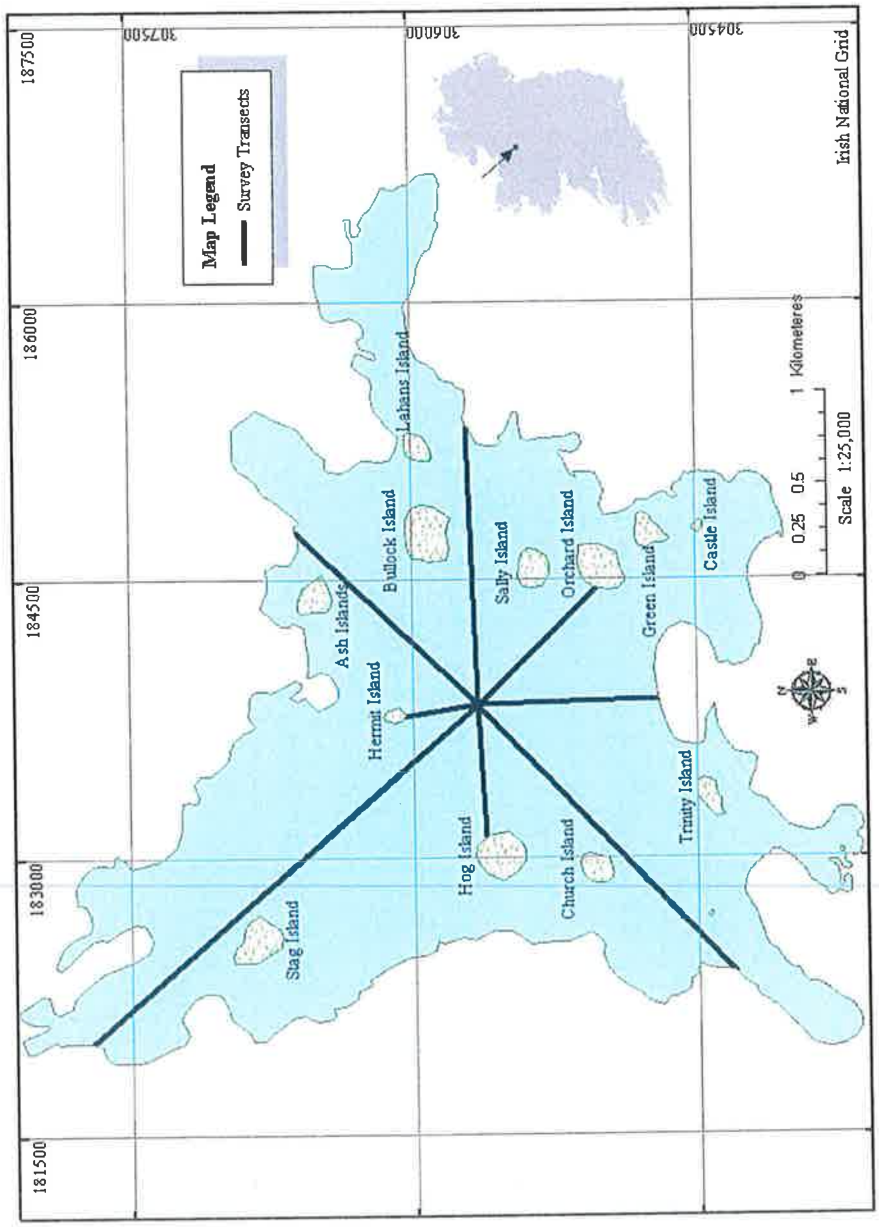


Figure 2.2 Transects used in 2002 Survey

2.1.3 Phytoplankton Sampling

Phytoplankton samples were taken by the EPA at sampling Station C (G 835 053) during the following periods: March 2000, 2002 and 2003; April 1998, 2001; July 1998-2002; September 1998-2001; October 1999. The EPA datasets produced were used in this thesis. Additional Station C datasets from 1995-1997 were also examined. A map of the EPA sampling stations is included in Appendix 11.

2.1.4 Phosphorus Sampling

- EPA data for the thesis is for the five Lough Key stations (A-E) (Appendix 11) 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 Sewage Treatment Plant (Boyle STP).
- Boyle River data (Lough Ree and Lough Derg project data, 2000-2003) was from two stations on the Boyle River. One was 0.5km (approx) upstream of Boyle STP at Boyle Abbey (G807 027) and the other was 1.1km (approx) downstream of the plant at Drum Bridge (G817 04). These sites were sampled on a monthly basis between 2000 and 2003.

2.2 SAMPLING AND ANALYTICAL PROCEDURES

2.2.1 Transparency and Chlorophyll *a*

(a) Transparency determination: A standard 25cm black and white Secchi disc was used to measure transparency, using standard procedures.

(b) 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 one litre samples for each site were filtered through GF 50 glass fibre filter papers within 3 hours of sampling. These were placed in individual bags, labelled and frozen according to standard procedure (www.epa.gov). Subsequent laboratory analysis was carried out regularly on sample batches included defrosting, followed by immediate chlorophyll *a* analysis according to standard spectrophotometric EPA procedure.

2.2.2 Temperature

A temperature datalogger (Vemco minilog V3.04) was deployed at Tara Cruisers to record temperatures every four hours between 2001 and 2003. Temperature was also recorded with an alcohol thermometer at both Tara cruisers (monitoring station D) and at Bullock Island Buoy (Fig 2.2) during monitoring (1998-2003).

2.2.3 Nutrients

Total phosphorus and orthophosphate were analysed in the EPA laboratory, Dublin and in the Lough Derg and Lough Ree system laboratory in Roscommon County Council using standard methods (APHA, 1999). Additional datasets were also obtained from 1995 to 1997. Results were collated and relevant parameters were reviewed for this thesis as outlined in Chapter 8.

The Boyle sewage treatment plant (STP) flow and total phosphorus data was used to determine total annual phosphorus loadings (tonnes TP/year) to Lough Key. Total phosphorus loadings/m^2 on Lough Key were calculated by dividing the annual Boyle STP loadings/kg by the surface area of the lake (9,000,000m^2).

Vollenweider's relationship (1975 and 1976) between annual phosphorus loadings (g P/m/yr) and the ratio of mean lake depth (Z = 4.5m) to hydraulic retention time (τ_{ω} = 0.16 year) as estimated by Toner (1979) was used to predict whether total phosphorus loadings would give rise to an oligotrophic or mesotrophic status in Lough Key during each year of the survey.

2.2.4 Phytoplankton and Cyanobacteria

All samples collected by the EPA were fixed in Lugols 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. These datasets were collated for the purpose of this thesis.

2.2.5 Zebra Mussel Life Stage Sampling

Sampling of early zebra mussel life stages (larva/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 Larval/Veliger Sampling and Analysis

(a) Veliger sampling

Three-metre vertical tows were carried out at four monitoring sites (A-D) in 1998 and 1999 and at five sites (A-E, weather permitting) from 2000-2003. A 64μm mesh plankton net with a 30cm diameter opening was used for veliger sampling, allowing collection of all veligers >70 μm.

(b) Estimation of Larval/Veliger Density and Size Distribution

For the monitoring programme each sample was examined under a high magnification (80-100x) (Olympus CX-41) using one-ml sub-samples in a Sedwick-Rafter Counting cell. Three one-ml sub-samples were counted and the veliger density per ml of concentrated sample calculated from the mean as below:

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

a = Volume in 25ml tube

b = 3 x 3.14 x $(0.3)^2$ = length of tow x π x radius of net mouth^2 = 848L

The microscope was fitted with an optical micrometer and size distributions of veligers from Sites B, C and E were measured to the nearest 10µm. Veliger density and size distributions were analysed by final year BSc students (Ni Chonmhara, 1999; Commons, 2000; Duggan, 2001; Marshall, 2002; O'Mahony, 2003; Lohan, 2004) following training and under the direct supervision of Frances Lucy.

Datasets were collated and analysed for this thesis. Size distribution and biomass results were compared statistically using t-tests, G tests, ANOVA and post-hoc Tukey HSD test ($p<0.05$) where data were normal and variances were homogenous (Levene statistic, $p>0.05$). When data were not normally distributed and the variances were heterogeneous (Levene statistic, $p<0.05$), Kruskal-Wallis and post-hoc Mann-Whitney test-tests ($p<0.05$) were applied. The statistical package SPSS 11 was used to carry out the various statistical analyses (Howit and Cramer, 2003).

2.2.5.2 Settled Juvenile Sampling

Settled juveniles were sampled using 15 x 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 monitoring 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 (3m depth approx). All plates were conditioned for one week to allow a bio-film to build up, thus encouraging settlement. The top plate at each site remained unchanged and was removed twice during the 2001 season (July 21 and Oct 21) and once during the 1998-2000, 2002-2003 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 two-week rotation. Once recovered, the plates were placed in a sectioned sample container and then examined using a microscope for the presence of newly settled juveniles. These were clearly visible on the surface of the plates. The mean of 30 x 1 cm^2 quadrats was obtained for each plate and an estimated settlement density/m^2 was calculated. A new plate was replaced each time a settlement plate was recovered.

Seasonal plate counts were compared with the cumulative two-weekly plate counts to see which would provide better data on overall seasonal settlement.

2.2.5.3 Adult Sampling

Adult sampling was undertaken as part of snorkel surveys (1998-1999, August 2000, 2001, 2003), during the course of the transect survey (2002) or as part of ongoing monitoring.

(a) Snorkel Surveys

Snorkelling and scuba diving methods were used close to the mainland shore west of Site 3, Church Island (G 825 055) and at various sites throughout the lake in 1999 (Lucy and Sullivan, 2001). 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 stoney substrate, *Anodonta* shell, *Phragmites australis* (old and new), *Schoenoplectus lacustris* and other plants where present.

- **Stoney Substrates**

  Stoney substrates were sampled at seven of the snorkel sites. Drummons Island (Site 1) did not have any stone present and therefore was excluded from this sampling. data for 1999 (Site 8) and 2000 (Sites 2-8) were based on counting and measuring the zebra mussels (1mm intervals) in multiple 4cm^2 quadrats in 1999 and based on weighing, counting and measuring in 2000. From 2001 a new improved method was used to assess zebra mussel biomass. Stones were removed from the substrate by the snorkeller and placed on the boat deck in a 625cm^2 quadrat. The biomass of zebra mussels was removed from the stones and weighed to the nearest gram (Balance: AND model 162). A correction factor was applied to the biomass obtained from the $4cm^2$ quadrats in 2000 as it was known to be large relative to results from 25cm x 25 cm quadrats. This was obtained by calculating the ratio of zebra mussel biomass in a $4cm^2$ and $625cm^2$ quadrat at Site 8 in 2003 and dividing the result for 2000 by the correction factor (2.46).

Size distributions were taken for >150 zebra mussels per sample. Firm substrates were also targeted for the detection of zebra mussels at varying depths using a Van Veen grab (1/40 m^2, i.e. $0.025m^2$).

- **Zebra Mussels on Reeds, Rushes and other Aquatic Plants**

Ten old and ten new common reeds of *Phragmites australis* were cut at their base from outer fringes of reed bed sites. Ten common rushes, *Schoenoplectus lacustris* were removed in the same way. Zebra mussel biomass and size distributions on these plants were compared. Numbers of zebra mussels colonising each plant were taken during survey work in 1999. A qualitative assessment was also undertaken on submerged and marginal plants including waterlily, *Nuphar lutea* and horsetail, *Equisetum fluviatile*.

- **Zebra Mussels on *Anodonta anatina***

Live and dead *Anodonta* were removed by divers at mainland shore west of Site 3, Church Island (G 825 055) in 1998 and at Site 8 in 1999 (n >30). In 2000, 2001 and 2003 thirty paired *Anodonta* shells were removed from each snorkel site. Various parameters were measured including the length and weight of living *Anodonta*, weight of zebra mussel fouling and estimated age of *Anodonta*. A Bosch SE 200 balance was used to weigh *Anodonta* and shells. The numbers of *Anodonta* per m^2 and other qualitative information were also assessed on all videotapes and during various dive survey (dive and rake) since April 1998.

Statistical analysis (t-test and ANOVA) were carried out on biomass estimates from various substrate datasets.

(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. Total wet weight has been determined to be the most stable measure of zebra mussel mass for both reproductive potential and filtering impact, both because of their thin shell and seasonal changes in soft mass due to spawning, (Karatayev, 1983).

In order to acquire good, complete datasets, two methods of sampling analyses were used, namely grab sampling and scuba diving. A quadrat frame size 25 x 25 cm, (sampling $0.0625m^2$) 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. $0.025m^2$). At each depth interval and for each transect, a replicate of 3 samples was collected, e.g. 3 samples between 0 and 1m, South transect. Maximum lake depth along each transect was also recorded (Table 2.1).

Table 2.1 Sample method and maximum depth for project transects

Transect	Dive (m)	Grab (m)	Max Depth (m)
North	0-6	3-7.6	7.6
South	0-5	4-18.7	18.7
East	0-4	4-11.5	11.5
West	0-4	4-19.3	19.3
Northeast	0-4	3-8.3	8.3
Southwest	0-4	4-19.1	19.1
Northwest	0-4	4-14.8	14.8
Southeast	0-6	4-20.0	20.0

A GPS was taken at all grab sampling stations, but it did not prove possible to take GPS readings at dive locations, since the boat was moored off-site (due to hazardous rocky substrates in shallow waters) and the diver collected samples from random, discrete locations underwater. The diver did however follow a strict bearing along a specific transect line at all times. Mussels were collected by the diver at depths of 1.0 metre intervals from the shoreline to a depth of 6 metres. The substrate category generally dictated the method of sampling required, i.e. once the substrate was predominantly transitional or mud (categories 2 or 1 respectively: see Section 3.2.1), it was deemed appropriate and feasible to sample by grab analyses.

A small pilot sampling programme of the effectiveness of grab sampling versus scuba diving sampling was carried out where the sediment categories moved towards transition and mud substrates, i.e. between 3 and 5m depth. The southeast transect was chosen for this study at a depth interval of 4–5m. Both methods of analyses showed the same substrate results. The grab sampler picked up small pebbles with zebra mussel druses attached and the remainder of the sample was mud. The diver also recorded the same sediment type by visual observation.

Table 2.2 Comparison of results from dive and grab samples (4-5m depth)

	Scuba Diving	**Grab**
Total No. x 3	153, 231, 296	129, 68, 67
Mean Total no.	227	88
Quadrat (m^2)	0.0625	0.025
Total No. (m^2)	3627	3520

The results of the pilot survey show that the total number of zebra mussels recorded per m^2 using a grab is 97% of the total recorded by the scuba diving methodology.

Dive samples (all surface substrate including plant material) were placed directly into collection bags and taken to the surface. Grab samples were hauled to the boat deck. Both dive and grab samples were washed through a 500µm mesh sieve. All plant matter, substrate and other debris was removed. Samples were blotted dry on absorbent paper and then counted and weighed (wet weight, soft tissue plus shell) to the nearest 1g. Representative samples (n = 250) from different depths, were frozen for size distribution analysis at a later date.

The total and average density/number and biomass of zebra mussels in Lough Key were calculated by following four statistical steps as below. Firstly, the mean density and biomass for each of the eight transects was calculated as follows:

1. From the datasets collected, the mean density of the mussels per each depth interval (0-1, 1-2, 2-3, etc.) was recorded as the average for all samples taken from these depths, i.e. average density/biomass of samples taken from 1 to 2 m gives the mean for a 1-2 m depth interval. e.g.

$D_{1\text{-}2m} = D_{1.0m} + D_{2.0m}$ / No. of samples

where $D_{1\text{-}2m}$ = mean density on the depth interval (1-2) of the transect

$D_{1.0m}$ = average density from samples taken on 1.0 m depth of the transect

$D_{2.0m}$ = average density from samples taken at 2.0 m depth of the transect.

2. The mean density for each depth is then multiplied by the area of that depth interval (for example, if 0-1 m depth interval in the lake occupies an area equal to 0.5 km^2 and 7-8 m occupies 0.3 km^2 etc. then corrective factors must be incorporated in the calculation). These areas were all calculated from Seabed Surveys Bathymetric charts created for the lake.

$D_{0\text{-}1m} * A_{0\text{-}1m}$

where $D_{0\text{-}1m}$ = mean density on the depth interval (0-1) of the transect

$A_{0\text{-}1m}$ = area under the depth interval 0-1 m in the lake.

3. All the mean values for each depth interval taken from each site along the transects (0-1, 1-2, ...19-20) are then added and this sum divided by the total area of the lake bed (again obtained from Seabed Surveys Analyses)

$$D_i\,section = \underset{j=0,\ n=1}{\overset{N}{\varepsilon}} D_{j\text{-}n} \times A_{j\text{-}n} \,/\, A_{lake}$$

where $D_i\,section$ = mean density of the i section

$D_{j\text{-}n}$ = mean density on the depth interval *j-n* (m) of the section

$A_{j\text{-}n}$ = area under the depth interval *j-n* in the lake

A_{lake} = total area of the lake

j, n = starting and ending depth of (j, n) interval where *j=0* N-1, *n=1*

N =maximal depths at which zebra mussels occur in Lough Key.

All mean values for each sampled section (equal to the number of sections sampled) were then calculated.

4. The average (+/- SD or SE) density and biomass of zebra mussels in Lough Key was then calculated using the mean values for each section as follows:

$$D_{lake} = \sum_{i=1}^{M} D_i$$

where D_{lake} = average density of zebra mussels in the lake

D_i = average density of zebra mussels at the *i* section

M = number of sections sampled in the lake

This procedure was repeated for calculation of the biomass of zebra mussels in the lake.

(c) Ongoing Monitoring

Adults were also sampled periodically during the three-year project from a jetty due east of Drummons Bay (Site 1). These were scraped from the vertical surface of the Rockingham jetty (G 845 043) using a scraper attached to a 3m pole (Minchin *et al.*, 2002). Samples were also taken from the underside of the buoys at Site A and B using the scraper. A size distribution and biomass were taken for each sample.

(d) Reedbed Video Survey Work

Four reedbeds at different locations within the lake were surveyed by the ROV (remotely operated vehicle) camera once per season, between summer 2001 and 2003. Methodology for the ROV is included in Section 3.3.1. The videotapes were analysed to assess presence and possible seasonal movement of zebra mussel populations on these plants during different seasons over the course of the project. Footage of zebra mussels on other substrates was also undertaken when the photo opportunity arose.

2.2.6 Estimation of Filtration Capacity of Zebra Mussel Populations in Lough Key

Methodology for filtration capacity of zebra mussels in Lough Key is given in Section 8.3.2

2.2.7 Roxann^{Tm} Survey, Computer Analysis, Ground-truthing and Video Surveys

Methodology for this survey is included in Section 3.2.

2.2.8 Photographs

A library of relevant survey photographs was filed during the course of the thesis. These included photographs of research work and zebra mussel fouled substrates.

CHAPTER 3

DEVELOPMENT OF SUBSTRATE, DEPTH AND HABITAT MAPS FOR LOUGH KEY

3.1 INTRODUCTION

In most lakes surveyed in zebra mussel research, stone and rock have been found to be the most suitable substrate (Morton, 1969; Mellina and Rasmussen, 1993; Nalepa *et al*., 1995; Burlakova, 1998). These hard substrates have been described in various studies using a number of terms (rock, stone, cobble, boulder) but were not strictly classified using a scientific scale, e.g. the Wentworth scale which includes major substrate classes (boulders, cobbles, pebbles, gravel and sand) with their numerous subdivisions (Wentworth, 1922). Littoral substrates are by their nature often heterogenous mixtures of different sized stones, with a proportion of mud or sand, reflecting local geology, deposition and wind current patterns. This level of complexity using strict substrate classification is not conducive to the operation of intensive zebra mussel surveys and this is why these systems have not been widely used in zebra mussel surveys.

In the partial or complete absence of stone substrates, other substrates may be used by expanding populations of zebra mussels within a lake, e.g. native unionid mussels or aquatic plants. Early survey work in Lough Key established that the majority of zebra mussels are found on stoney substrates on the periphery of the lake and islands (Lucy and Sullivan, 2001). Other notable substrates were identified as *Anodonta* (Unionidae) and various macrophytes. The colonisation of stoney substrates, unionid shells and aquatic plants are dealt with in detail in Chapters 5, 6 and 7 respectively. Zebra mussel populations have also been known to spread onto soft substrates such as in Lake Erie, where *Dreissena polymorpha* is known to occur to depths up to 63m (Dermott and Munawarr, 1993). As suitable substrates are usually found in shallow waters (Karatayev *et al.*, 1998), the physical factors of depth and substrate type are closely linked. It was considered crucial therefore, to map the major environmental variables of substrate and depth to provide significant data prior to zebra mussel habitat assessment and population surveys in Lough Key.

Habitat assessment is often considered a prerequisite for wildlife and fisheries management (Brower *et al.*, 1990) and was considered a fundamental part of developing research on the dynamics of zebra mussel populations in Lough Key. A few geographic information system (GIS) analyses have included substrate and/or depth mapping in Great Lakes' zebra mussel population surveys in parts of Lake Erie (Haltuch *et al.*, 2000) and Lake Huron (Chakraborti *et al.*, 2002). The large scale of many East European and North American lakes and the technical challenges involved have however, probably made total-lake zebra mussel habitat mapping impractical in most cases. With a size of $9km^2$ it was feasible to map both substrate type and depth throughout Lough Key. This allowed the development of a zebra mussel habitat map for the lake.

The main objectives for carrying out this mapping research were to:

- Develop a working habitat map for zebra mussel survey work in Lough Key
- Investigate the relationship between substrate and also depth on the distribution and abundance of zebra mussels within Lough Key, linking directly with objectives laid out in Chapter 5
- Provide information on depths and substrates for safe research navigation

This chapter details research carried out in summer 2001 including the development of the lake sediment and depth models, subsequent ground-truthing, and video survey work in areas < 2m depth. It also gives results of substrate analysis from transect work carried out in 2003.

3.2 MATERIALS AND METHODS

3.2.1 Depth and Substrate Mapping – RoxAnn ^{Tm} Survey

A RoxAnn™ acoustic ground discrimination system (AGDS) was used to collect bathymetric and sediment data in Lough Key (Appendix 1). This system allowed the collection of large volumes of data, achieved remotely with no disturbance caused to the lake substrate. The post-processed hydro-acoustic data from the survey of Lough Key was integrated with Geographical Information System (GIS ARC/INFO) Technology, which was employed using latitude and longitude readings to develop depth and sediment models of the surveyed lake. A bathymetric/depth survey chart was produced using data from the GIS mapping software and relevant vector tiles from the Irish Ordinanace Survey Irish Grid. Total areas of different depth at intervals of 0.5m or more were calculated using data from the GIS mapping software. A detailed substrate map was also produced by GIS, which identified sixteen sediment types (Appendix 1). This mapping incorporated only basic ground-truthing elements, which required a more detailed survey.

3.2.2 Ground-truthing of Roxann^{Tm} Survey

Specified lake areas were identified for ground-truthing to verify the electronic data sets given by the RoxAnn^{Tm} substrate map. Separate maps and data sheets were generated for the various lake substrates, created by the RoxAnn^{Tm} survey (examples in Appendix 1). Lake maps were plotted showing ground-truth target areas for particular substrate types identified by RoxAnn^{Tm} – mud, transitional, transitional with possibly sandy gravel in places, gravelly sand, unknown substrates, gravel and stones, stones and rock. Latitude and longitude points were given for all target areas.

The mapping positions chosen for ground-truthing reflected each of the main substrates deduced by Roxann^{Tm} signals and also included areas with similar echoes whose substrate was not clearly defined. Some isolated signals for rock were also assessed. A GPS was used to locate these positions, which were then ground-truthed with at least three replicate Van Veen grab samples ($0.025m^2$). GPS waypoint numbers were assigned to each grab sample. In total, the substrate classes were ground-truthed at approximately fifty locations (212 grab samples) around the lake.

As the RoxAnn^{Tm} sediment map was more complex than considered necessary for this project it was simplified into four main substrate types, considered relevant to zebra mussel research work.

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

A map was produced in GIS format showing the location of these substrates in water > 2m depth. It was not possible to carry out the RoxAnn^{Tm} survey on depths < 2m and hence video survey work was employed in shallow littoral zones around the mainland and island lake shores.

3.2.3 Video Survey Work

A VideoRay remotely operated vehicle (ROV) was used to collect additional information on shallow water substrates and depths < 2m, using inferometric methods. The video surveyed the shallow shoreline around the lake and its 13 islands. The VideoRay is a highly portable ROV (Remotely Operated Vehicle)

The ROV system incorporates a full colour camera, with pan & tilt functions, twin variable illumination halogen lights, horizontal and vertical thrusters. The system outputs a PAL video signal, which is subsequently recorded to VHS cassette. Geographical positions of video work were maintained using a Garmin 12 XL GPS receiver in addition to a CSI ABX differential beacon receiver.

Plate 3.1 ROV camera

Stations were surveyed at 200m spacing around the lake frontage, with footage recorded along transects from the shoreline to the waypoint location, in an East-West direction. A metadata report for each survey day, recorded weather conditions, station depths and a commentary of *in situ* observations were made.

The ROV was piloted over an area of substrate, initially panning from the surface down to a plan view. This allowed the viewer to obtain a view of the surrounding conditions, in addition to specific details of the benthic environment for species identification. The ROV provided an effective system to record underwater environments, particularly shallow waters (< 2 metres) within Lough Key.

The videotapes were analysed and waypoints assessed according to substrate classification, recording the percentage cover of rock, stone, mud, *Anodonta*, plant debris gravel and also the presence of various aquatic plant species.

3.2.4 Substrate Analysis of Lake Transects

In summer 2003 a substrate survey of three lake transects was carried out to determine the proportion of different substrates from the shoreline to a five metre depth interval. For each transect, the video camera was lowered three times at each depth interval and percentage substrate was evaluated and recorded. These transects were selected from those used in the zebra mussel population transect survey in Chapter 5. As young-of - year zebra mussels often settle on older year classes or dead shell, the results of the transect substrate survey also included zebra mussels as a substrate. This was a refinement of the substrate analysis and was not included in the original video survey. A basic substrate analysis at snorkel sites was also carried out during survey work in 2001 and 2003 (Appendix 7).

3.3 RESULTS

3.3.1 Depth and Substrate Mapping – RoxAnn^{Tm} Survey

Fig 3.1 shows a bathymetric map in A4 format produced from the RoxAnn^{Tm} datasets. This map version gives depth contours as follows: 0.5 - 5m, 5.1 - 8.5m, 8.6 - 12m, 12.1 – 16.5m and 16.6 - 22.5m. More detailed maps were also produced for specific surveyed areas. Some sections of the lake were too shallow and/or rocky for the RoxAnn^{Tm} survey track and although these are not highlighted on the map, they are known to be in the 0.5 – 5m depth category.

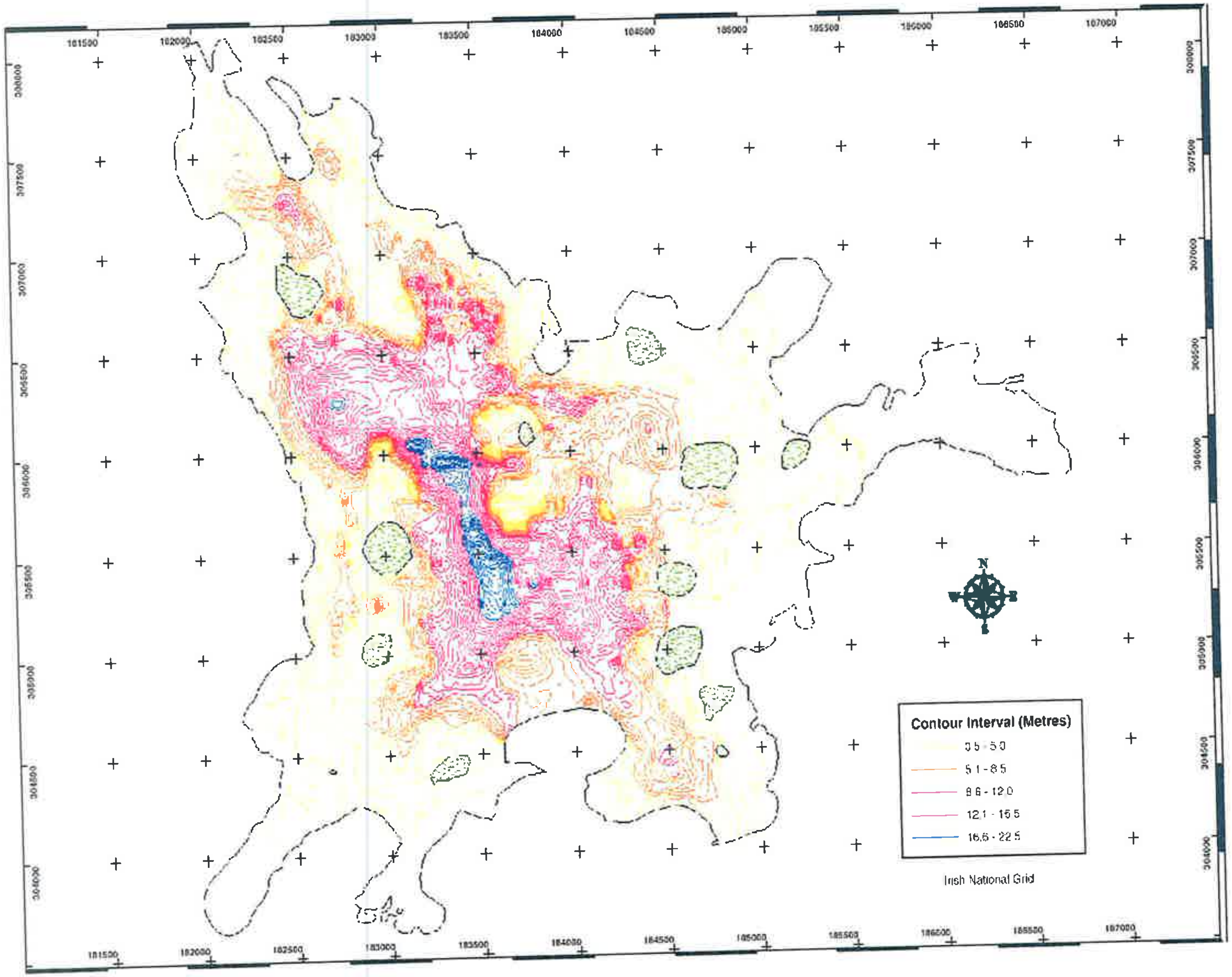


Fig 3.1 Bathymetric chart of Lough Key

Table 3.1 gives the total area and percentage of depth zones in Lough Key, estimated by RoxAnn^{Tm}. Fifty-eight point nine percent of the lake is less than 5m in depth. The mean depth of the lake is estimated at 4.5m, slightly less than the 5 m result in Toner (1979). Eighty-four point seven percent of Lough Key is less than 10m depth. The deeper sections of the lake run in a North-West to South-East axis, with the deepest part of the lake, known as the Hog Island' Deep (22.5m depth, EPA station C) found in the mid section of the 16.6 – 22.5m map contour.

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

Depth Zone	**Area m^2**	**% Lake**
0-<2	673123.7	8
2-<3	1628143.8	19.3
3-<4	1809059.39	21.5
4-<5	849639.33	10.1
5-<6	506684.03	6
6-<10	1663773.69	19.8
10-<14	805489.69	9.6
14-<18	355156.93	4.2
18-20	61619.00	0.7
18-<22	46297.02	0.5
>22	25085.6	0.3
Total	**8424072**	**100**

The detailed sediment/substrate map produced by the RoxAnn^{Tm} survey is included in Appendix 1. The map was modified due to reclassification, following the ground-truthing survey results.

3.3.2 Ground-truthing Results

Results of individual ground-truth waypoints are given in Appendix 2. The following is a substrate account of ground-truthing on mud (category 1), transitional substrates (category 2), rock and stone (categories 3 and 4). Waypoint listing began at waypoint 62 due to the GPS numbering system.

3.3.2.1 Category One: Muddy Substrates

Mud was the most extensive of all the substrate types determined and therefore it was important to examine a large number of different sites at varying depths and locations within Lough Key (Appendix 2: waypoints 66-74, 203-204, 209-212). The consistency of mud substrates varied. Waters deeper than 10m tended to be composed of a fine 'silky' mud with occasional fine shell fragments. Some areas, e.g. near the Hog Island Deep had very fine, 'silky' mud, devoid of any particulate matter. In other parts mud contained up to 5% approximately of shell content, with shells mainly buried in the mud substrate. These were mainly the shells of gastropods. In a few cases zebra mussels were found attached to shell overlaying the mud substrate. *Anodonta* shell and shell fragments were also recovered from muddy substrates (in most cases in depths <7m). As expected from results of other survey methods, zebra mussel attachment to *Anodonta* was frequent. Small zebra mussel druses were found occasionally to a depth of 17.8m. Some of these druses had recent settlement attached and were associated with mud.

In muddy shallows, submerged aquatic macrophytes e.g. *Potamogeton, Sparganium* and the alga *Cladophora* were frequently encountered. Surface strewn shells of gastropods and *Pisidium* and *Anodonta* (dead shell) were common. Plant debris was frequently found to depths of 4m.

3.2.2.2 Category 2:Transitional Substrates

Transitional substrates were identified at waypoints 62-64, 105 -128, 167-168 (Appendix 2). Some areas identified by Roxann^{Tm} as gravely-sand were found to be predominantly mud with a small component of shell. In some cases also, small rounded pebbles were present. In both cases these were categorised as transitional substrates. In Lough Key there were extensive areas of mud adjacent to hard surface substrates (categories 3 and 4). In some areas of the lake (e.g. waypoints 167 and 168) it was evident that there was a transition zone between hard and soft substrates because embedded pebbles or stones were occasionally recovered. These substrate areas were classified as transitional.

3.3.2.3 Categories 3 and 4: Rock and Stone

Zebra mussels were found associated with stones, boulders and rock at varying depths to 17.5m (Appendix 2: Waypoints 132-135, 213-246). At greater depths it seems that such substrata may be covered with mud and silt. An apparent rocky ridge occurs adjacent to the Hog Island Deep (EPA station C) with a NW-SE alignment.

While working on these hard substrates, the operator frequently felt the impact of the grab striking a hard object prior to closure of the grab. In these cases the sample often contained zebra mussel druses but no actual bedrock was recovered. Occasionally pebbles, stones, *Anodonta* or rock fragments were recovered, sometimes with attached zebra mussels and pebbles. Druses were sampled frequently indicating that this may be part of a transition zone between hard substrate and mud.

At some locations the target areas for ground-truthing were small, which gave rise to difficulty in maintaining the GPS position. In waypoints 142-153, sample points were thought to be outside the target area. These consisted mainly of mud with some shell.
In general, ground-truthing results concurred with the Roxann^{Tm} survey. The most important aspects were defining the composition of the transitional substrate and establishing the presence of occasional zebra mussels on mud and transitional substrates. Fig 3.2 maps the four main substrates found in Lough Key by the Roxann survey^{Tm}. It also includes depth contours at 3m depth intervals. The main limitations of the survey in mapping depths <2m was overcome by the video survey of shallow areas described in Section 3.3.3.

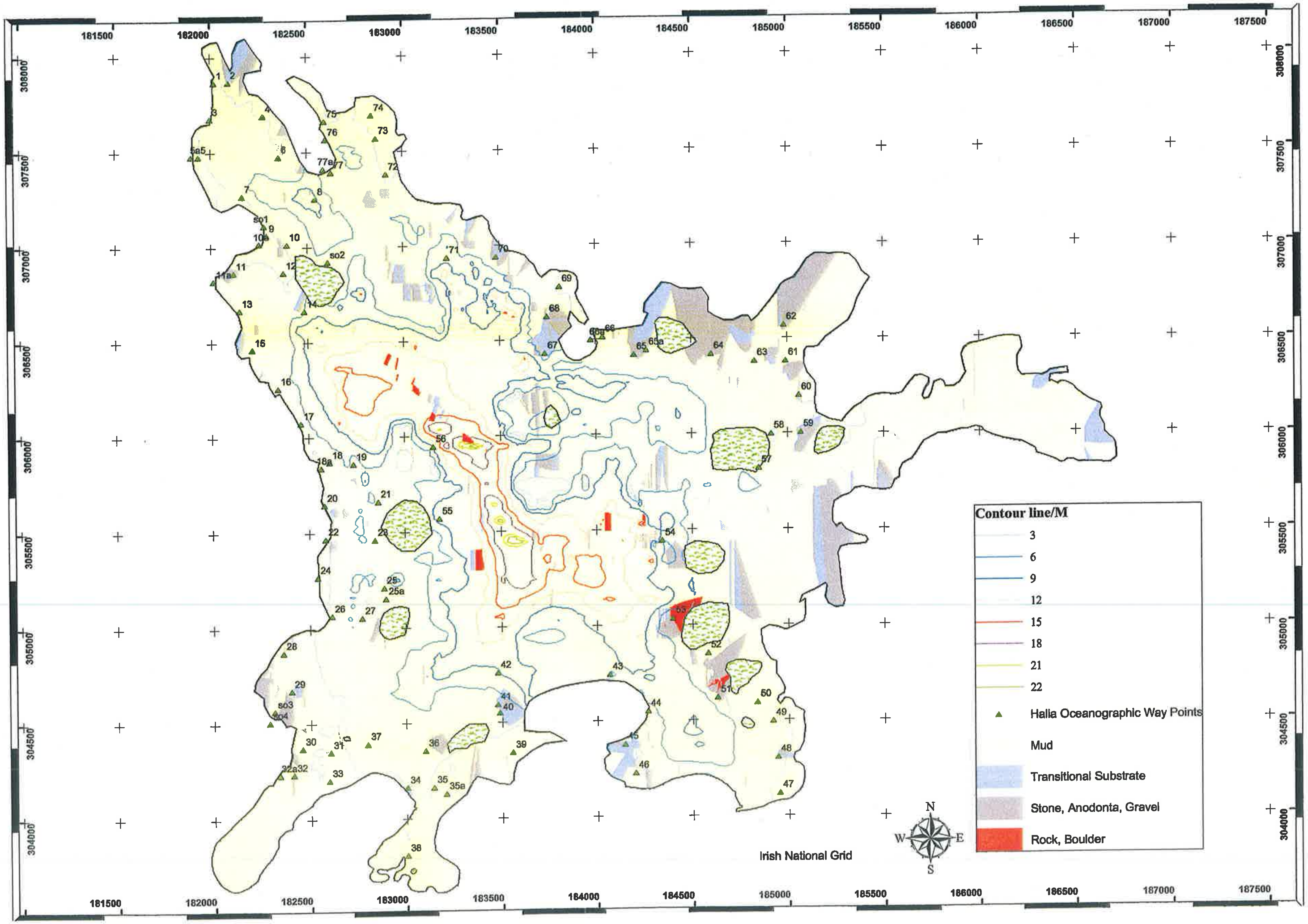


Fig 3.2 Map of Lough Key showing the four main substrates and depth at 3m contour levels

3.3.3 Video Survey Work

Fig 3.2 shows waypoints (Halia Oceanographic waypoints, represented by triangles) used for the video survey work of lake substrates in depths of <2m. Appendix 3 gives detailed results for the substrates found at each of these points. Substrates given can be related to the four substrate categories outlined previously. The shallow margins of the lake were often suitable for zebra mussel settlement, with 33% made up of rock, stone, pebble and *Anodonta* (Fig 3.3). The remaining 67% was comprised of mud. Some parts of the lake perimeter were not sampled, e.g. at the eastern side (lake outlet) which, was not accessible by boat due to the rocky nature of the substrate. Shore-based investigations revealed that these rocky shallow areas of the lake outlet can be considered to fit into categories 3 and 4.

3.3.4 Substrate Analysis of Lake Transects

Shallow areas (<2m) close to shorelines typically had heterogenous substrate with a high component of hard substrate (Categories 3 and 4) and varying components of transitional (Category 2) and mud (Category 1). Rock and stone dominated the first 3m of depth in each transect (75-95%). The proportion of these dropped to approximately 50 % at the 3-4m range (Fig 3.4).

Substrate in waters >3m typically had a higher component of mud. Mud dominated the substrate types in depths greater than 4m. Overall hard substrates made up 23% of the total bed areas, with 76% being comprised of mud (Category 1) (Fig 3.4). These results compare well with overall results from the video survey (Fig 3.3).

Some transects had zebra mussels present on transitional substrates, when located close to stoney substrate (Category 3). In these cases pebbles, or zebra mussels attached to pebbles provided the hard substrate required. Results for snorkel survey substrates also indicated heterogeneity, with varying percentages of hard substrate (Appendix 7).

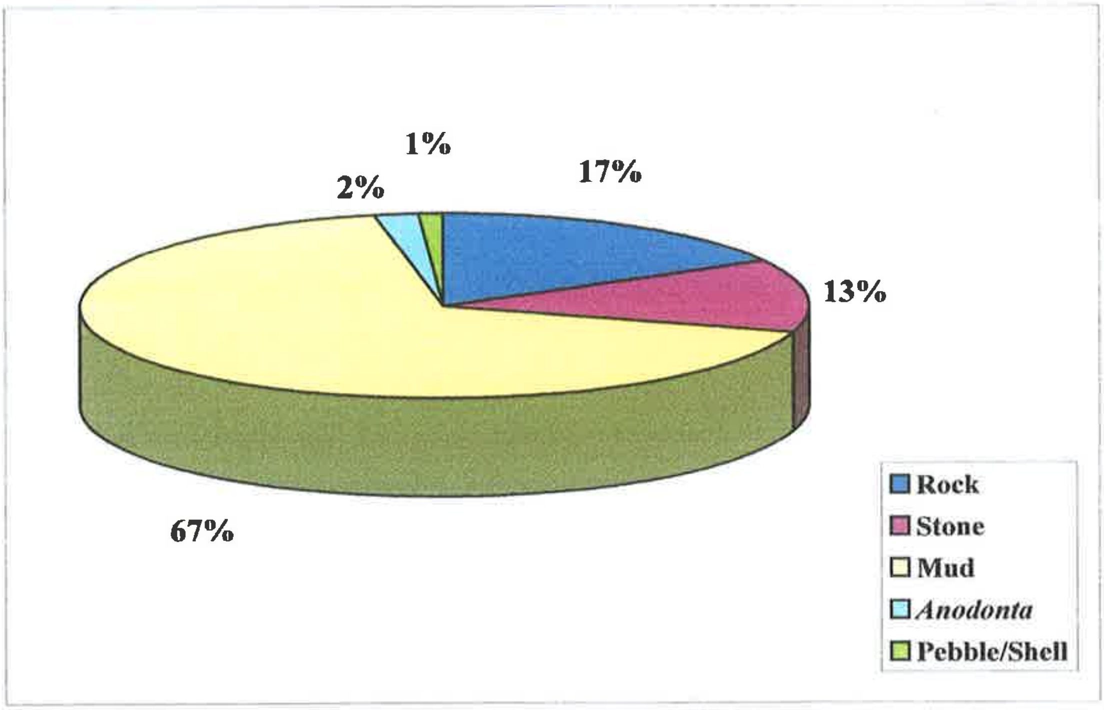


Fig 3.3 Substrate analysis of video survey

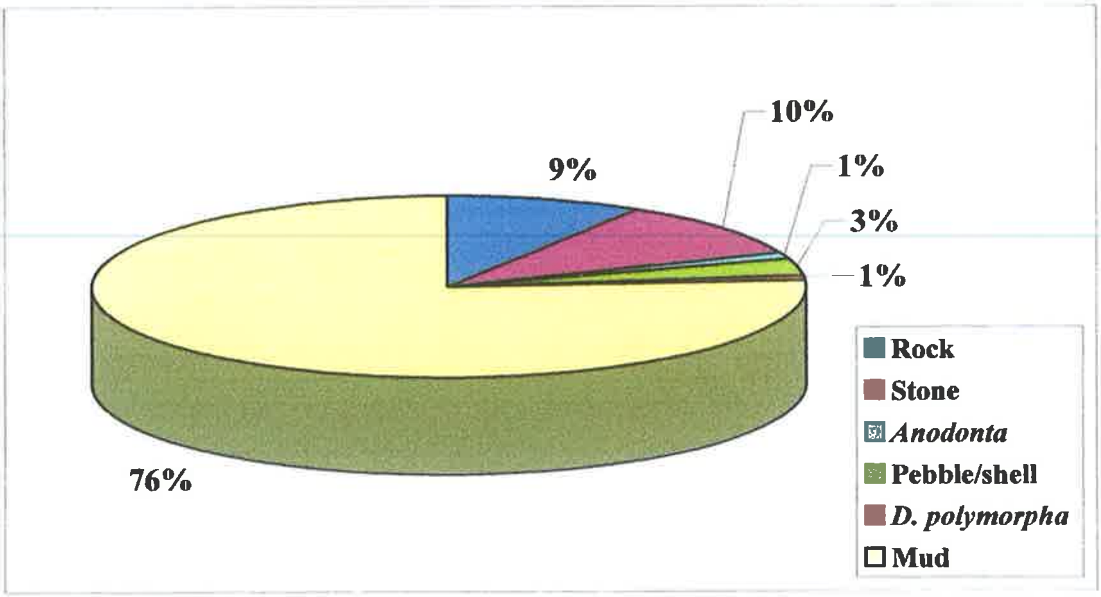


Fig 3.4 Substrate analysis of combined lake transects

3.3.5 Habitat Map

Fig 3.2 can also be viewed as a habitat map, with areas marked as substrate categories 3 and 4 being suited to zebra mussel colonisation. Categories 1 and 2 may be classified as being occasionally suited to zebra mussel colonisation. Shallow areas close to shorelines, mapped by video survey were generally suitable for zebra mussel colonisation as most have a percentage of rock, stone, gravel, *Anodonta* or aquatic plants present. Colonisation of shallow areas was corroborated by snorkel and dive work for transect and snorkel site surveys (1999-2003).

3.4 DISCUSSION

The development of a GIS mapping system for substrate and habitat mapping of Lough Key was considered an essential tool for researching zebra mussel populations in the lake. The digitised mapping system provided information on any section of the lake which had been surveyed by the RoxAnn^{Tm} or video surveys. Ground-truthing of the RoxAnn^{Tm} survey proved that in most all cases the virtual substrate analysis was correct.

The maps produced were used throughout the survey for the reasons outlined in the objectives given in this chapter. The usefulness of the maps could not be fully determined until the research on total population estimates was complete. They were extremely useful however, for safe navigation purposes on Lough Key as they provided information on depth and substrate. The mapping also established the grid point reference for the centre point of the lake, which was later used to develop transects for total lake population surveys.

There were a number of limitations to the mapping survey. The main problem was that the hydroacoustic survey result for total surface area of the lake ($8.42 km^2$) was significantly less than it should have been because it could not map areas <2m deep. Another shortcoming was that some shallow rocky areas could not be surveyed by either the RoxAnn^{Tm} or video camera and thus were not integrated into the mapping system. In addition to the above, the mapping of the video system was also in a different format to that of the RoxAnn^{Tm} survey. It is considered however, that this is not really a problem in the context of a GIS mapping system as the lake database can be interrogated to give results for any of the sampling stations from both surveys.

In terms of an overall assessment it is considered that the survey succeeded in generating intensive and extensive information about lake substrates and depths. This element of the research facilitated the development of a functional habitat map for zebra mussel population surveys in Lough Key and provided the essential substrate data required for Chapters 5, 6 and 7.

CHAPTER 4

EARLY LIFE STAGES OF LOUGH KEY ZEBRA MUSSELS – LARVAE AND JUVENILE SETTLEMENT

4.1 INTRODUCTION

It is a fundamental ecological principle that both successful reproduction and the survival of sufficient early life stages to maturity are necessary for the success of any species' population. The zebra mussel shares characteristics of many successful invasive species: rapid growth, prolific reproduction at an early age (0-1+) and a relatively short life span. This usually provides the potential for rapid exponential growth of populations within a waterbody (Ehrlich, 1989, McMahon, 1999, Nichols, 1998).

Researching the dynamics of early *Dreissena* life stages involves sampling veliger densities, measuring larval size distributions and estimating settlement of juveniles (plantigrade stage). This was carried out annually in Lough Key from 1998 to 2003. Zebra mussel veligers in Lough Key are sourced from their own in-lake populations as there were no significant populations upstream of the lake in the Boyle River. The aim was basically to provide information on larval development within the plankton and survival to a settled juvenile stage throughout the sampling seasons at a whole lake level or more specifically in different Lough Key monitoring sites.

This research involved interrogating annual datasets to determine various facts and to examine the dynamics of early life stages in Lough Key. These included the following:

- How early in the season and at what water temperature was larvae detected in the water?
- What was the duration of spawning season in Lough Key and did duration of the reproductive season vary between years?

- Was there a significant difference in larval size for the same sampling week in different years and did a significant difference exist between size distributions in consecutive weeks?
- Did the proportion of large larvae (>200µm to settlement) in the plankton correlate with density and settlement data?
- How long did larvae remain in the plankton?
- Were larval densities positively correlated with settlement rates and did settlement vary at different sites within the lake?

4.2 MATERIALS AND METHODS

Information on sites, sampling and the laboratory procedures used for analysis between 1998 and 2003 are given in Chapter 2. Sites A to D were the main sites used for analysis in this chapter. Occasional observations were made for Site E, but in general that site was excluded from data analysis because it was not included as a sampling site until 2000. It was also sometimes inaccessible due to weather conditions. Weeks for summer months are assigned numbers, weeks 1- 4 for each month, in the format July week 1. This system was used for text, figures, tables and corresponding appendices for this chapter.

Mean veliger densities were calculated from data for Sites A-D (1998-2003). It was considered more representative to take mean values for all sites rather than site-specific ones, due to the known patchy distribution of larvae.

Size distribution results were compared statistically using descriptive statistics. As datasets were not normally distributed and the variances were heterogeneous (Levene statistic, $p<0.05$), Kruskal-Wallis and post-hoc Mann-Whitney test tests ($p<0.05$) were applied to compare sample distributions.

For size distribution analysis datasets, Site A was chosen for 1998, as more data were available for that site in that year for that station. Sites B and C were used in most cases from 1999-2003 as these sites provided the most complete datasets. Statistical analysis determined that the size distributions of veligers were not significantly different (Mann-Whitney test, $p>0.05$) at Sites B and C in sampling weeks (2001-2003). Annual datasets from both sites were therefore subsequently pooled for analysis to give a larger sample size for each week (>250 in most cases).

Statistical analysis was carried out to determine whether there was a significant difference ($p<0.05$) in larval size for the same sampling week in different years. Samples taken in consecutive weeks were also analysed to determine whether they varied with regard to size distribution. Where significant differences were found, post-hoc tests were carried out to determine which paired samples were significantly different ($p<0.05$). The percentage of veligers greater than 200µm/sample was calculated for each sample week (1998-2003) to determine the proportion of veligers close to settlement.

Settlement analysis was based on cumulative means for Sites A to D. Correlation analysis was used to compare the following:

- Veliger density *vs* settlement (same week)
- Veliger density *vs* settlement (following week, n+1)
- Veliger density *vs* % veligers > 200µm
- Settlement *vs* % veligers > 200µm

4.3 RESULTS

4.3.1 Seasonal appearance of larva in Lough Key

The first seasonal appearance of larvae occurred from the beginning to the end of May (2001-2003, earlier years unknown) corresponding with site temperatures greater than 12.5^{0}C. Larvae were detected in the plankton at the end of March, 1999 (11^{0}C). In mid February 2000 (7.2^{0}C) two veligers were observed in a sample, one of which was attached to a tiny piece of organic debris. These were possibly overwintering larvae as observed by Kirpichenko (1971).

4.3.2 Temperature

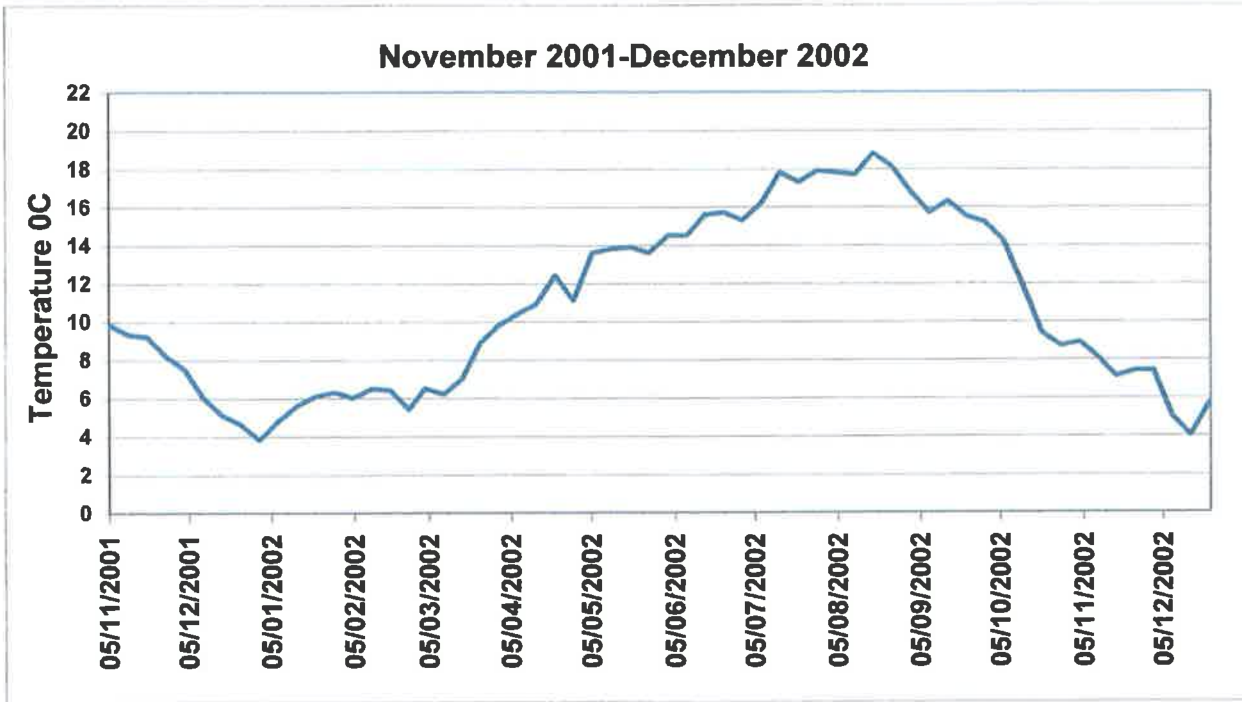
Table 4.1 outlines water temperature for each sampling date between 1998 and 2003. Fig 4.1 shows converted output from the temperature datalogger between November 2001 and February 2004. This highlights the seasonal variation in water temperature and also shows that summer 2003 was somewhat warmer than the previous summer. Weekly monitoring of temperatures also indicated that 2003 had higher comparative water temperatures than 2000-2003. A minimum of 3.1 ^{0}C was observed in January 2002 with a maximum temperature of 22.4^{0}C observed at Site D on 12/8/03.

A temperature-*vs*-depth profile taken at the Hog Island Deep (EPA station C) in August 2001 indicated a drop of 1.4^{0}C between the depths of 6 and 10m (Fig 4.2). Slight thermal stratification has been recorded previously at this site in July 1995-1999 (Bowman, 1998, 2000) but is not common or prolonged in Lough Key.

Table 4.1 Lough Key water temperature ^{0}C on sampling dates 1998-2003

Week/Year	1998	1999	2000	2001	2002	2003
June week 2	nd	nd	nd	15	14	17
June week 3	nd	nd	nd	16.5	16	18
June week 4	nd	nd	19	17	15.5	18
July week 1	nd	nd	18	16.5	15.5	18
July week 2	nd	nd	16.5	17	17	18
July week 3	17.5	17	19	16.5	18	18
July week 4	16	15	18	18.5	18.5	18
August week 1	17	18	17.5	18.5	17.5	20
August week 2	16	nd	17.5	18	18	21
August week 3	15	17	18.5	18.5	17.5	19
August week 4	17	16	19	17	18	18.5
September week 1	18	16	17.5	18	17.5	17.5
September week 2	14	14	nd	15.5	16.5	17

nd = no data



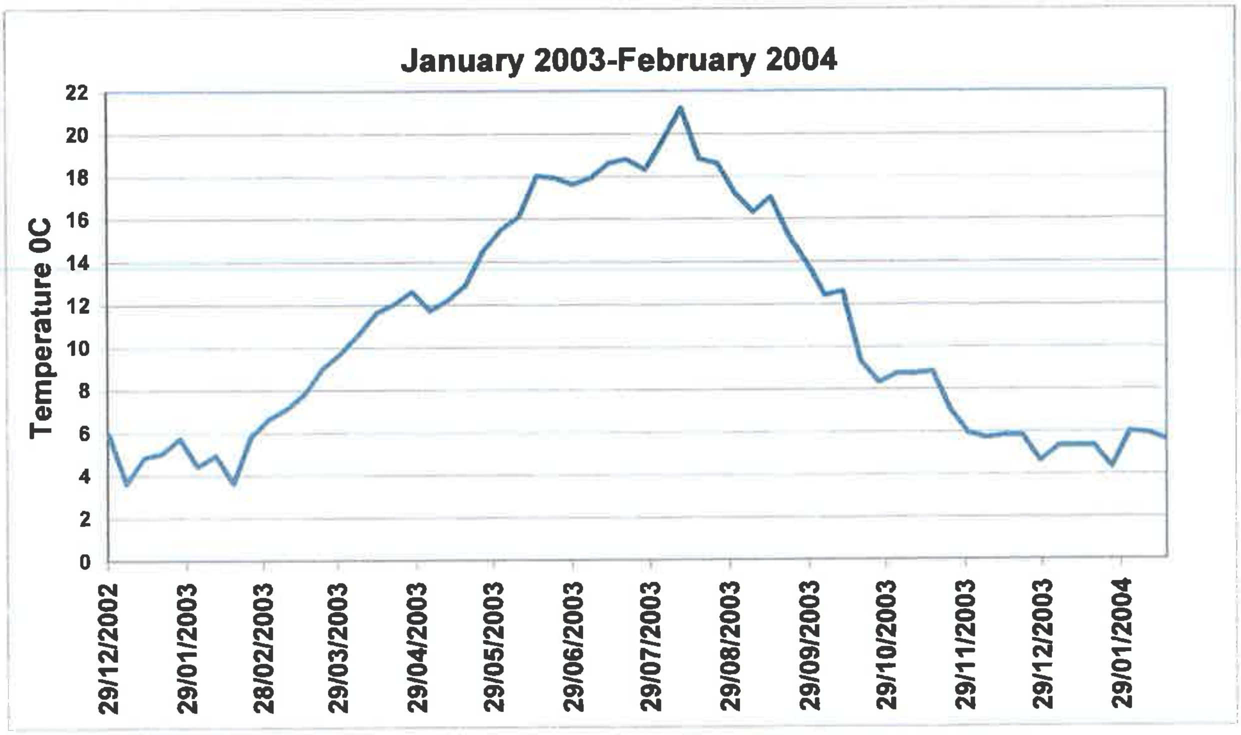


Fig 4.1 Water temperature in Lough Key, November 2001-February 2004

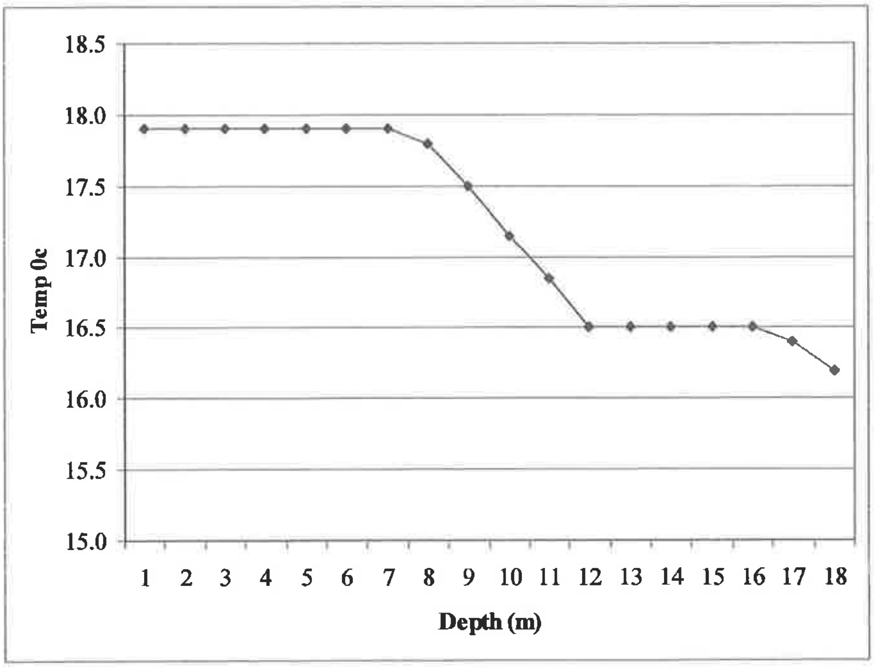


Fig 4.2 Depth profile, EPA station C, August 2001

4.3.3 Larval Density

Fig 4.3 shows larval densities from 1998-2003 with associated water temperatures. The annual start of significant spawning in the lake was early July, with larvae appearing in samples until the beginning to the middle of October. Peak annual spawning was typically from June week 4 to August week 4.

Larval densities (veligers/L) for all five sites, from the start of significant spawning, are included in Appendix 4. This figure indicates seasonal variation between years. In 1998 spawning was not detected at any site until July week 4. In 1999 and 2000 the spawning season was longer, particularly in 2000 when significant densities were recorded from June week 4. The spawning season was particularly long in 2003, with larvae detected from the second week in June and with significant numbers of larvae still present in the plankton in mid September 2003.

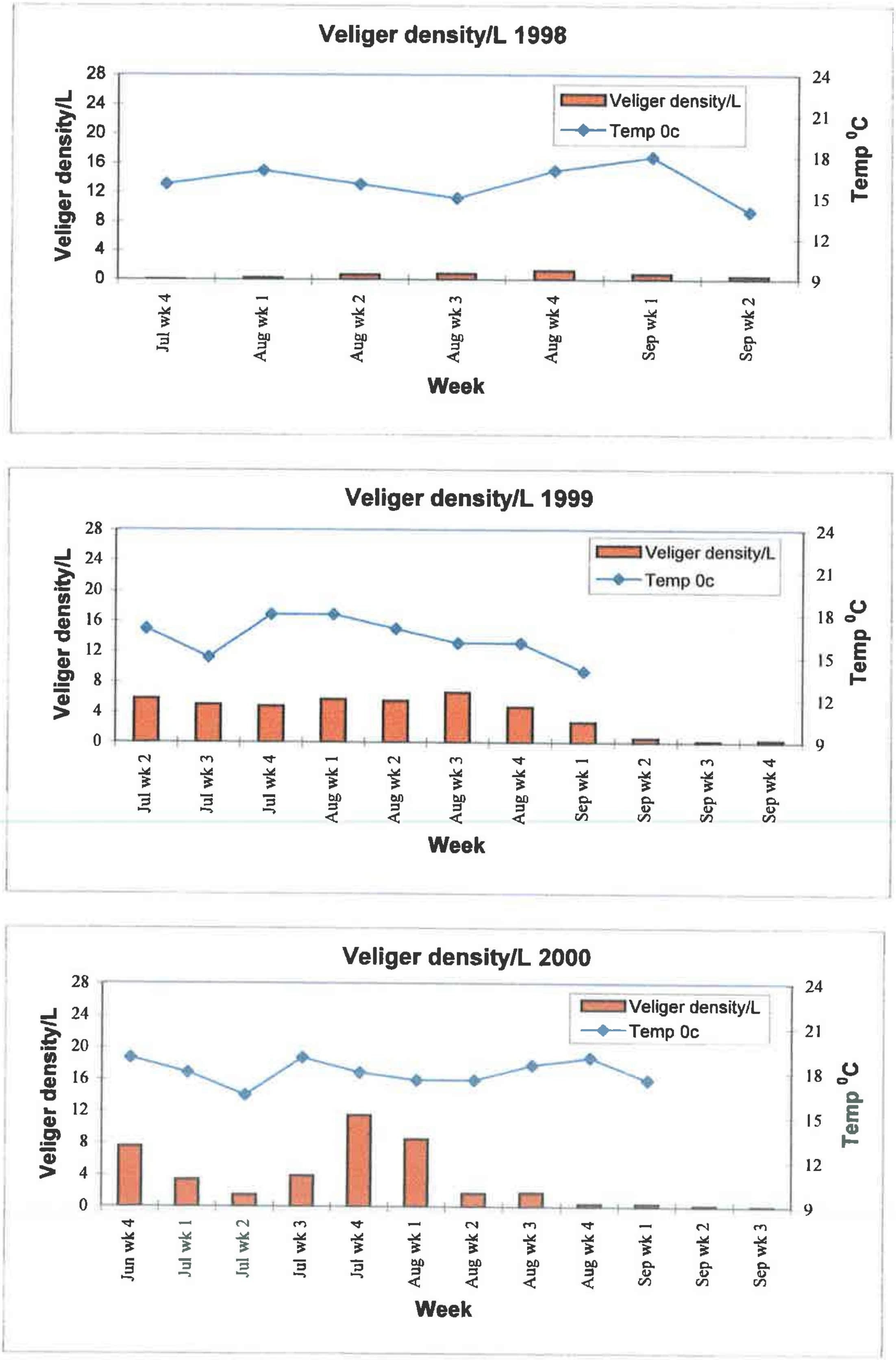
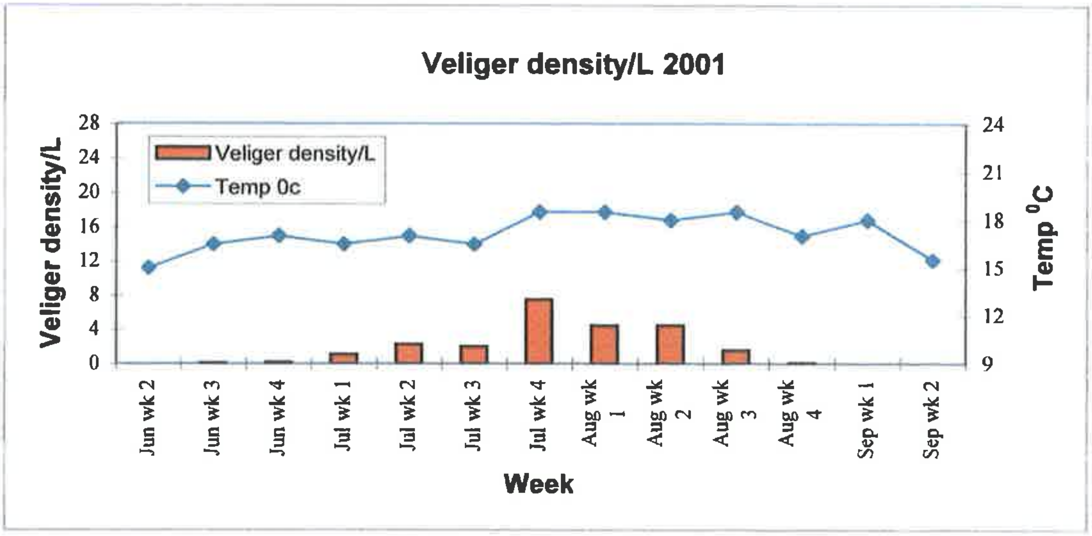
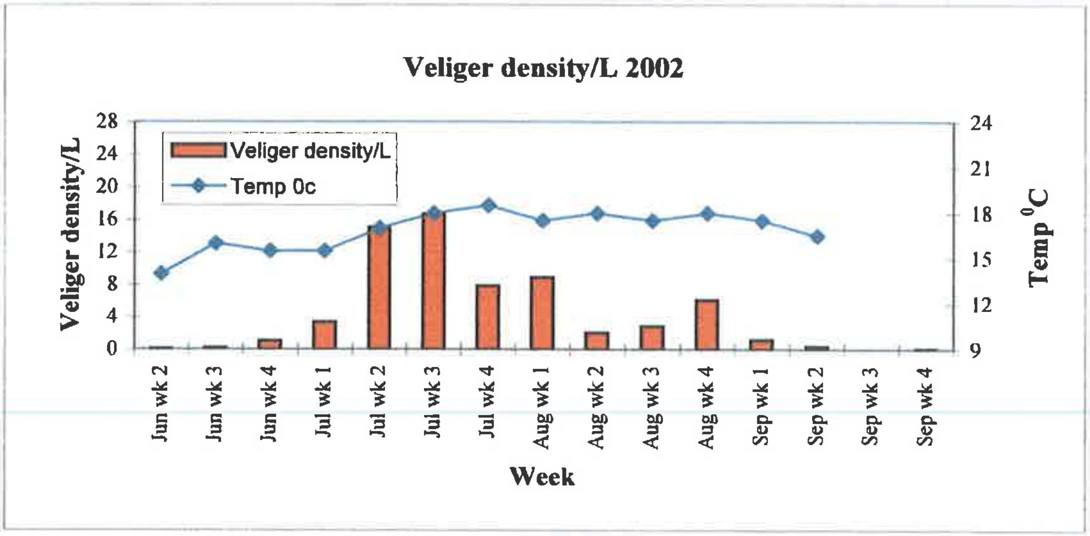


Fig 4.3 Mean larval density/L (1998-2000) with temperature °C





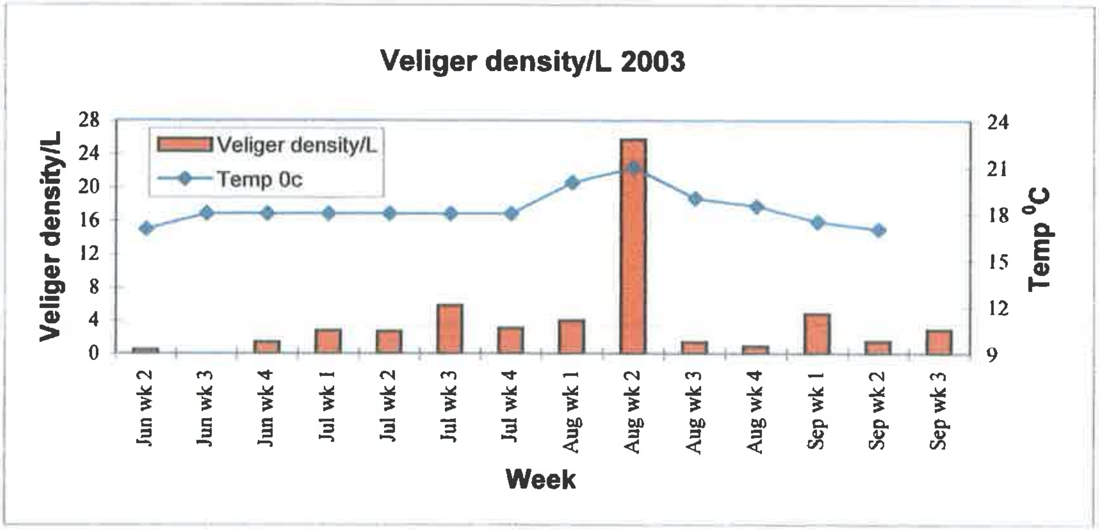


Fig 4.3 (ctd) Mean larval density/L (2001-2003) with temperature ^{o}C

Water temperature was generally in excess of 15^{0}C during reproduction, except at the end of the spawning season in 1998 and 1999 when it was slightly lower (Table 4.1). There appeared to be no relationship between water temperatures and larval densities in 1998 or 1999. In 2000 the highest larval density occurred the week following peak water temperatures. The maximum larval density coincided with peak temperatures in both 2001 and 2003 and appeared to be also related to temperature rises in 2002.

Individual recorded peak densities increased yearly, from 1998 to 2003, with the exception of a slight decrease in 2001 (Fig 4.4). Site D recorded the peak larval density in 1998 (3/L). In 1999 Site C peaked at 9/L. Site B yielded the highest veliger densities in 2000 and 2001 (20/L and 17/L) and the second highest in the two subsequent years (25/L and 18/L). Peak densities were recorded at Site A in 2002 (39/L) and at Site C in 2003 (45/L). Throughout the project relative densities were relatively low at Site D. This sampling point is located inside the entrance of a jetty.

At each site larval numbers decreased during autumn period, at the end of the spawning period and were detected in only low numbers in October.

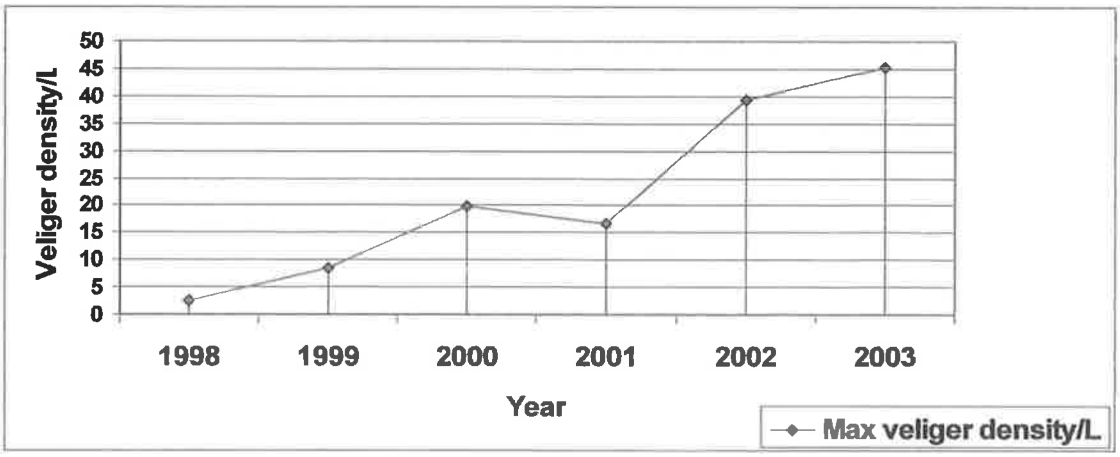


Fig 4.4 Peak larval density 1998-2003

4.3.4 Larval Size Distributions

Larval size distributions for Lough Key sites are given in Appendix 5. Table 4.2 shows the descriptive statistics for veliger size distributions 2001-2003 (Sites B and C combined).

Table 4.2 Descriptive statistics for veliger size (µm) distributions, 2001-2003

2001

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
July week 2	308	138.31	33.128	1.888	134.60	142.03	80	240
July week 3	151	145.70	45.775	3.725	138.33	153.06	80	250
July week 4	33	105.76	19.690	3.428	98.78	112.74	80	180
August week 1	276	125.07	25.944	1.562	122.00	128.15	80	250
August week 2	284	149.79	46.052	2.733	144.41	155.17	80	260
August week 3	244	144.02	25.984	1.663	140.74	147.29	90	200
August week 4	176	149.55	34.852	2.627	144.36	154.73	90	230
September week 1	152	147.11	43.164	3.501	140.19	154.02	90	240
Total	1624	140.99	37.366	.927	139.17	142.81	80	260

2002

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound	Minimum	Maximum
July week 1	336	140.71	25.323	1.382	138.00	143.43	100	200
July week 2	344	140.93	26.688	1.439	138.10	143.76	90	210
July week 3	302	137.65	29.290	1.685	134.33	140.97	100	250
July week 4	301	142.09	33.684	1.942	138.27	145.91	100	230
August week 1	301	153.92	48.558	2.799	148.41	159.43	100	260
August week 2	105	167.71	42.091	4.108	159.57	175.86	100	260
August wek 3	278	149.82	39.054	2.342	145.21	154.43	100	260
August week 4	301	124.65	41.557	2.395	119.94	129.36	70	260
September week 1	304	160.16	36.383	2.087	156.06	164.27	100	260
September week 2	66	166.06	43.034	5.297	155.48	176.64	100	260
Total	2638	145.13	37.713	.734	143.69	146.57	70	260

Descriptives

veliger size

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean: Lower Bound	95% Confidence Interval for Mean: Upper Bound	Minimum	Maximum
July week 1	300	130.9000	21.62751	1.24866	128.4427	133.3573	90.00	200.00
July week 2	300	114.5667	27.95384	1.61392	111.3906	117.7427	70.00	210.00
July week 3	300	127.0000	27.48669	1.58695	123.8770	130.1230	70.00	240.00
July week 4	300	127.9333	40.46216	2.33608	123.3361	132.5306	70.00	240.00
August week 1	300	132.4667	37.82439	2.18379	128.1691	136.7642	70.00	240.00
August week 2	329	147.0821	51.78517	2.85501	141.4656	152.6985	80.00	290.00
August week 3	300	135.0333	33.73612	1.94776	131.2003	138.8664	70.00	250.00
August week 4	300	96.6000	24.70779	1.42650	93.7927	99.4073	70.00	210.00
Sept week 1	299	117.2575	28.29324	1.63624	114.0375	120.4776	70.00	240.00
Sept week 2	290	136.0690	31.89074	1.87269	132.3831	139.7548	70.00	250.00
Total	3018	126.6600	36.37964	.66221	125.3616	127.9585	70.00	290.00

It was determined that in most cases there was a significant difference in size distributions for the same week in different years (Table 4.3).

Table 4.3 Significant difference (Mann-Whitney, $p < 0.05$) in larval size for the same sampling week in different years (2000-2003)

Week	2000 *vs* 2001	2000 *vs* 2002	2000 *vs* 2003	2001 *vs* 2002	2001 *vs* 2003	2002 *vs* 2003
July week 1	*	*	*	*	*	*
July week 2	ns	ns	*	ns	*	*
July week 3	*	*	ns	*	*	*
July week 4	ns	*	*	*	*	*
August week 1	ns	*	*	ns	*	*
August week 2	ns	*	*	*	*	*
August week 3	*	ns	*	ns	*	*
August week 4	ns	ns	*	ns	*	*
September week 1	nd	nd	nd	nd	nd	*
September week 2	nd	nd	nd	nd	nd	ns

* = significantly different ($p < 0.05$); ns = not significantly different; nd = no data

Statistical analysis determined that there was also often a significant difference between size distributions in consecutive weeks in 2002 and 2003 (Table 4.4). This was rarely observed in 2001.

Table 4.4 Significant difference (Mann-Whitney test, $p < 0.05$) between larval size distributions in consecutive weeks (2001-2003)

Week	2001	2002	2003
July week 1 and July week 2	nd	ns	*
July week 2 and July week 3	ns	ns	*
July week 3 and July week 4	*	ns	ns
July week 4 and August week 1	*	ns	*
August week 1 and August week 2	*	*	*
August week 2 and August week 3	ns	*	ns
August week 3 and August week 4	ns	*	*
August week 4 and September week 1	ns	*	*
September week 1 and September week 2	nd	ns	*

* = significantly different ($p < 0.05$)
ns = not significantly different
nd = no data

Fig 4.5 shows veliger size distributions at Site A in 1998 and Fig 4.6 shows Site B in 2003. Small D veligers (70-80µm) were not well represented in the majority of samples. In most sampling weeks, veligers >260µm were not generally present in the plankton. Larger individuals were also occasionally recovered, including one at 840µm sampled in September 2002.

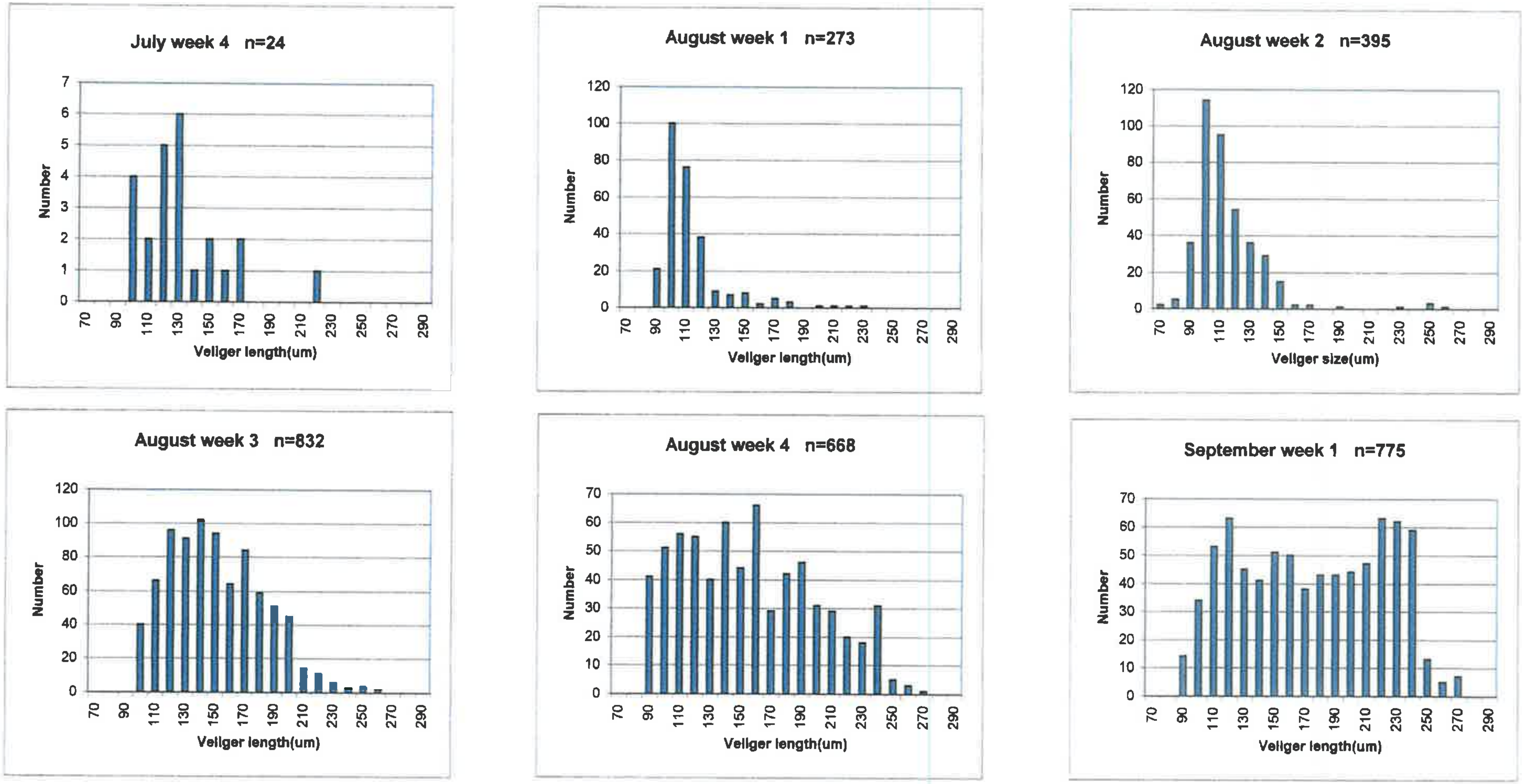


Fig 4.5 Zebra mussel veliger size distribution, 1998, Site A

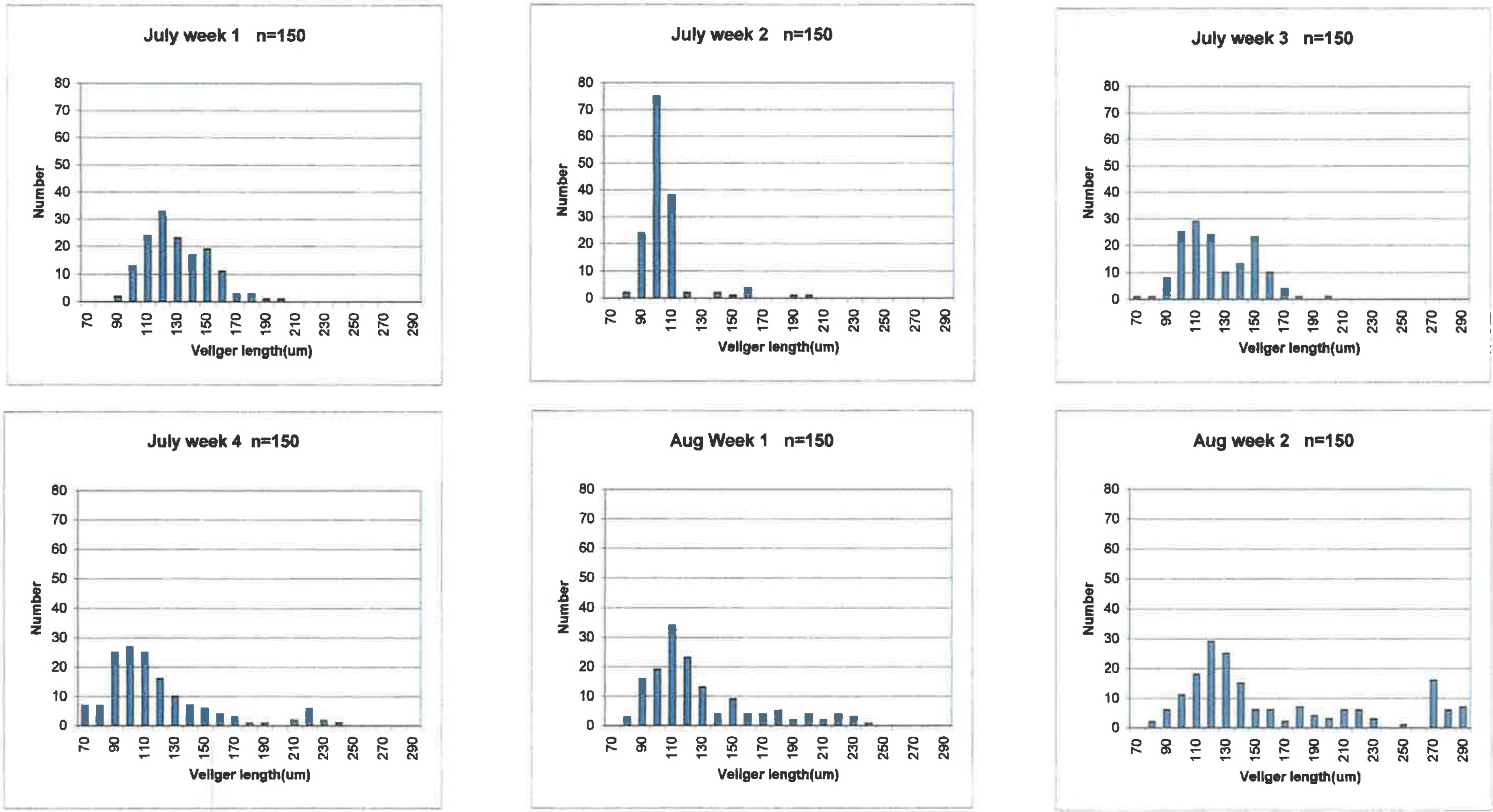


Fig 4.6 Zebra mussel veliger size distributions, July week 1 - August week 2, 2003, Site B

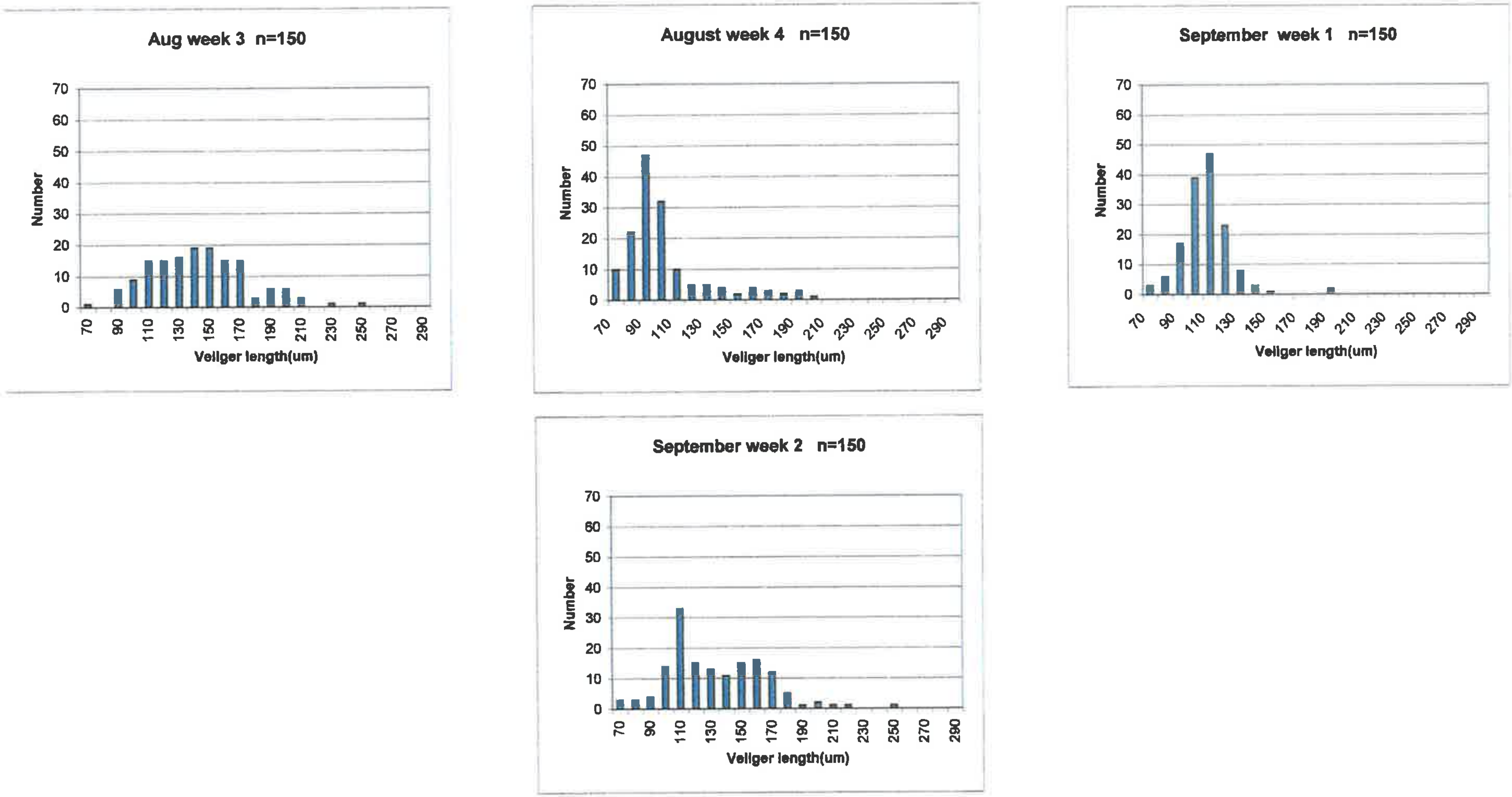


Fig 4.6 (ctd.) Zebra mussel veliger size distributions, August week 1 - September week 2, 2003, Site B

The percentage of veligers >200µm (Site A and B combined) is given in Table 4.5.

Table 4.5 Percentage of veligers > 200 µm in plankton samples, 1998-2003

% > 200 µm	July wk 1	July wk 2	July wk 3	July wk 4	Aug wk 1	Aug wk 2	Aug wk 3	Aug wk 4	Sep wk 1	Sep wk 2
1998	nd	nd	nd	4.20	1.50	1.50	10.20	27.50	44.30	51.1
1999	nd	nd	nd	3.8	1.4	76.8	85	5.4	14.2	2.3
2000	0.3	1.5	4.7	7.9	11.2	12	10.1	1.1	nd	nd
2001	9.1	15.1	0	2.5	19.7	2.9	12.5	19.7	nd	nd
2002	0	1.2	6.3	8	26.9	30.5	14	6.6	18.4	27.3
2003	1	1.3	2.3	10.3	11.3	16.7	7	1	3.3	4.3

In general, the proportion of larger veligers increased from July week 4 to August week 4, with an elevated percentage also occurring during the first two weeks of September in 1998 and 2002. There was no correlation between seasonal veliger density and % of veligers > 200µm, except in 2003 when a strong correlation was found ($r = 0.71$, $p = 0.02$).

4.3.5 Settlement

4.3.5.1 Cumulative Settlement

Fig 4.7 shows cumulative settlement during the spawning season (1998-2003). Annually, the highest settlement occurred during the entire month of August (weeks 1 to 4) (Appendix 6).

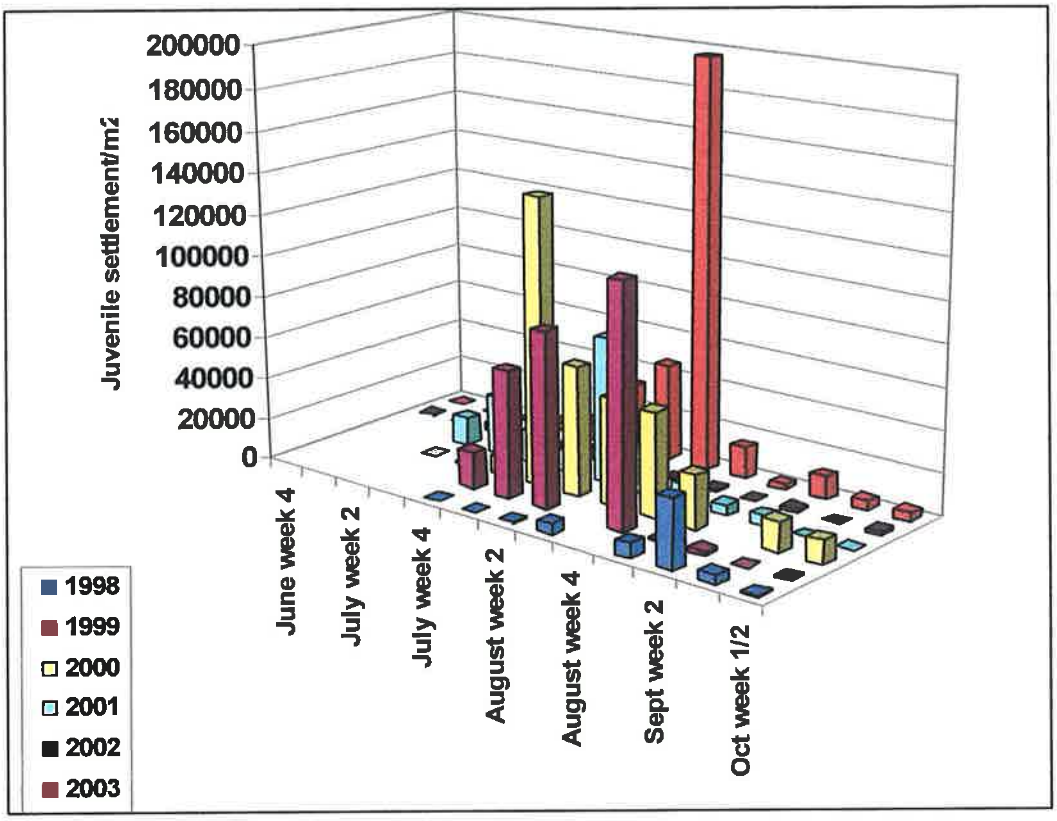


Fig 4.7 Cumulative juvenile settlement, Lough Key, 1998-2003

Fig 4.8 shows cumulative settlement *vs* mean larval density for the years 2001, 2002, 2003. Overall settlement was very poor in 2002 (maximum, 4,000/m^{2,} Site B, August week 2). Peak settlement in 2001 and 2002 occurred two weeks after peak larval density. In 2003, relative settlement was high and appeared to occur only one week after peak larval densities. The only year that settlement *vs* larval density showed a correlation within individual sampling weeks was 1999 ($r = 0.81$, $p = 0.009$). Statistical analysis showed larval densities (week n) *vs* settlement (week n +1) to be positively correlated in 1999 ($r = 0.76$, $p = 0.017$) and 2000 ($r = 0.79$, $p = 0.06$) and highly positively correlated in 2003 ($r = 0.96$, $p = <0.001$). No correlation was found in 1998, 2001 or 2002. The proportion of veligers > 200µm was highly correlated with settlement (week n+1) in 2003 ($r = 0.85$, $p = 0.002$). No correlation existed for other years.

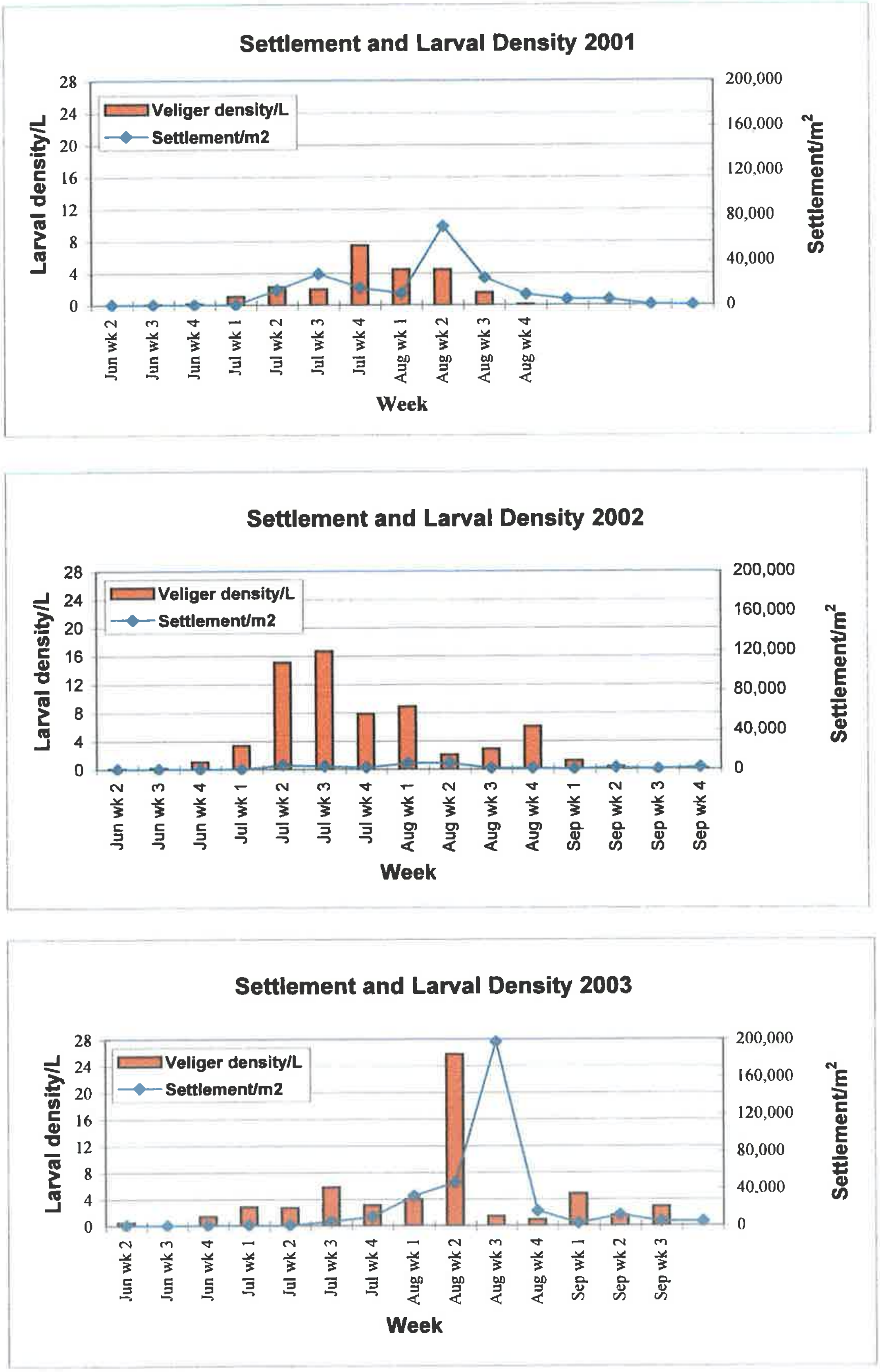


Fig 4.8 Settlement vs larval density (Cumulative values) 2001-2003

4.3.5.2 Individual Sites

Site B had the highest settlement of any week in 2000 (86,500/m^2) and 2002 (4,000/m^2), whereas Site C was highest in 1998 (52,000/m^2), 1999 (43,000/m^2), 2001 (39,000m^2) and 2003 (169,670/m^2). Site C also had the highest cumulative settlement in the period from 1998 to 2003 (Table 4.6).

Table 4.6 Cumulative settlement/m^2, Sites A-D, 1998-2003

	Site A	Site B	Site C	Site D
Total plate settlement/m^2 1998-2003	205,615	372,425	541,535	81,355

Settlement was low at all five sites in 2002, peaking at 4,000/m^2 at Site B in August week 3 (Appendix 6). In 2003, Site C peaked (August week 3) with approximately 170,000 settled juveniles/m^2 (Plate 3.1), the highest settling density obtained since monitoring began in 1998.

Results from seasonal settlement plates were low due to periphyton growth and did not relate to cumulative settlement from biweekly plates. For example, at Site C the seasonal settlement plate for 2003 had far fewer juveniles attached (total for 15 x 15cm^2 plate = 6) than was present on the August week 3 biweekly sample plate (mean = 17/cm^2). For this reason, seasonal plate data have not been included in this thesis. The size range of settled juveniles varied from 200 – 400μm, with occasional larger zebra mussels up to 1.5 mm in length.

4.4 DISCUSSION

4.4.1 Temperature

The temperate Irish climate is ideal for *Dreissena polymorpha* as lakes rarely freeze in winter (species lower lethal temperature 0°C) and never reach the upper temperature limits of greater than or equal to 32^{0}C (Karatayev *et al.*, 1998). The maximum temperature range recorded during the survey was 3.1^{0}C to 22.4^{0}C (2002-2003). As noted in Section 1.3.2, increase in water temperatures during spring has been reported as the primary environmental factor in triggering the timing of reproduction in zebra mussels. Water temperatures of 15^{0}C have been cited in many European studies, as the level at which larvae were first observed (Kachanova, 1966; Kirpichenko, 1964; Einsle, 1973; Stanczykowska, 1977; Karatayev *et al.*, 1998).

Although occasional early veligers were recorded in May at temperatures of 12.5^{0}C to 13^{0}C, these may have spawned from adult mussels in the littoral zone where temperatures had reached the 15^{0}C required spawning threshold. Similarly, the 14^{0}C recorded mid-lake in June week 2, 2002 is likely to have had a corresponding near-shore temperature of 15^{0}C.

Temperature readings indicate that in general the temperature during summer months ranged between 15 and 18^{0}C. The higher temperatures recorded during the 2003 season resulted from prolonged warm weather during July and August. The drop in temperature recorded in the vertical temperature profile would not have impacted spawning, subject to other suitable environmental factors (e.g. suitable substrate, oxygen and food availability) as the temperature remained >15^{0}C on the benthos.

4.4.2 Veliger Density

The length of the spawning season (June–September) was typical for zebra mussel infested lakes in FSU, Europe and North America (Sprung, 1989). The presence of occasional large postveligers outside the normal spawning season may have resulted either from prolonged duration in the plankton with delayed development due to low temperature (Lewandowski, 1982b) or more likely from resuspension from the substrate as reported by Martel (1993). The latter could easily occur following stormy weather incidents, where settled juveniles could get washed off stones in the littoral zone, becoming resuspended in the plankton.

Zebra mussel veligers were patchily distributed within the lake. The lake is exposed to prevailing winds, which may play a role in the patchiness of larvae. Even when densities were at their highest at one site, results could be very different for other sites within the lake (Appendix 5). This emphasises the need for multiple site analysis, even within a small lake like Lough Key.

Vertical distribution of larvae changes in response to diurnal cycles (Lewandowski, 1982a) and horizontal distribution, can be altered by water currents, wind and storm events (Hunter and Bailey, 1992, Martel *et al.*, 1993; Stanczykowska and Lewandowski, 1993).

Veliger densities in this study fall within the wide range reported in the literature (Kirpichenko, 1964; Lewandowski, 1982b; Haag and Garton, 1992, Nalepa *et al.*, 1995). Results from Lough Key indicate that peak densities were found at three separate sites in summers 2000-2004. It is not possible to determine the role that weather conditions may have played because detailed local meterological information is not available. Taking means of monitoring site results was one way of reducing the impacts of climactic factors on the variation in research results.

Overall results from 1998 to 2000 seem to indicate that larval densities and length of spawning season are influenced by three main factors; parent population size; maturity of parent population and temperature of lake water. It is interesting to note that even though the temperature range is small in terms of other international studies carried out in continental climates, it still appears to have an impact on spawning patterns.

Ninteen ninety eight was considered the first year of significant spawning in Lough Key (Lucy and Sullivan, 2001). Overall densities were very low in that year, as could be expected from a small parent population comprised of mainly 1+ individuals (Chapter 5). The late start of the spawning season may relate to the reproductive development of the

1+ parent generation, many of which may have taken until August to reach sexual maturity.

In 1999 larval densities were relatively uniform between July week 2 and August week 4; although spawning probably started before this but was not detected as it was outside the sampling regime. The constant spawning level probably reflects the presence of a large proportion of 1+ individuals. Juhel *et al.* (2003) reported non-synchronous development of gonads in Irish zebra mussels, resulting in prolonged spawning over a number of weeks.

The early peak in 2000 (June week 4), probably reflected the high water temperature present at that time (19^0C). This temperature is relatively unusual at that early stage of the summer. The early peak also indicated that mature zebra mussels were present. By 2000 there was a well-established cohort of 2+ zebra mussels and these would certainly have been ready to reproduce in addition to early maturing 1+ individuals. Peak larval density that year (July week 4) succeeded the second week of peak temperature in that year. Both these events indicate how important temperature is as a trigger to mass spawning. Temperature effects may be considered direct due to development and growth of adult mussels at greater than 10^0C (Chapter 5) or indirect due to increased availability of food (Mantecca *et al*., 2003).

In 2001 the spawning season was shorter (June week 3 – August week 4), with peak mean density coinciding with peak temperature in July week 4. The maximum veliger density was also lower that year than any year since 1998.

Larval peaks in 2002 and 2003 were closely related to maximal water temperatures. The continued high water temperatures in late summer resulted in increased densities in early September, with larvae well represented until the end of sampling in September week 3.

a) In spawning, each zebra mussel in principle is able to release gametes over a period of six to eight weeks (Walz, 1973; Borcherding, 1991). So the same individuals may be spawning sequentially, which could result in bimodal patterns in size distribution.

b) Separate age cohorts of zebra mussels may develop at different rates and smaller (1+) individuals may spawn later in the season than older (2+) zebra mussels. One-year-old zebra mussels are known to spawn in Irish waters (Juhel *et al*, 2003). Similar age cohorts may develop at different rates and spawn over the entire summer season. Smaller 1+ individuals become mature and spawn later in the season. In one study Borcherding (1991) observed this phenomenon in zebra mussels and similar results have also been derived for marine species.

4.4.3 Veliger Size Distribution

Seasonal size distribution patterns (veliger height) actually provide more useful information than larval densities, because it is possible to trace larval size patterns through to settlement stage over the summer period. This provides a bridge in information between the veliger and settlement stages. High proportions of small veligers (less than110μm) were present early in each season with corresponding low numbers of larger veligers, corresponding with the start of the spawning season.

From the summary statistics it is possible to see a trend of increasing larval size throughout July until August week 3. In both 2002 and 2003 mean size decreased in August week four due to a pulse in spawning increasing the proportion of small veligers (less than 110μm). This was particularly apparent in 2003, where the mean size was only 96.6μm. The week of highest larval density was two weeks earlier in August week 2 of

2003, which recorded the greatest size range of veligers (80-290µm). This suggests that highest densities sampled represent the maximal spread in larval development resulting from continual spawning rather than peaks achieved from single spawning incidents. Seasonal reduction in peak densities represent both increased rate of settlement (as in 2003) and a reduction in overall spawning.

It was determined in this study that there was often a significant difference in size distributions for the same week in different years. This indicates variation in spawning and development patterns in separate years which could relate to differences in adult zebra mussel populations (i.e. varying proportions of reproducing age cohorts) or to water temperature variations or to differing food availability. Both temperature and food availability can influence the course of the annual gametogenetic cycle, the rate of oocyte development, gonad size and the onset of spawning (Borcherding, 1995). Other potential influencing factors are differences in mortality rates or variation in settlement size. Stoeckel *et al.* (2004) found highest larval mortality during the transition from D stage to umbonal stage, supporting the suggestion of a developmental bottleneck as found in previous field studies (Schneider *et al.*, 2003).

As statistical analysis showed, there was often variation in size distributions between different sequential weeks during the sampling season, particularly from August onwards. This would appear to indicate that veligers were growing and settling, with more appearing at the smaller cohorts of the range, following new spawning incidents (Appendix 5). The increase in the proportion of larger veligers as the season progressed indicated the development of veligers from the D-shaped stage to pediveligers.

The majority of veligers measured in samples over the three-year period were between 100 and 150 µm (mainly umbonate). This may relate to early settlement, dispersal or is more likely due to high mortality rates prior to metamorphosis into the juvenile (Sprung, 1989). It may also relate to variation in size of same-aged larvae, which have been found to differ by as much as 120µm (Stoeckel *et al.*, 2004).

The presence of significant numbers of larvae in late September 2003 was a new recording event for Lough Key and a definite new peak in veliger density at that time was probably related to the high water temperatures during the summer. This increase could easily be explained by factors (a) or (c) above. There is no doubt that the spawning season was prolonged in 2003. Theoretically, if temperatures were maintained above 15^0C, spawning would continue indefinitely as more zebra mussels matured and began to reproduce. The increase in spawning at the end of August coincided with the late summer algal bloom and may result from chemical cues from phytoplankton (Ram *et al.*, 1996).

The strong correlation between seasonal veliger density and the percentage of veligers greater than 200µm in 2003 also showed that the higher densities reflected the presence of a large size range of veligers, some as great as 290µm. The correlation could also indicate increased survival of larvae or shorter development time due to increased water temperatures. It is interesting to note that larger veligers (>260µm) were sampled in the early years of the invasion (1998 and 1999), but were not found again until 2003. This could relate to one or more environmental factors. Larvae appearing in samples at the beginning to the middle of October of sampling years were usually larger (> 200um) indicating that the spawning season was over for the year.

Data from settlement plates indicate that postveligers in Lough Key settled from 200µm upwards. Veligers larger that 200µm were, however, well represented in samples, indicating that settlement takes place generally between 200 and 260µm.

4.4.4 Settlement

Settlement rates reflect the survival of veligers through the postveliger stage to the settled juvenile. Following mortality at the trochophore to D-stage (Sprung, 1989), and from the D stage to the umbonal stage (Stoeckel *et al.*, 2004), studies indicate that larval mortality can also occur late in the cycle during metamorphosis and settlement (Stanczykowska, 1977; Lewandowski, 1982a). Given that the size range of settled juveniles on plates varied from 200-400μm, it is probable that the low proportion of larger veligers in the plankton reflected a combination of both early settlement and mortality. Mortality (range 20-100%) could be due to a number of factors such as water turbulences (Rehmann *et al.*, 2003), predation by fish (Molloy *et al.*, 1997), filtering by copepods or by adult *Dreissena* (MacIssac *et al.*, 1991), bacterial infection, egg quality or starvation (Sprung, 1989).

Settlement plate data did provide some indication of overall survival of veligers to the settlement stage during each sampling season (1998-2003). Size distribution analysis of adults from stoney substrate in the years consecutive to settlement also provided information on settlement rates and survival to the 1+ stage.

It is not possible to determine exactly how long veligers remain in the plankton due to a number of reasons:

- Spawning is ongoing throughout the summer, providing a number of cohorts. Development rate is also known to differ within cohorts (Sprung, 1989). This results in size overlap, which complicates exact estimation of cohort settlement.
- The data suggest that postveligers settle at different sizes as recorded in the literature (Ackerman *et al.*, 1994; Nichols, 1996).
- There were a low number of veligers greater than 200μm in most larval samples and also a high variation in the sample proportion of these 'close-to-settlement' veligers.
- Veligers were already present in the plankton when seasonal sampling began each summer. It was not possible therefore to gauge time of first seasonal settlement.

The graphs and correlation analysis (settlement *vs* veliger density; settlement *vs* veligers greater than 200μm) did, however, definitely indicate that a development cycle exists. Most veligers were greater than or equal to 100μm in weeks of peak density and would be well into their first week of life, according to growth rate of 4μm/day from a trochophore larva (70μm) (Sprung, 1989; Kern *et al.*, 1994). By combining this information with the size distribution analysis in Lough Key, a two to three-week development time for 2001 and 2002, and a one to two-week development time for 2003 can be estimated. The amount of time required for larval development varies inversely with temperature (Nichols, 1996). Higher water temperatures may therefore have resulted in a shorter development time for 2003 as noted in another study by Borcherding (1991).

The high settlement rate in 2003 may have been due to a decrease in development time related to the high water temperatures (degree-day related), which lead to an increased survival rate. Faster development would decrease the opportunities for predation, as larvae would be present in the water column for a shorter length of time. The higher temperatures in 2003 also resulted in an increase in productivity (food availability) which would also give higher settlement. The two to four-week development time concurs with Sprung (1989) but estimates vary within the literature with some as high as five weeks (Walz, 1973).

Recruitment on settlement plates in 2002 was poorer than in any other year, for reasons unknown (Appendix 7). Zero + individuals were nevertheless well represented as the first age cohort in adult samples taken in early 2003 (Chapter 5). This highlights the fact that only a very small proportion of zebra mussels (2 settled juveniles out of 10,000s of veligers produced) need to survive to juvenile stage to maintain their numbers in the lake. These inconsistencies in the abundance of developing life stages and in successful recruitment are consistent with other studies (Haag and Garton, 1992; Doka, 1994, Nalepa, 1997).

Larval densities were not correlated with settlement data in terms of individual sites due to the changing distribution patterns of veligers, whereby water currents disperse larvae derived from spawning adults in the local population (Garton and Haag, 1993). It was noted however that Site C had by far the greatest overall settlement during the study period (1998-2003). This site is close to the stoney shore of an island, with associated high densities of zebra mussels. It is likely that the high settlement at this site is related to both favourable conditions for settlement and significant existing colonies of adult zebra mussels.

The lowest settlement was at Site D, where the plates were placed inside the entrance of a jetty. Although adult zebra mussels were observed in close proximity to the plates (video survey), veliger densities were always low relative to other sites, indicating the reduced opportunity for settlement in this enclosed area. Variation in adult zebra mussel densities was also noted in different areas of the lake (Chapter 5).

In the early years of invasion (1998-2000), during the exponential growth phase, extensive settlement was noted on aquatic plants (Chapter 7), on buoy chains to a depth of 7.5m and also on the ropes used for attaching settlement plates. While settlement can be defined as the transfer from the pelagic phase to the benthic, recruitment shows settlement combined with post-settlement mortality. The increase in adult zebra mussel densities in Lough Key in 1999 and 2000 indicates that recruitment was high in 1998 and 1999. Even though veliger densities continued to increase in 2001 and 2003, the phenomenon of widespread settlement on various substrates noted above was not noted from 2001 onwards, suggesting lower overall recruitment.

Chapters 3 and 8 elaborate on substrate and food availability respectively, which are the two main limiting factors for survival to the adult stage. It would seem likely that the overall observed reduction in settlement was due to lack of food resource for veligers in the plankton. Veligers depend on food particles (phytoplankton, Cyanobacteria, bacteria and detritus) of between 1-4μm and may starve when phytoplankton is dominated by larger or smaller algal species (Sprung, 1989).

4.4.5 Life Cycle Strategies

The life cycle strategies of *Dreissena* equip the species with the maximum opportunity to succeed, given the availability of suitable environmental factors. As already noted, the two most important potentially limiting factors in a lake where it has become established are food availability and space.

While becoming established in Lough Key, the species engaged in broadcast spawning with veligers developing over a two to three week period, settling out on all hard lake substrates (Chapter 5 and 6) and on aquatic plants (Chapter 7). There was a high survival rate from egg to juvenile/adult in the early years (1998 and 1999) ensuring an exponential increase in the zebra mussel population. This depended on an initially relatively small parent population reproducing successfully (100s-1000s per adult) from one year of age. Subsequent chapters will show that the population had stabilized by 2000, probably related to food availability (Chapter 8).

From 2000-2003 high larval survival was no longer critical to the success of the species and in fact would not be beneficial in terms of overall food resource. Greater numbers of adults (1+ and 2+) needed to produce fewer offspring (settled juveniles) to maintain the population in the lake. In theory this meant one 0+ successfully recruited settled juvenile per adult. Settlement appeared poor in 2002, but as already noted was sufficient to provide a successful year class. As the species continues to spawn over a long periodof time each year, *Dreissena* also increases the chances of species survival by staggering its reproductive phase. This allows it to maximise favourable environmental factors, (e.g. cycles of phytoplankton growth) while minimising impacts due to potential negative factors (e.g. toxic Cyanobacteria or temporary deoxygenation). The ultimate line of defense is the presence of at least two (1+ and 2+) reproducing age cohorts. In the event of a disastrous year in terms of reproduction, the species therefore has a further years' opportunity to recover the zebra mussel population in the lake.

CHAPTER 5

ZEBRA MUSSELS ON STONEY SUBSTRATES

5.1 INTRODUCTION

An initial snorkel survey in November 1998 found zebra mussels attached to stones in the littoral zone of Lough Key (Ni Chonmhara, 1999). By summer 1999 it was established that stone was the main substrate for zebra mussel settlement in Lough Key with an estimated 62.8% of the lake population found there (Lucy and Sullivan, 2001).

In Lough Key stoney substrate included a range of stone size from boulders (>30cm diameter) to gravel (2cm diameter). These geomorphological hard substrates were termed rock, stone and gravel (Chapter 3). The habitat mapping confirmed that suitable hard substrates (Categories 3 and 4) were available in the littoral zone of the mainland and island shores, with occasional stoney substrate present in other areas of the lake.

Various experimental (cage based) zebra mussel growth studies have been reviewed in Chapter 1. This study on Lough Key sampled zebra mussels in their natural state attached to stone substrate. With datasets available from 1998 onwards this substrate formed a focal point for investigating population dynamics of zebra mussels in Lough Key. Both the spread and the success of this invasive species was studied by investigating size distributions, percentage cover, density (numbers/m^2) and biomass (kg/m^2), ash free dry weight, (AFDWmg), total number and total biomass (kg) of this species in Lough Key.

The aims of zebra mussel investigation on stoney substrate were to:

- Compare size distribution patterns from 1998 onwards on a temporal basis
- Examine variation in size distribution between sites, within sites and at different depths throughout the lake thus linking with the objectives set out in Chapter 3
- Calculate the total biomass and number of zebra mussels in Lough Key

- Determine whether biomass varied at snorkel sites between 2001 and 2003
- Establish how biomass and density varied with depth
- Research whether condition factor in zebra mussels varies over the calendar year and compare with AFDW results from other studies

5.2 MATERIALS AND METHODS

Materials and methodology for sampling and processing (size distribution and biomass) of zebra mussels from snorkel, transect and other sites have been outlined in Chapter 3. In most cases it was difficult to separate the age cohorts present due to merging of modes and although statistical models exist to attempt this division (Pauly and Caddy, 1985; Sparre and Venema, 1992) it was considered more appropriate to examine each sample visually on its own merit. A t-test was carried out to determine differences in size distributions with depth ($p<0.05$). Biomass results were compared statistically using t-tests, ANOVA and post-hoc Tukey HSD analysis ($p<0.05$) where data were normal and variances were homogenous (Levene statistic, $p>0.05$). When variance results showed that data were not normally distributed and the variances were heterogenous (Levene statistic, $p<0.05$), Kruskal-Wallis and post-hoc Mann-Whitney tests ($p<0.05$) were applied. G tests were carried out to determine differences in size distributions ($p<0.05$).

The condition index of zebra mussels was calculated as the AFDW of a sample ($n = 30$) of 15mm zebra mussels. The experiment was carried out monthly in November 2002 and monthly from March 2003 to January 2004. Fifteen-mm specimens were removed from fresh samples taken from the Rockingham jetty site. Soft tissue from at least 30 zebra mussels was removed from the shell and placed in previously combusted preweighed crucibles. These were dried at 60^0C for at least 48 hrs, cooled in dessicators and weighed individually to 0.1mg (Electronic balance, Bosch SAE 2000). They were subsequently ashed at 550^0C for one hour as in Nalepa *et al.* (1995) and again were placed in dessicators before the ashed weight was taken. AFDW was calculated by subtracting the ashed weight (mg) from the dry weight (mg). ANOVA and post-hoc Tukey HSD analysis ($p<0.05$) were applied as variances were homogenous (Levene statistic, $F = 1.58$, $p = 0.10$).

5.3 RESULTS

5.3.1 Size Distributions

Individual sizes of zebra mussels measured during the project varied from <1mm to 34 mm, which is believed to reflect the presence of three main year classes (0+, 1+ and 2+ age cohorts), with very occasional older specimens (3+). Plate 5.1 shows a variety of sizes of zebra mussels from 1mm upwards.

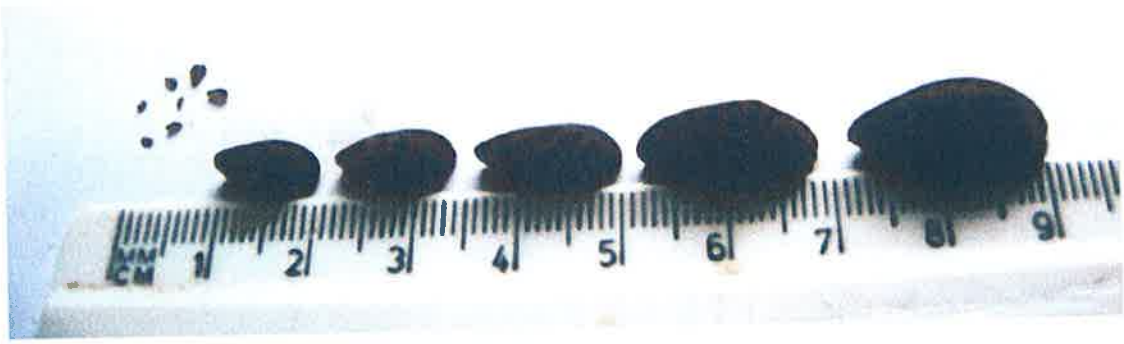


Plate 5.1 Zebra mussels with scale

5.3.1.1 Size Distributions During the Early Invasive Stage

A sample from July 1998 shows the presence of 1+ and 2+ zebra mussels, recovered from a wall at the main boat marina at Rockingham. The absence of small (<7 mm) zebra mussels indicates that settlement had not yet occurred in 1998. The size distribution present may represent settlement from 1997 (<20mm). Larger individuals may represent the founder population in the lake (>20mm) from 1996.

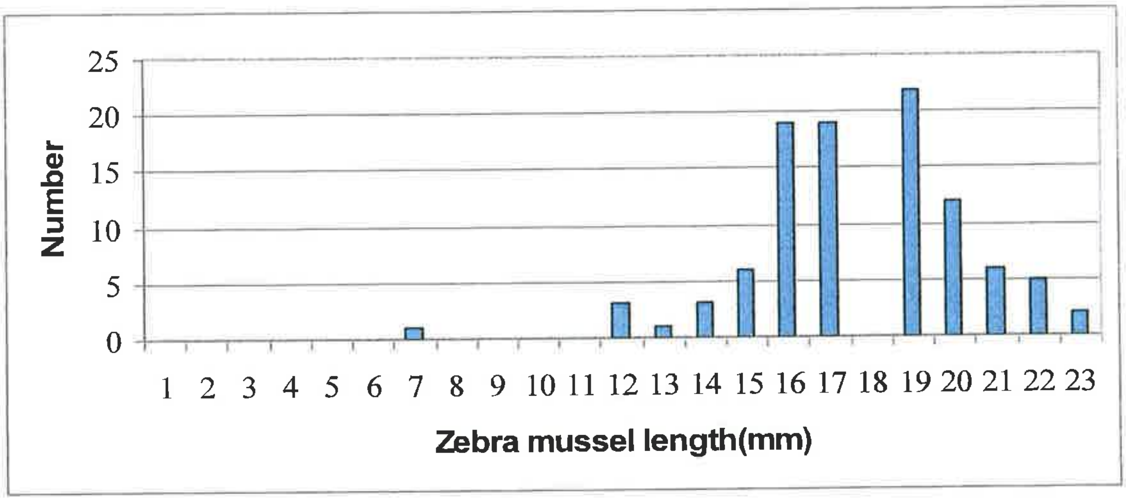


Fig 5.1 Zebra mussel size distribution, Rockingham, Lough Key, July 1998

Fig 5.2 shows a series of adult zebra mussel size distributions from November 1998 to January 2001, taken from navigational buoys in Lough Key. Age cohorts can be identified by following the shape of the size distributions over a period of 26 months. The November 1998 sample contains only one large individual, presumed to be 2+ years old, indicating the relative scarcity of larger zebra mussels in 1998. As noted in Chapter 4, 1998 was the first year of significant reproduction and settlement in Lough Key. The 1998 cohort can be followed in samples from 0+ stage (19/11/98, 29/4/99) to 1+ (20/8/99, 6/5/00) and 2+ (28/1/01). The 1999 cohort can be followed on the chart from May 2000 (0+) to January 2001 (1+). The 2000 cohort are present in the January 2001 sample.

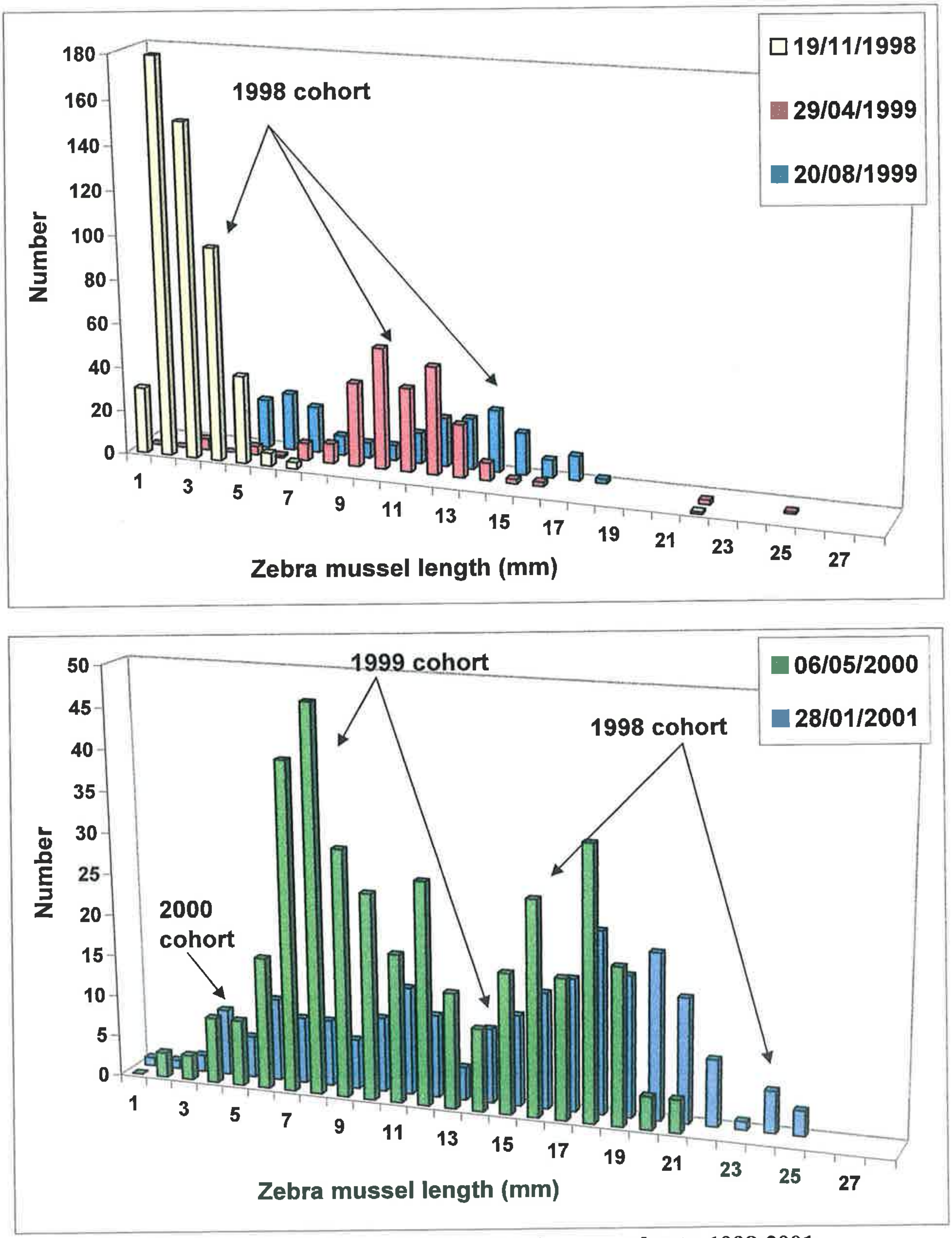


Fig 5.2 Size distributions of zebra mussels indicating age cohorts, 1998-2001

5.3.1.2 Size Distributions at Different Sites

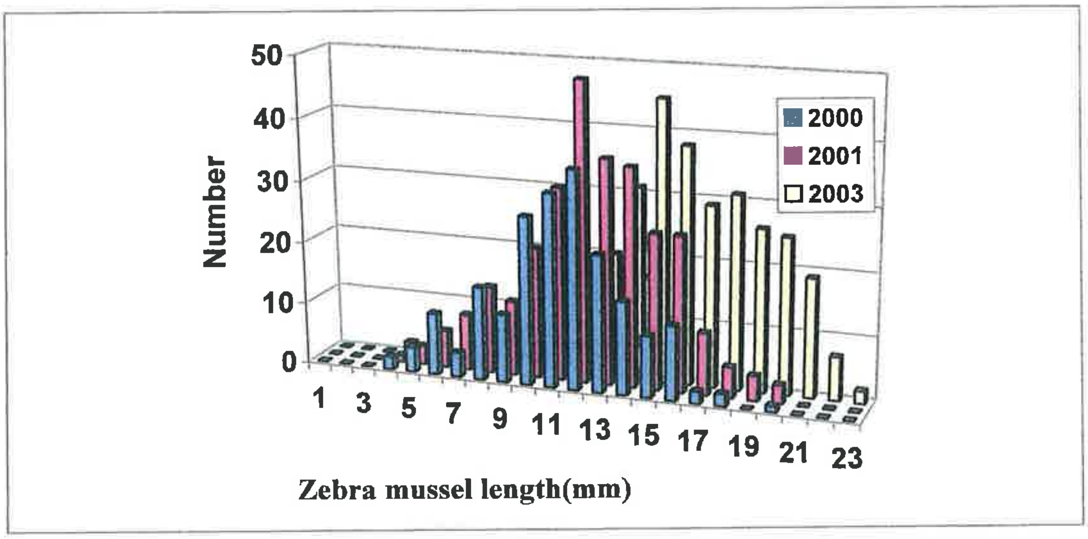
With the introduction of the 2000 cohort it became more difficult to define the modes from different years. Fig 5.3 shows size distributions of zebra mussels at Sites 2, 6 and 7 for 2000, 2001 and 2003. Although clear modes cannot be defined, it is apparent from the similarity with earlier data (Fig 5.2) *re* the maximum size achieved, that most zebra mussels survive only to the 2+ age cohort. The largest individuals measured were only 23mm (Table 5.1). Large worn individuals (24-34mm) were occasionally found in the centre of druses and may have been 3 years of age or older but these were rare. Dead shell in druses varied from 7 to 26mm, indicating that mortality takes places throughout the adult life cycle. Small zebra mussels (<3mm) obtained in samples may represent either late settlement from the previous year or early settlement in the specific sampling year. Size distributions were significantly different in different years at each site (G test, $p<0.05$).

Table 5.1 Minimum and maximum length/mm of zebra mussels found on stone at Sites 2, 6 and 7 in August 2000, 2001 and 2003. Standard deviations are also given.

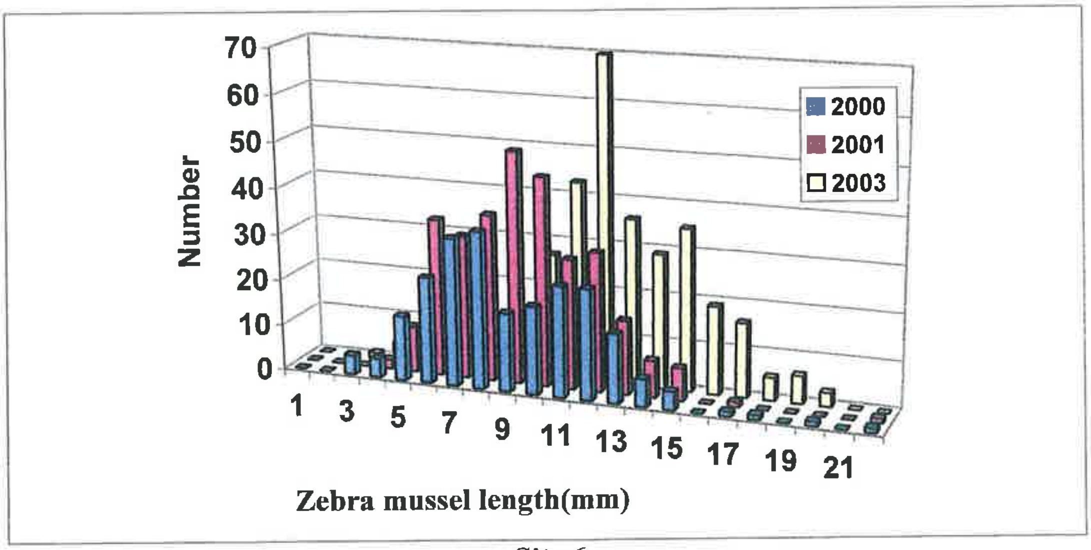
	Site 2			Site 6			Site 7		
Year	**Min (mm)**	**Max (mm)**	**SD**	**Min (mm)**	**Max (mm)**	**SD**	**Min (mm)**	**Max (mm)**	**SD**
2000	4	20	2.9	3	22	3.1	2	24	2.5
2001	4	20	3.0	4	22	2.6	3	17	2.7
2003	4	23	3.4	3	20	2.9	4	18	2.6

SD = standard deviation

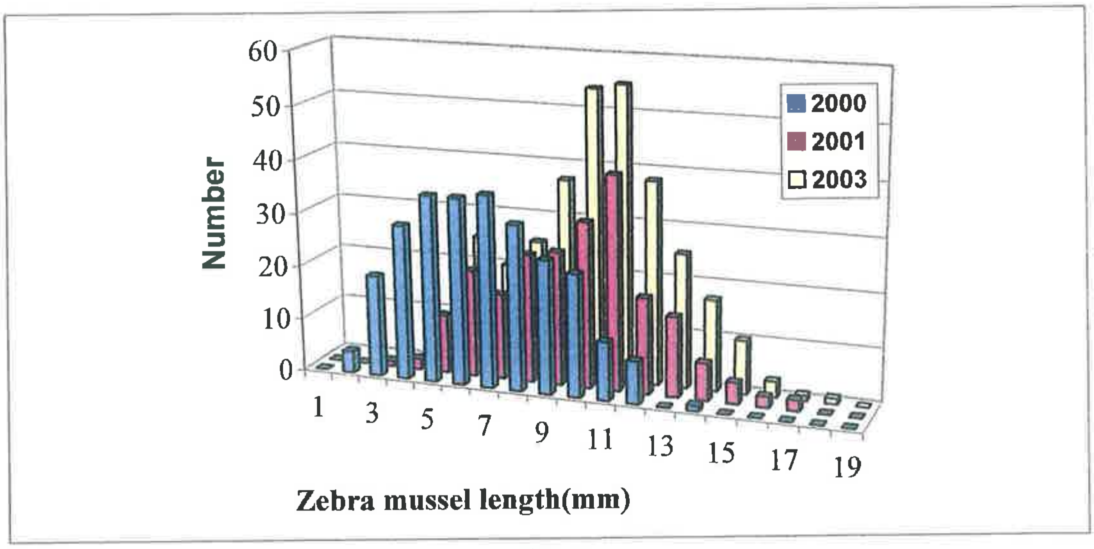
The 2000 and 2001 samples appear well represented by 1+ and 2+ modes. The 2003 samples had significantly less numbers of individuals < 10mm observed, than expected ($p<0.05$). This may equate with the poor settlement in 2002 (Fig 4.8) indicating lower numbers of small 1+ individuals relative to large 1+ or 2+ ones. In summary Fig 5.3 represents the presence of three age cohorts 0+, 1+ and 2+ but the merging of modes makes it difficult to divide these cohorts.



Site 2



Site 6



Site 7

Fig. 5.3 Size distributions of adult zebra mussels at sites 2, 6 and 7 in 2000, 2001, 2003

5.3.1.3 Bimonthly Size Distributions at Rockingham Site

Fig 5.4 illustrates size distributions (Rockingham jetty) for every second month from April 2003 to February 2004. The presence of small mussels (<5mm) in April and June 2003 samples represented late settlement and /or slow growth of young of the year 2002. August samples show the beginnings of the 2003 settlement (1-3mm). The size distributions in August and October were significantly different, with October samples having greater numbers of 0-2mm mussels than statistically expected (G test, $p<0.05$). October, December and February samples show high numbers of these small zebra mussels, representing high rates of successful settlement in late summer 2003 as noted in Chapter 4. It is apparent from these size distribution figures that it is not possible to delineate 0+ from 1+ age cohorts or 1+ from 2+ year groups due to merging of modes. No growth interruption lines were visible on Lough Key zebra mussels. Zebra mussels at this site attained larger sizes in summer 2003, with 2+ individuals attaining up to 28mm in samples by October that year. Occasional large (>27mm) brittle-shelled mussels were found mid-druse. These may represent an older cohort of 3+ or older individuals.

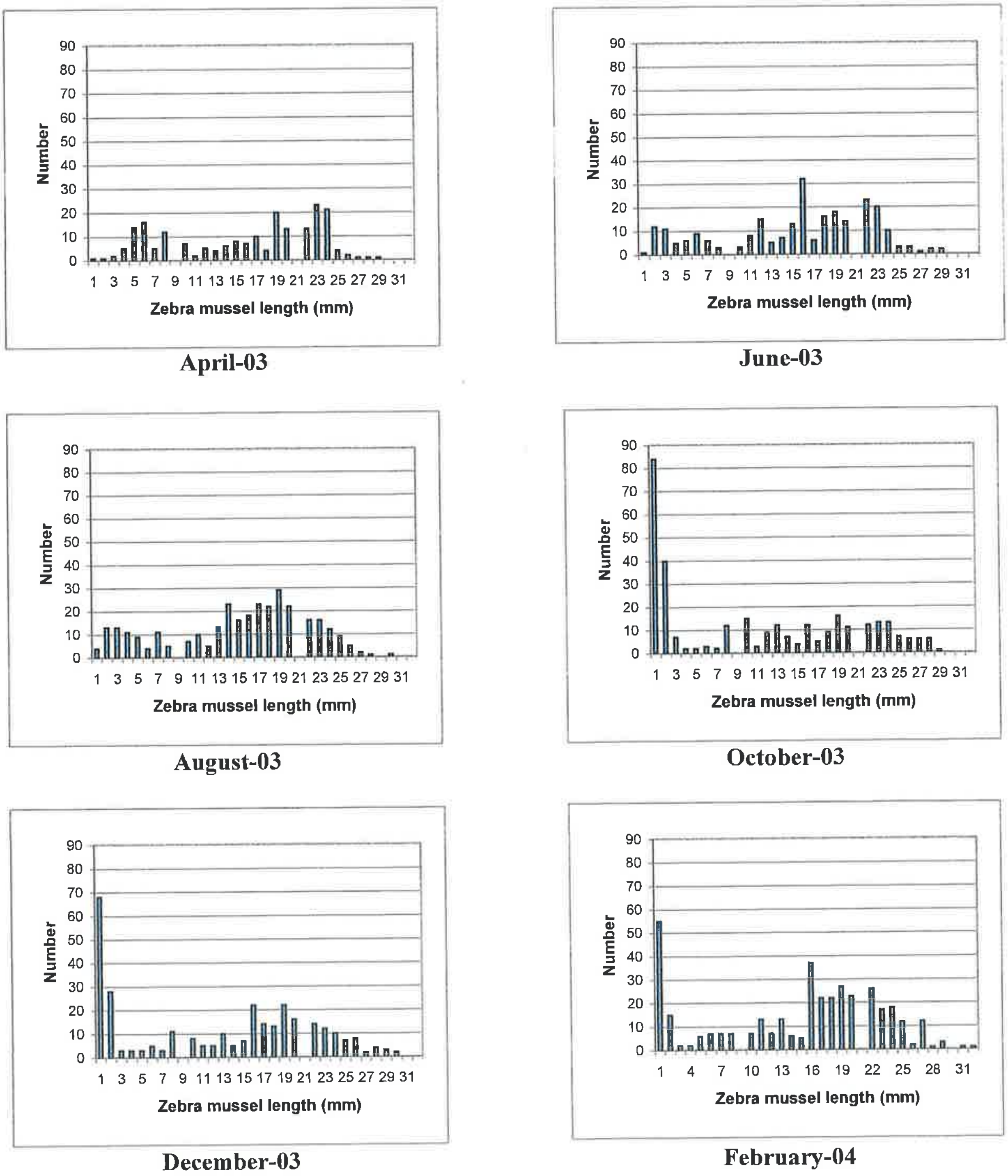


Fig 5.4 Seasonal size distribution of adult zebra mussels at Rockingham, Lough Key

5.3.1.4 Annual Comparison of Size Distributions at Rockingham Site

The late successful settlement of 2003 can be contrasted with that in 2001 and 2002 by examining size distributions from Rockingham in November/December of each year (Fig 5.5). There is a higher proportion of 1-2mm zebra mussels in 2003, than expected (G test, $p<0.05$). This 1-2mm size range is absent in 2001 and 2002, with the 0+ cohort in those years >3mm. In each year the frequency range with the most zebra mussels occurs between 15 and 22mm. This is likely to contain individuals from both the 1+ and 2+ age cohorts. Zebra mussels at the top end of the size range (>25mm) represented large 2+ individuals.

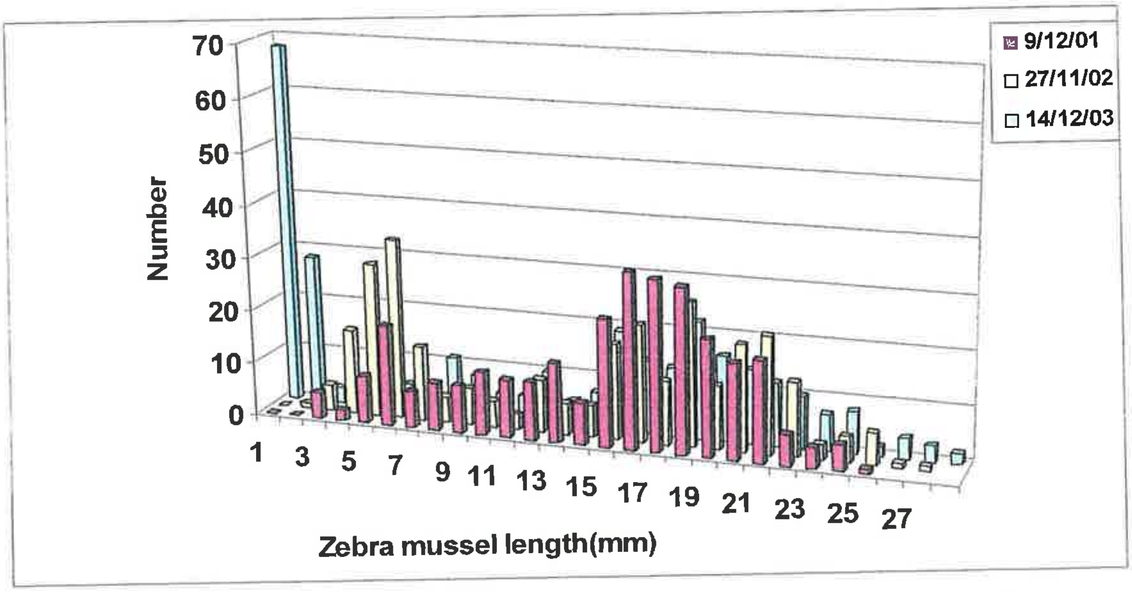


Fig 5.5 Zebra mussel size distributions from Rockingham, November/December 2001-2003

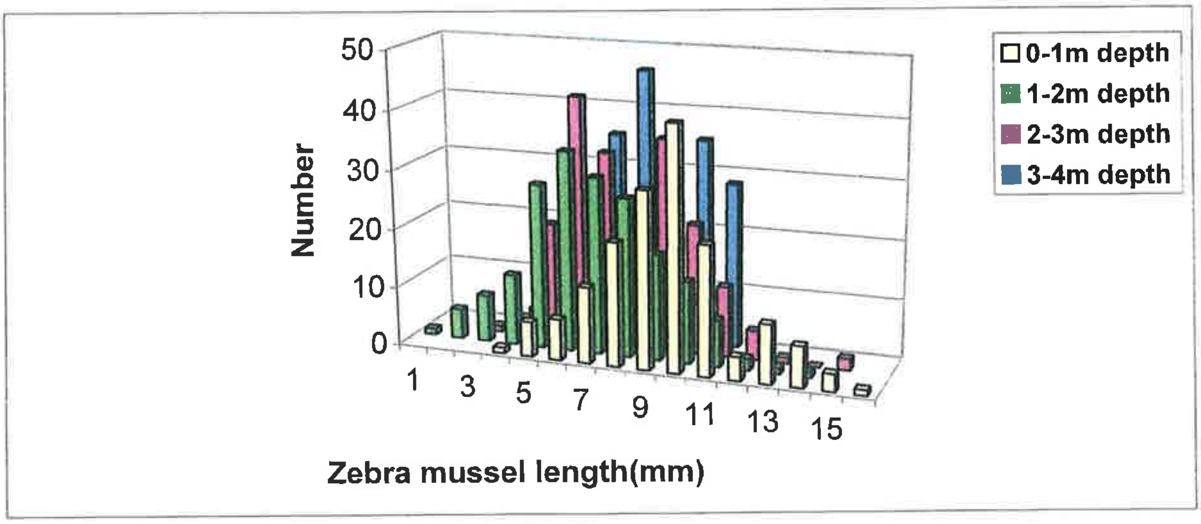
5.3.1.5 Size Distributions at Different Depths

Table 5.2 gives the minimum, maximum and mean sizes of zebra mussels at one metre interval depth ranges from 0 to 4m at the North, South and West transects sampled in August 2002 (n = 250 for each sample). Associated standard deviations are also given. Fig 5.6 shows the overall size distributions at these different depth ranges.

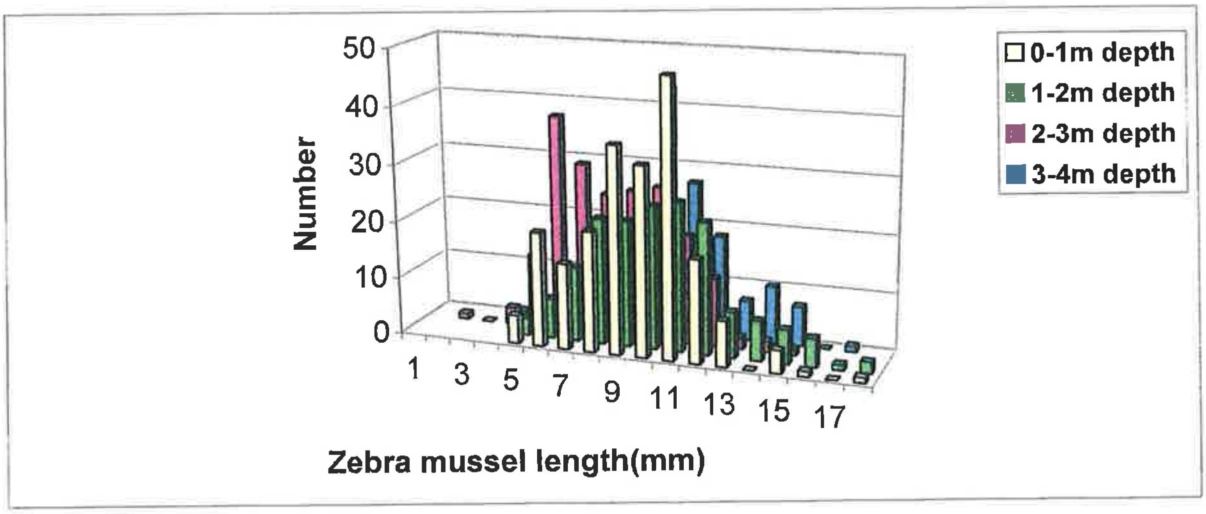
Table 5.2 Size range of zebra mussels from North, South and West transects at different depth ranges

	North				South				West			
Depth/m	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**
0-1m	4	16	9.56	2.3	**5**	**18**	**9.59**	**2.2**	2	14	8.55	2.1
1-2m	1	14	6.85	2.3	**5**	**18**	**10.4**	**2.7**	2	15	9.92	2.4
2-3m	3	15	7.81	2.1	**2**	**15**	**8.26**	**2.3**	3	15	9.58	2.3
3-4m	4	12	8.38	1.8	**4**	**17**	**10.32**	**2.5**	2	19	12.58	3.5

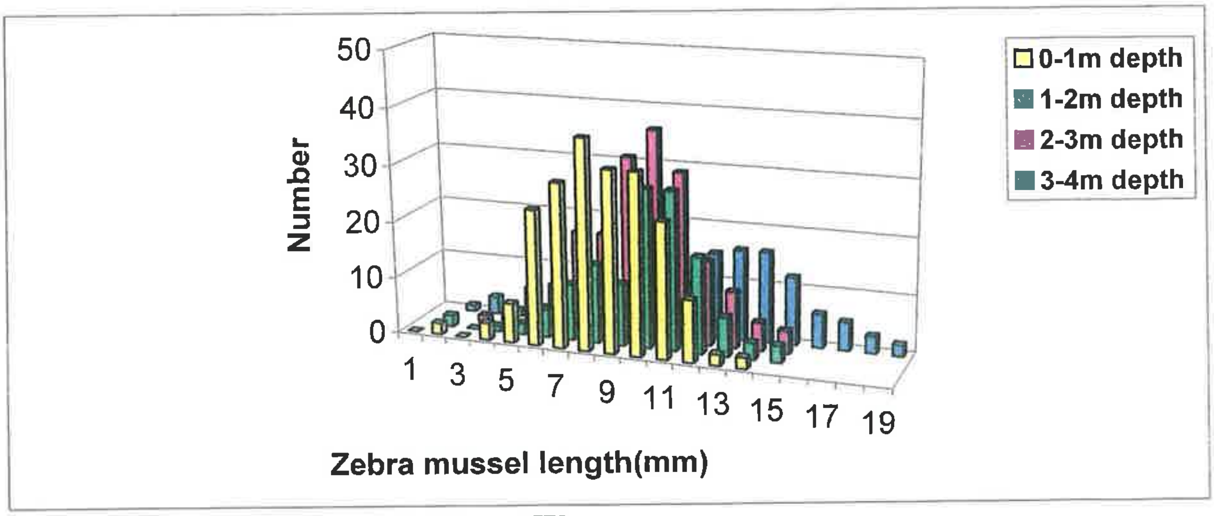
None of the eight transects had zebra mussels > 20mm in samples at any depth range and shells were of similar quality in terms of colour and hardness. This indicated that only 0-2+ age cohorts were present in transect samples.



North



South



West

Fig 5.6 Size distributions of adult zebra mussels from North, South and West Transects at different depths

Fig 5.7 shows the similarity of size distributions at 0-1m (Site 7) and at 12-13m (mid-lake) in August 2003. These were not significantly different in mean size (Mann-Whitney, $p>0.05$). At a greater depth zebra mussels were discovered at 17.5m on a rocky ridge near the centre of the lake (size distribution, 1 -13 mm length). The quality of shell at these greater depths was similar to that in shallower water, both in terms of colour and hardness.

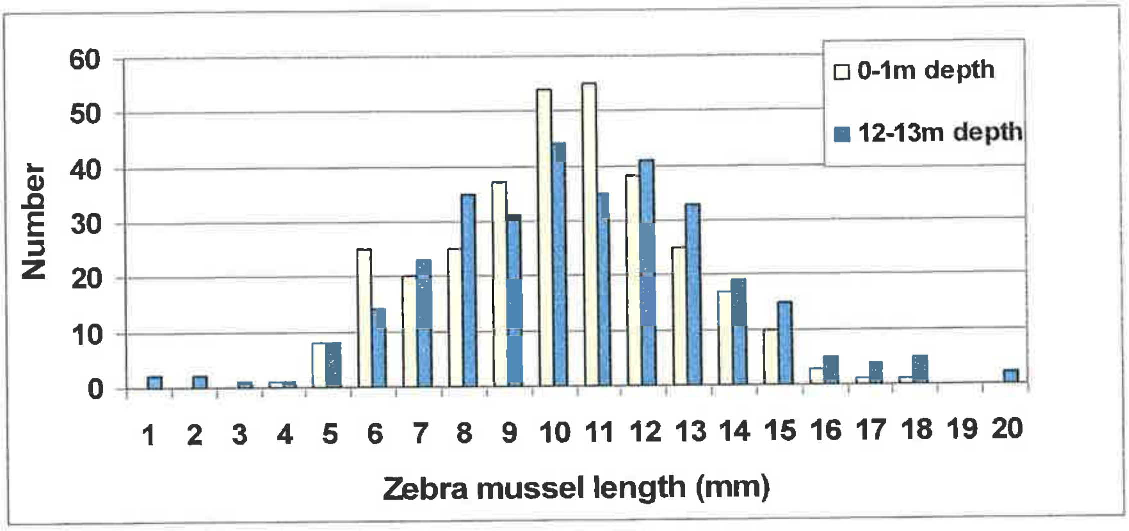


Fig 5.7 Size distributions at 0-1m depth (Site 7) and at 12-13m depth (mid-lake) in August 2003

5.3.2 Biomass/Density

Comparative information in early survey years was based on percentage cover of stone by zebra mussels close to snorkel Site 3 in 1998, and close to a number of the snorkel sites in 1999. Percentage cover estimates were also taken at snorkel sites in 2001 and 2003. These data were not available for 2000. Percentage cover was assessed as 11% in the littoral zone of a mainland shore west of Site 3 in November 1998 (Ni Chonmhara, 1999). At this stage colonisation was noted in small clusters, found either on the sides or bottoms of stones. Available data for percentage cover from 1998 to 2003 is presented in Table 5.3. Most sites show an increase in cover between 1999 and 2001 and then a subsequent decrease in percentage cover in 2003. Mean cover in 2001 was 80%, which had reduced to 69% in 2003. Percentage cover at video taped sites (2001) is presented in Appendix 3. The mean percentage cover was estimated at 82%, which is similar to the 80% estimate for snorkel sites. All percentage cover data is cover on stone or other hard substrates and does not reflect bare muddy areas. Plate 5.2 shows 95% cover on a sample of stones from Lough Key.

Table 5.3 Estimation of % cover on stone (1998 - 2003)

% Cover	1998	1999	2000	2001	2003
Site 1	nd	No stone	No stone	No stone	No stone
Site 2	nd	35	90	75	50
Site 3	11	70	95	90	50
Site 4	nd	20	100	80	80
Site 5	nd	2.5	80	80	70
Site 6	nd	30	95	95	85
Site 7	nd	10	85	40	50
Site 8	nd	100	100	100	100
Mean	nd	38	92	80	69

nd = no data

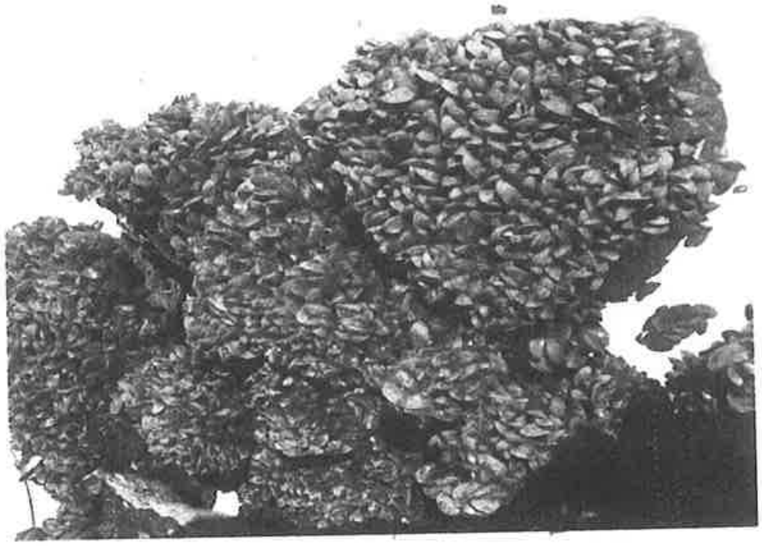


Plate 5.2 Zebra mussel cover (95%) on stones

5.3.2.1 Snorkel Site Biomass

Biomass results from 2001 and 2003, for each site are given in Table 5.4.

Table 5.4 Mean biomass (kg/m^2) at snorkel sites, 2001 and 2003

Site	2001 Mean Biomass(kg/m^2)	SD	2003 Mean Biomass(kg/m^2)	SD
Site 2	4.1	1.5	3.3	1.4
Site 3	6.1	1.1	3.2	0.5
Site 4	5.3	1.8	6.4	2.2
Site 5	4.2	0.7	3.8	0.6
Site 6	4.4	0.9	3.2	0.8
Site 7	4.5	1.1	0.1	0.4
Site 8	nd	nd	11.5	1.0

nd = no data

There was no overall significant difference in zebra mussel biomass in the snorkel sites between 2001 and 2003 (ANOVA, $p > 0.05$). The mean biomass for 2001 was 4.8 kg/m^2 while the mean for 2003 was 4.5 kg/m^2. Plate 5.2 shows zebra mussels covering stone taken from Site 4 in August 2003. The estimate for the year 2000 based on the 2 x 2 cm^2 quadrat was 4.4 kg/m^2.

5.3.2.2 Transect Biomass and Total Number of Zebra Mussels

Appendix 8 gives the zebra mussel biomass and numbers for each of the eight transect samples. The total areas for each depth interval were given in Table 3.1 (Roxann^{Tm} survey). These datasets were used to calculate the total number and the total biomass/kg of zebra mussels in Lough Key. The total number of zebra mussels in Lough Key estimated by this method was 33 x 10^9 with a total biomass of 4.4 x 10^6 kg. The mean density of zebra mussels over the total lake bed was 3,900m^{-2}, with a biomass of

520g/m^2. The highest mean density (6,800 zebra mussels/m^2) and mean biomass (1.05 kg/m^2) was found in the first 3m of depth. Table 5.5 gives mean density/m^2 and biomass/kg for different depth ranges between 0-6m (n = 24 for each sample). There was no significant difference in biomass/kg (ANOVA, $p>0.05$) or density/m^2 (Kruskal-Wallis, $p>0.05$) among the first three depth intervals (0-1m, 1-2m, 2-3m).

There were significant decreases both in biomass (t-test, $p<0.05$) and density (Mann-Whitney, $p<0.05$) between the 2-3m and 3-4m depth intervals, with further decreases in these values occurring between 4 and 6m depths. Very few zebra mussel were found below 6m depth, due to lack of suitable substrate. It is likely that this number is an underestimate since the substrate mapping estimated the total area of the lake as 8.4km^2, due to the limitations of mapping areas with a depth less than 2m (Section 3.2.2). The geographic mapped area of the lake is actually 9km^2 (Ordinance Survey of Ireland, Discovery Series 33). The biomass for transect sites was significantly lower than that found for the snorkel sites.

Table 5.5 Biomass and number of zebra mussels at different transect depth intervals in Lough Key

Depth range/m	Mean density (m^2)	Mean biomass (kg/m^2)
0-1	5779	1.15
1-2	7545	1.12
2–3	7056	0.879
3–4	3154	0.500
4–5	1677	0.327
5–6	1178	0.226

A zebra mussel density estimate of 1,200m^{-2} was made by Ni Chonmhara (1999) in November 1998. This included all specimens ≥1mm. In 1999, zebra mussel density estimates ranged from 4,000 – 148,000m^{-2} (Lucy and Sullivan, 2001). This result is likely to be an over estimate as it was calculated from total area and percentage cover based on the premise that stone was the only substrate present. It nevertheless is considered to be an increase from the previous year.

5.3.3 Ash Free Dry Weight – Condition Index

Mean ash free dry weight (AFDW) of Lough Key *Dreissena* in November 2002 was 6.8 mg. Fig 5.8 shows the monthly results from March 2003 to February 2004. Weight loss occurred between May and July 2004. AFDW then began to rise and peaked in October 2003 at 14 mg. October results were significantly higher than those in March, April, June, July, August and November 2003 (ANOVA, $p<0.05$). AFDW in November was less than in any other month, at 9.8 mg. Table 5.6 shows a comparative table for AFDW results from 15mm zebra mussels in other lake studies (Nalepa, 1995). These results are from November samples as this was believed to be when minimum weight was detected following the end of the spawning season. Lough Key samples fall within the range of these other European and North American studies.

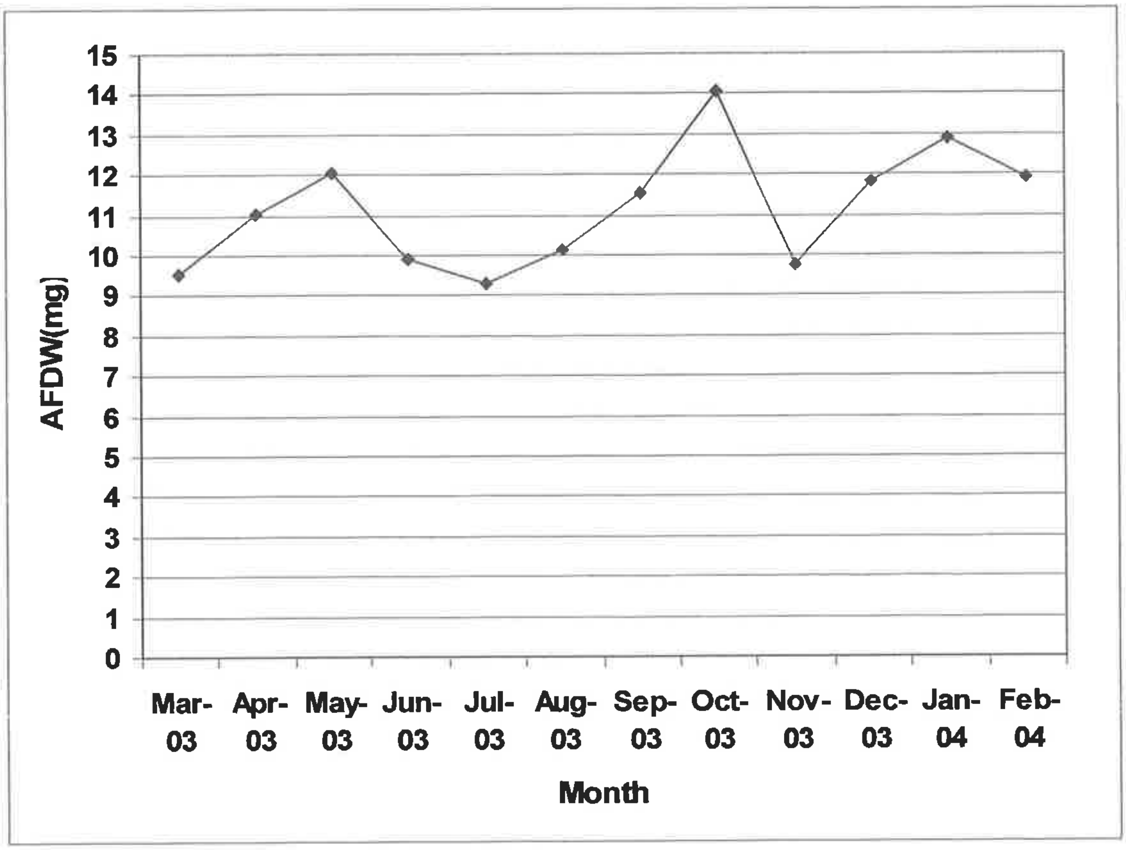


Fig 5.8 AFDW(mg) of 15mm zebra mussels (n=30), March 2003-February 2004

Table 5.6 Comparative table for AFDW(mg) results for November samples

Location	Year	AFDW(mg)	Reference
Lake Volkerak, Netherlands	1989	12.1	Smit and Dudok van Heel, 1992
Lake St. Clair, USA	1990	10.7	Nalepa et al., 1993
Hollandsch Diep, Netherlands	1987	9.8	Smit and Dudok van Heel, 1992
Lake IJsselmeer, Netherlands	1983	9.1	Bij de Vaate, 1991
Lake St. Clair, USA	1991	9.1	Nalepa *et al.*, 1993
Lake Huron, USA	1991	8.6	Nalepa *et al.*, 1995
Lake Huron, USA	1992	4.6	Nalepa *et al.*, 1995
Lake Huron, USA	1993	3.1	Nalepa *et al.*, 1995
Lough Key, Ireland	2002	6.8 ± 2.0	This study
Lough Key,Ireland	2003	9.8 ± 3.2	This study

5.4 Discussion

5.4.1 Size distributions

The size distribution taken in July 1998 represented two age cohorts (1+ and 2+). It seems likely from the relatively high numbers found, that reproduction took place in the lake in 1997 following introduction in 1996. The largest mussels (2+, >20mm) may be the parent population involved. It is not possible to know whether these older mussels spent their entire life in the lake or whether they were introduced as boat drop-offs (propagules) or spawned from boats moored at this jetty site. Small numbers of large mussels were also observed when zebra mussels were detected in Lough Key in Spring 1998 at another boating area near Site 3. It is interesting that no representatives of the 1998 cohort were yet present in this July sample. This fits in with the settlement plate data which indicated that no settlement took place until the second week of August.

These early populations in Lough Key may have been quite localised at leisure boat jetties. The size distribution datasets from a mid-lake buoy in November and December 1998 shows the presence of only one large zebra mussel (22mm), the rest are all settled 0+ individuals. Nalepa *et al.*, (1995) also recorded these young cohorts early in the invasion of Saginaw Bay, Lake Huron. It was possible to take an educated estimate of the growth of the 1998 age group to the end of the 2+ lifespan as noted in Fig 5.2. In subsequent year groups, it became more difficult to divide cohorts.

The 1998 age group was easier to track because it formed the vanguard of the invasion. So from following the growth of settled 0+ juveniles in the autumn, one could follow the age group as the last 2+ survivors grew and survived to 27mm by January 2001. This could be interpreted with confidence because the data at the start and finish of the size ranges was relatively easy to determine. Once the 1998 age group reproduced for the first time in 1999 the subsequent definition of mid-size range age cohorts by summer 2000 became more complex (Fig 5.3). The merging of 1+ and 2+ modes seems to occur from a size range of approximately 10mm upwards.

There may be three principal reasons why this merging occurs.

1. **Position within druses**: zebra mussels typically live in tightly packed druses. Most studies on growth do not take this into account and separate zebra mussels in cages. Burks *et al*., (2002) discovered that larger mussels are less able to migrate out of the base of an aggregate to the surface. Tuchman *et al*., (2004) found in a laboratory based experiment, that depending on the flow rate individuals within the colony may experience restricted food availability. Large worn individuals (24-34mm) were found occasionally in the centre of Lough Key druses. Manoeuverability of zebra mussels becomes difficult as soon as a 1+ zebra mussel becomes settled on by juveniles. If food becomes a limiting factor due to position within a druse then the better positioned mussels of the following year group could merge in size with the parent group they have settled on. Tuchman *et al*. (2004) also found that at all vertical positions within the colonies, smaller mussels showed higher ingestion rates per unit mass than smaller mussels.

   This druse effect occurs only when percentage cover builds up in a lake. In early colonisation individual zebra mussels tend to position themselves on the sides and underneath stones (Polish lakes: Stanczykowska, 1964; Irish lakes: Loughs Key, Arrow and Sheelin, pers. obs. 1998-2003).

2. **Time of Settlement**: The previous chapter showed that settlement may take place over a four month period (June–September). Juveniles which settle early in the season have a growth advantage over those which settle in late summer. They also have an advantage in developing faster due to higher summer water temperatures, which increase bivalve growth rates (Almada-Vilela *et al*., 1982). Food availability is far higher for these young settlers in summer months, than for late settlers in autumn months. Food supply has been shown to be the most important factor in determining bivalve growth in both hatchery and wild populations (Gosling, 2004). Temporal variation in settlement may lead to the presence of separate merging cohorts within an age group. The earliest and fastest growing of

one year may then proceed to merge with the slow growing late settlers of the previous age group.

3. **Survival**: Mortality can be extremely high at settlement and may continue at a lower rate throughout the life of the zebra mussel, due to predation (Molloy *et al.*, 1997), substrate availability (as reviewed in Karatayev *et al.*, 1998), food availability (Stanczykowska and Planter, 1985; Holland, 1993; Nalepa *et al.*, 1995; Mellina *et al.*, 1995; Johengen *et al.*, 1995) and possibly cannabilism of larvae (Mac Issac *et al.*, 1991). Dead zebra mussel shells of different sizes were found within druses indicating that mortality takes places throughout the life cycle. Predation by birds or fish would result in the removal of shells from druses. The mallard duck, *Anas platyrhynchos* is the only predator that has been observed in Lough Key (pers. obs.). Varying rates of mortality may also therefore make it difficult to determine age groups.

The druse/3-D structure should be seen as a dynamic unit of varying size, shape and depth where zebra mussels live and reproduce in aggregate, dying off after their second year of reproduction as 2+ individuals.

The size of age groups in subsequent years did not exceed that of the 2+ 1998 age class, with the exception of small numbers of large mussels sampled in summer and winter 2003, some of which reached 30mm. It is possible that occasional Lough Key *Dreissena* are surviving to three years or more as larger mussels were found in consecutive years (maxima 25 mm in 2001, 27mm in 2002, 28mm in 2003). As the growth rate of mussels is slow after the first two years (1-3mm a year) it is not possible to definitely age these mussels, which may be survivors of the early invasive cohorts in Lough Key.

Differential growth due to different temperature regimes have been noted in laboratory studies (Bij de Vaate, 1991) and also can be used to predict growth rates in lakes (Smit *et al.*, 1992). Irish water temperatures are lower in summer than waters of many of the continental climate lakes that zebra mussels inhabit and this may result in lower seasonal growth rates. Although filtration has been demonstrated to commence at 3-4°C (Mikheev, 1967a, 1967b; Kondratiev 1969), growth and development in *Dreissena* requires much higher temperatures. The temperature of 10°C was found by many authors involved in field studies to be the minimal for growth and development in *D. polymorpha* (Lvova-Kachanova, 1972, Alimov, 1981; Lvova, 1977; Karatayev, 1983; Mackie, 1991; Karatayev and Lvova, 1993, Jantz and Neumann 1992, Lyakhnovich *et al.*, 1994). Morton (1969) found that *D. polymorpha* grow only when water temperature is greater than 11°C. In River Rhine, shell growth stopped in autumn between 15°C and 10°C in autumn (Jantz and Neumann 1992). However, according to Bij de Vaate (1991), in Lake Ijsselmeer (Netherlands) *Dreissena* growth began at about 6°C. Another author Smit *et al.* (1992) claimed a minimum temperature of 3°C was needed for shell growth to occur but this minimum temperature is much lower that those found by all other authors cited above. Studies have shown that in continental waters zebra mussel growth stops during winter, and resumes in April-May after water temperature has reached the various thresholds given above.

Data-logger results indicated that Lough Key water temperatures were less than 10^0C from the start of November to the beginning of April each year (Fig 4.1). International data suggests that growth and development would occur in Lough Key for 7 months of the year based on the 10°C limit. A 6°C limit based on temperature datasets from 2001 to 2003 would include both November and March for annual growth, giving a nine-month growth period. A series of cage-based experiment would be required to carry out specific growth studies in Lough Key to determine growth rates and also whether growth occurs below 10^0C.

It is known that *Dreissena* reach the appropriate size for sexual development in Irish waters by their second summer as 1+ individuals (Juhel *et* al., 2003). Lough Key size distributions are often similar to those from other countries (Bij de Vaate, 1991; Smit *et al.*, 1992; Martel, 1995; Nalepa *et al.*, 1995; Chase and Bailey, 1999) despite different water temperature regimes. Morton (1969) found a maximum shell size of 40mm (4 year old mussel, England) and Burlakova (1998) a 43mm individual (Lake Gartov, Germany). In Lough Key, small numbers of zebra mussels >25mm occurred at the end of each year (Fig 5.5) but these were no longer present at the start of the following season (Fig 5.4). The Lough Key, 2+ estimated normal lifespan (with very occasional survival to three or more years) is similar to that cited in some North American studies (Garton *et al.*, 1993; Nalepa *et al.*, 1995; Mackie and Schloesser, 1996; Garton and Johnson, 2000) but is less than many of the European studies which cite survival to at least four years (Stanczykowska, 1964; Morton, 1969; Bij de Vaate, 1991; Smit *et al.*, 1992).

The significant difference in size distribution frequencies at different sites within Lough Key shows how variation can occur even within a small lake system. This variation was also seen in settlement which was shown to be different at separate lake locations. The size distribution of adults in the following season may reflect the success of settlement over the previous summer season. The low numbers of mussels <10mm in 2003 reflect poor settlement in 2002. The greater size attained by 2+ zebra mussels in August 2003 relative to 2002 was recorded at each of the snorkel sites. This may have reflected higher water temperatures and hence increased growth rates and productivity within the lake. Sampling different sites within a relatively small lake as Lough Key gives greater detail on temporal and spatial variation in size distributions than sampling a small number of sites within the large lake systems reviewed in Chapter 1.

Examining seasonal size distributions at one site shows how difficult it is to divide age groups. Growth and survival can be inferred from length/frequency distributions, only if there is little or no overlap in size between cohorts (Nalepa *et al.*, 1995). Samples from Rockingham show no clear distinction between year classes, either between 0+ and 1+ (e.g., April and August 2003) or between 1+ and 2+ (e.g., October and December 2003).

International literature which reviews size at different ages (Chapter 1) may have sampled at any stage of the growing season, at different temperature regimes so it is not possible to make direct comparisons. From handling many samples each August from

2000 to 2003, it was judged from examining the shell condition that the maximum size of a 1+ individual in August was 15mm. It is recognized however, that this is a subjective judgement and not based on scientific fact as no growth interruption lines were present on the shells.

The variance in the maximum size attained by zebra mussels in the lake probably related to food availability; either in a microscale in terms of mussel position in a druse or on a macroscale in terms of food availability in the entire lake. Dorgelo (1993) found that yearly variation in the composition of dynamic algal communities was probably the key factor in determining growth rate.

Late successful spawning in 2003 resulted in very high numbers of 1mm juveniles in October 03 - February 04 samples, thereby providing high densities of a replacement generation for the 2+ age group. As noted in Chapter 4, having two reproducing age groups gives zebra mussels a major insurance policy – the poor settlement in 2002 was compensated by high growth and reproduction in the following year.

Similar size ranges occurred at different depth intervals. Zebra mussels less than or equal to 3mm were considered to be 0+ (Fig 5.6). Some early settlement was noted, particularly at the west transect. As in other size distribution it was not possible to divide 1+ and 2+ modes. The transect surveys in 2002 did not locate any zebra mussels over 20mm at any depth although these were relatively common in August samples of other years. This may relate to less food availability due to reduced trophic level. This may also have impacted on reproductive rates as successful settlement rates were low that year. In 2003, high growth rates of adults coincided with increased settlement. Maximum dreissenid size may also relate to the time of sampling. Zebra mussels over 20mm were relatively common in samples collected three months later in November 2002 (Fig 5.5).

Karatayev *et al.* (1998) reviewed the minimum depth where zebra mussels occur as from 0.1 to 0.5m, depending on local water fluctuations and probability of freezing. It would also be expected that mussels would have greater exposure to water movements in shallow depths which could be either a disadvantage (turbulence) or an advantage (greater food supply). It is known that wave activities can inhibit zebra mussel growth rate. In the littoral zone of the Kuybyshevskoe Reservoir (exposed to wave activities), the average length of yearling mussels was 4-5mm, and maximum length was 8-10 mm. In contrast, at the same depth but without wave activity, the average length of yearling zebra mussels was 7.2 mm and maximum length was 14mm (Mikheev 1964). According to the same author, the average length of the young-of-the-year *Dreissena* in parts of the Tsimlyanskoe Reservoir exposed to the strong wave activity was 9mm (maximum 12.5 mm), whereas in quiet places at the same depth the average *Dreissena* length was 12mm (maximum 19.2mm). In Ireland the prevailing winds are south to south-westerly and wave impacts would be greatest at the northern transect of Lough Key but this was not the case. There was no significant difference in density or biomass in the first three depth intervals (0-1m, 1-2m and 2-3m) indicating that wave action did not appear to impact on *Dreissena* growth in Lough Key. Reduction in biomass and density in this lake at depths >3m instead relate to lack of available stone substrate.

Water levels in Lough Key fluctuate very little annually, due to the relatively high levels of rainfall of up to 3,000mm/year (Reynolds, 1998), which add considerable water to the catchment. There is no water abstraction from the lake. In February 2000, the lake froze from the lakeshore out to approximately 100m and the ice was approximately 1-2cm thick for a period of one week. This was the only time between 1998 and 2004 when the lake water was frozen.

As there was no significant difference between size distribution means of *Dreissena* samples found at 0–1m and 12–13m, food availability did not seem to be a limiting factor to growth at this depth as long as available substrate was present. Zebra mussels taken from 17.5m did have a lower upper size limit (13mm) but represented specimens from 1mm (recently settled) upward. As shell quality remained the same (colour and hardness) for larger mussels at each depth it can be assumed that larger mussels at depth did not represent stunted individuals older than 2+. The authors' hypothesis was that the decrease of the growth rate was due to the temperature and food decline with depth. Walz (1978) kept *D. polymorpha* samples at 60 m depth in Lake Constance with temperature variations from 4.5 to 5.5°C. During the 2 years period of the experiment, *Dreissena* shell length remained constant in this cold lake, while the dry weight, protein and carbon content of the soft body decreased exponentially.

Low oxygen due to eutrophy (Stanczykowska and Lewandowski, 1995), the presence of a thermocline (Garton and Johnson, 2000), and suitable substrate (reviewed in Karatayev *et al.*, 1998) are considered the depth limiting factors in zebra mussel colonisation. Mixing of water in Lough Key ensures a supply of dissolved oxygen at all depths where zebra mussels are found (Appendix 11). The only place where a thermocline has been occasionally observed in summer is at the Hog Island Deep (EPA station C), where the substrate is muddy and no zebra mussels occur. Water movement and mobility of phytoplankton (Chapter 8) also ensure a food supply of seston to zebra mussels at different depths. Results of the substrate, groundtruthing and transect surveys indicate that the absence of zebra mussels in significant numbers at >6m depths is due only to lack of available stone substrate rather than water characteristics.

5.4.2 Biomass and Density

From the size distribution datasets from July 1998 and percentage cover datasets from November 1998 onwards, it can be concluded that zebra mussels took three to five years from their introduction to the maximum exponential growth phase. This covers the period 1996 (probable earliest arrival) to 2000 (known highest percentage cover). The time duration from time of detection (April 1998) to peak in exponential growth was two to three years. The increase in percentage cover from 1998 (11%) to 2000 (92%) shows an exponential increase typical of the early stages in zebra mussel invasions (Caraco *et al.*, 1996; Strayer *et al.*, 1996; Miller and Payne, 1996).

It is often assumed that there is a lag time between when zebra mussels first invade a new waterbody and when they are abundant enough to detect and have ecologically relevant effects (Lvova, 1980, MacIssac *et al.*, 2001). It is possible that zebra mussels existed in Lough Key before 1996. These may not have been detected in samples taken in 1998 due to low densities or mortality prior to sampling. It seems likely though, that there would have been a time lag of several years between the arrival of zebra mussels in the lower Shannon (estimated as 1994 or earlier, Minchin *et al.*, 2002b) and their successful transport more than 150km upstream to Lough Key *via* settled individuals on boat hulls, which probably occurred in the summer of 1996. Major advantages exist in terms of estimating the lag phase involved for Lough Key as there is a fairly well established time scale in terms of the initial Irish invasion, a known pathway (the Shannon), vector (leisure craft) and recognised sampled boat marinas. This has allowed an A to Z approach for the early phase of invasion in Lough Key. The relatively rapid spread of zebra mussels within waterways was also noted in North America (Kraft and Johnson, 2001).

It is recognised that estimating percentage cover is subjective but the same operators were used for individual snorkel sites in different years. The results from the videotapes were also very similar to the snorkel results in 2001, which is a good comparative indicator. Mellina and Rasmussen's model (1994) on distribution and abundance of zebra mussels was based on substrate as the only limiting factor whereas Nalepa *et al.* (1995) Strayer *et al.* (1996) also indicated food as a limiting factor. Reduction in percentage cover on stone in 2003 could indicate that suitable substrate was not the main limiting factor in the lake in that year. It corroborated the poor settlement obtained on plates in 2002, which may have been caused by lack of suitable phytoplankton for larval food (Chapters 4 and 8). This could also be explained by low reproductive success or predation or a combination of all these factors.

Mean biomass at snorkel sites was not significantly different between these years, indicating a relatively stable population of zebra mussels in the lake. It is possible that the percentage cover data for 2003 could reflect a higher proportion of 2+ zebra mussels in 2003 samples. The result for 2000 was also similar, but some caution must be exercised with interpreting this result as the methodology was different and even with the application of a correction factor may have given an erroneously high result in 2000. Snorkel biomass estimates (greater than 4.5 kg/m^2, depths 0-3m) are much higher than those obtained in the transects survey for the same depths. As the substrate was usually not 100% stone, this may have lead to higher results.

In the transect surveys the quadrat was placed on the substrate by the diver and everything was removed into a sample bag. A diver can get more realistic results because they are not hampered by the time-restraints of a snorkel operator. The transect results are considered to be more accurate and were used to give information on number and biomass of the whole lake and also for different depths. These data corroborated information obtained in the groundtruthing survey (Chapter 3) that zebra mussels were not found on muddy substrate except attached to *Anodonta* or other shells, including *Dreissena* shells. As stated above, very few zebra mussels were found at depths greater than 6m, as this was almost entirely mud apart from isolated rocky patches. As substrate did not appear to be a limiting factor in 2003, it is not clear how percentage cover would be affected if stoney substrate extended to greater depths. With food as a limiting factor it is likely that overall percentage cover on stone would be reduced.

The densities of zebra mussels on stone substrate in transects, compare well with data obtained on stone for Lake Majcz Wielki and Mikolajskie in Poland (Stanczykowski and Lewandowski, 1993), Naroch Lake in Belarus (Burlakova, 1998), Lake Huron (Nalepa *et al.*, 1999), Lake Erie and Lake Ontario (Chase and Bailey, 1999), Lake St. Clair (Nalepa *et al.*, 2001) in North America (Table 1.2).

Wet biomass per number of zebra mussels/m^2 (520g in 3,900m^2) was greater than that found in Lake Constance in 1989 (350g in 5,000 m^2), Cleven and Frenzel, 1993) but similar to that found on stone in Naroch lake in 1997 (2647 ± 559/m^2 and 609 ± 126 g/m^2) Burlakova, 1998). Such comparisons are really only useful when full lake surveys are compared, such as information on invasion of lake, physical and chemical parameters and trophic status and when similar methods are employed. Many North American studies, e.g. Chase and Bailey (1999) have used dry weights instead of wet biomass and this does not allow for any biomass comparisons to be made.

The AFDW results did show a close relationship with other studies for November samples and also showed a definite drop from May to September 2003, coinciding with the summer spawning season. Maximum weight per unit length would be expected to occur in Spring when gonads are ripe (Nalepa *et al.*, 1995). The peak in September was actually higher. This may reflect increased productivity in 2003 due to the relatively high summer water temperatures. It is not clear why a sudden drop occurred in the November sample or why AFDW rose in December and January. This experiment was very limited as it was carried out for one continuous year only, with a limited sample size (n = 30) and at just one site. It would be more appropriate to carry this out monthly on a number of sites of varying depth range. This could be used to combine research between biomass at different depths and standard condition factor experiments.

Total biomass in the lake is important in terms of calculating filtration capacity and this topic is dealt with in Chapter 8. Total biomass and density are useful data for a comparative repeat exercise in the future. Repeating this survey every few years would allow long term fluctuations in the population to be monitored.

This chapter has reviewed size distributions, zebra mussel density and biomass estimates on stoney substrates – these datasets are all considered necessary to present maximum information on Lough Key zebra mussel population dynamics.

CHAPTER 6

ZEBRA MUSSELS ON *ANODONTA ANATINA* (L.)

6.1 INTRODUCTION

A review of *Anodonta anatina* has been given in Chapter 1 of this thesis. Unionacean mussels constitute a high proportion of the benthic macrofauna of shallow freshwater habitats, sometimes exceeding 90% of the biomass of the benthic fauna (Okland, 1963; Mann, 1964). Prior to the invasion of zebra mussels in Lough Key densities of *Anodonta anatina* were described as common in the lake (Ross, 1984). Although other macroinvertebrates could not be studied as part of this thesis due to time restraints, it can be acknowledged that *Anodonta anatina* was a major constituent of the macrofauna and the main filter feeding organism before the arrival of the zebra mussel to Lough Key (Ross, 1984, 1988).

Karatayev *et al.* (1997) formed a hypothesis that *Dreissena* may have higher impact on unionids in North America, where there is no co-evolution, than it does in Europe, where zebra mussel and unionid species commonly co-exist. In some European waters, extensive overgrowth of unionids by *Dreissena* resulting in mass mortality, is characteristic of periods of rapid population growth, when *Dreissena* invades a new waterbody, for example Lake Balaton in Hungary (Sebestyen, 1938) and the Naroch Lakes in Belorussia (Burlakova *et al.*, 2000). Unionids are still abundant in other waters where zebra mussels have been present for longer, e.g. in Lake Lepelskoe where zebra mussels were first recorded in 1929 (Ovchinnikov, 1933). *Anodonta anatina* is known to co-exist with zebra mussels in that lake and in other Belorussian rivers, lakes and reservoirs (Burlakova *et al.*, 2000).

In terms of impacts, zebra mussels which colonise unionids in high numbers are believed to negatively affect native unionids if they (1) impair normal locomotion and burrowing activities, thus preventing escape from environmental extremes, (2) prevent valve closure, thus exposing the unionid to predation, parasitism and environmental extremes, (3) prevent valve opening and thus prevent respiration, (4) smother siphons, thus stopping metabolic activities, (5) eliminate food from water reaching the unionid, thus causing starvation, (6) cause shell deformities, thus preventing normal growth, (7) generate metabolic wastes, thus causing toxic effects, and (8) add weight to the unionid shell, thus causing the host to sink in soft sediments, where smothering would occur (Schloesser and Kovalak, 1991).

Several studies have shown diminished glycogen levels in heavily infested unionids (Haag *et al.*, 1993; Baker and Hornbach, 2000; Hallac and Marsden, 2000), which implies interference with feeding patterns and increased stress levels. Other studies have concentrated on competition for food due to the decrease in phytoplankton levels caused by zebra mussels (Strayer and Smith, 1996; Strayer *et al.*, 1999) or have suggested that zebra mussels occupy otherwise available space (Tucker, 1994). The effect of zebra mussels on unionids may depend on the type of bottom sediment. In the Svisloch River (Belarus), sandy and rubble sediments alternate with silt. In sandy and rubble areas, unionids have up to 100 attached zebra mussels per individual, whereas in silt, the unionids bury in sediments and are completely free of *Dreissena* (Karatayev and Burlakova, unpublished data reviewed in Karatayev *et al.*, 1997). As of yet no one single factor has been identified as causing extirpation in lakes.

In North American lakes and rivers that support high densities (>3,000m^2) of zebra mussels, native mussel populations are extirpated within 4-8 years following invasion (Ricciardi *et al.*, 1998). In Lough Key, *Anodonta anatina* became extirpated between the end of 1999 and the summer of 2000. Using datasets from 1998 onwards, this chapter aims to establish the timescale for the demise of this unionid in Lough Key and to evaluate the usage of *Anodonta* shells as substrates for zebra mussel colonisation between 2000 and 2003.

6.2 MATERIALS AND METHODS

Methodology is outlined in Section 2.2.5.3. Initial sampling in April 1998 was carried out using a long handled rake on the mainland shore west of Church Island (Fig 2.2). This shore was also used as a dive site to collect *Anodonta* in November 1998. *Anodonta* recovered in 1999 were removed from Site 8 in July and November of that year. The length and weight of each *Anodonta* (live and dead); the numbers of zebra mussel fouling and estimated age of *Anodonta* were taken in 1998. In 1999 the length and weight of the living *Anodonta*; length of dead *Anodonta* shells; the numbers and biomass of zebra mussel fouling and weight of associated debris were analysed in the laboratory following sampling. Proportional loading was estimated by dividing the weight of the living *Anodonta* (g) by the weight of the zebra mussels (g) attached. In snorkel surveys (2000, 2001, 2003) the length of the *Anodonta* shell, the biomass of zebra mussel fouling and estimated age of *Anodonta* were measured on board the research vessel. Shells were aged by examining growth rings from the inside of the shell. The condition of the inside of the shell in snorkel samples was recorded as dull, pearly or dull and pearly in surveys from 2000 to 2003.

Size distribution and biomass results were compared statistically using t-tests, ANOVA and post-hoc Tukey HSD test ($p<0.05$) where data were normal and variances were homogenous (Levene statistic, $p>0.05$). When data were not normally distributed and the variances were heterogeneous (Levene statistic, $p<0.05$), Kruskal-Wallis and post-hoc Mann-Whitney test tests ($p<0.05$) were applied.

6.3 RESULTS

6.3.1 Results for *A. anatina* in 1998

Twenty-three living *Anodonta anatina* were removed from the shore west of Church Island on 5 April 1998 in the initial sample that detected zebra mussels in the lake (Minchin, unpublished, no size range available for *A. anatina*). No empty shells were recovered. *Anodonta* were either uncolonised or else lightly fouled by *Dreissena*. Seven *Anodonta* had zero fouling, six had one zebra mussel attached, eight had two zebra mussels attached, one had four and another had five *Dreissena* attached. Fig 6.1 shows that the size range of zebra mussels attached varied between 3 and 13mm, representing what is believed to be a 0+ age group only.

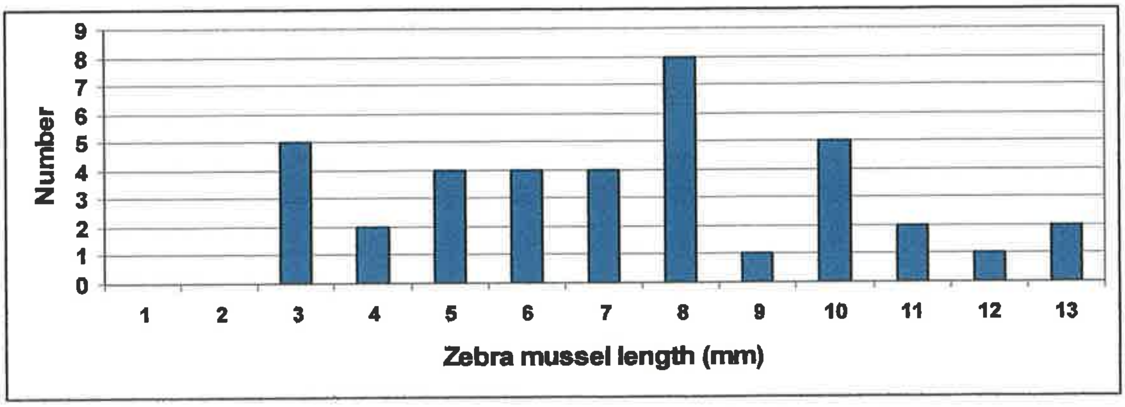


Fig 6.1 Size distribution of zebra mussels/mm on *Anodonta anatina*, April 1998 (Minchin, unpublished)

Anodonta removed in November 1998 included both living shellfish (n = 72) and dead shell (n = 32). Both living and dead were fouled by zebra mussels (live/dead ratio 2.3:1). It was not possible to ascertain whether the latter had died as a result of biofouling or whether empty paired shells had become fouled subsequent to death as no note was taken of whether fouling was at the posterior end of shells. There were significant differences in the numbers of zebra mussels fouling live (mean = 78 ± 68) and dead (mean = 176 ± 164) *Anodonta* (Mann-Whitney test test, p = 0.002). The majority of these zebra mussels were of the 0+ age group, with the exception of occasional large zebra mussels as represented in Fig 6.2; the 24mm zebra mussel probably came from the 1996 cohort (2+). The shells of dead *Anodonta* were significantly longer (mean = 9.2 ± 0.99cm) than those of living bivalves (mean = 8.3 ± 0.93cm) (t-test, $p < 0.05$).

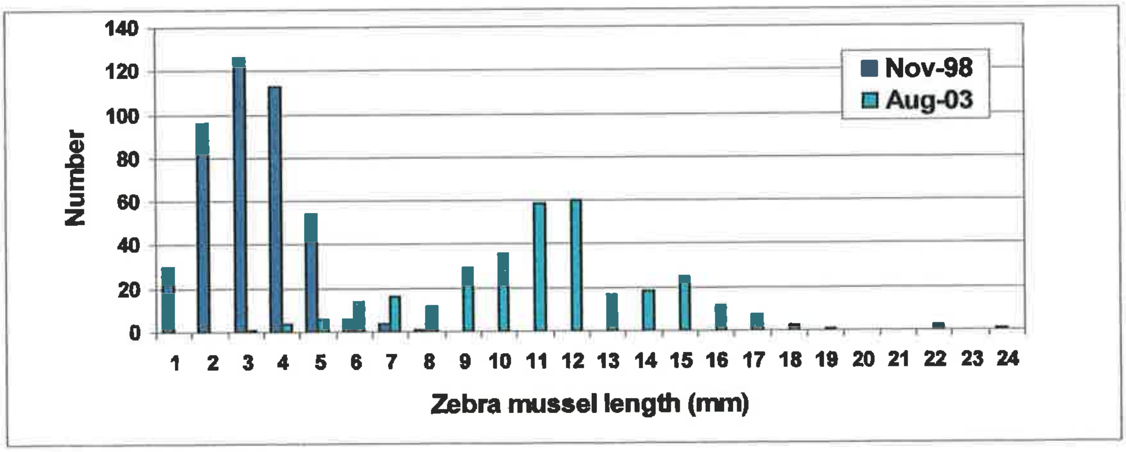


Fig 6.2 Zebra mussel length(mm) on live *Anodonta*, November 1998 and on *Anodonta* shell, August 2003

There was a small significant correlation between unionid length and the numbers of zebra mussels loading on either live shellfish ($r = 0.257$, $p = 0.03$) or on dead shell ($r = 0.085$, $p = 0.60$). Fig 6.3 shows the variation of zebra mussel numbers, which fouled live *Anodonta anatina* (range 0-314, mean 78). This highlights the lack of small *A.anatina* in samples, as none less than 51mm were collected. Fouling was found on the posterior ends of living *Anodonta*.

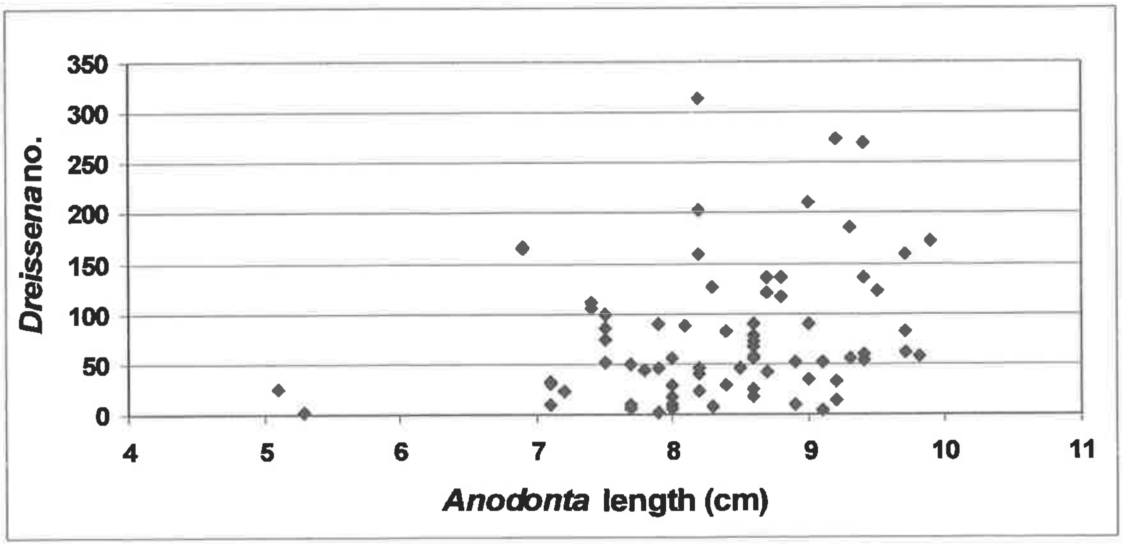


Fig 6.3 Zebra mussel loadings on living *A. anatina*, Lough Key, November 1998

6.3.2 Results for *A. anatina* in 1999

No live *Anodonta anatina* were found at depths > 6m in various dive surveys in 1999. Live samples taken from depths < 3m in July 1999 showed no significant correlation between numbers of zebra mussels on *Anodonta* and length of living *Anodonta* ($r = 0.44$, $p = 0.05$) (Fig 6.4). Loadings on individual *Anodonta* were much higher than in the previous November (number range 81-923, mean 294) (Appendix 9). In a limited sample of 12 dead *Anodonta* shells, the maximum number of attached zebra mussels was 1,066 (Appendix 9). Total numbers of *Anodonta* sampled in July 1999 ($n = 58$) indicated a 3.8:1 live/dead ratio (Lucy and Sullivan, 2001).

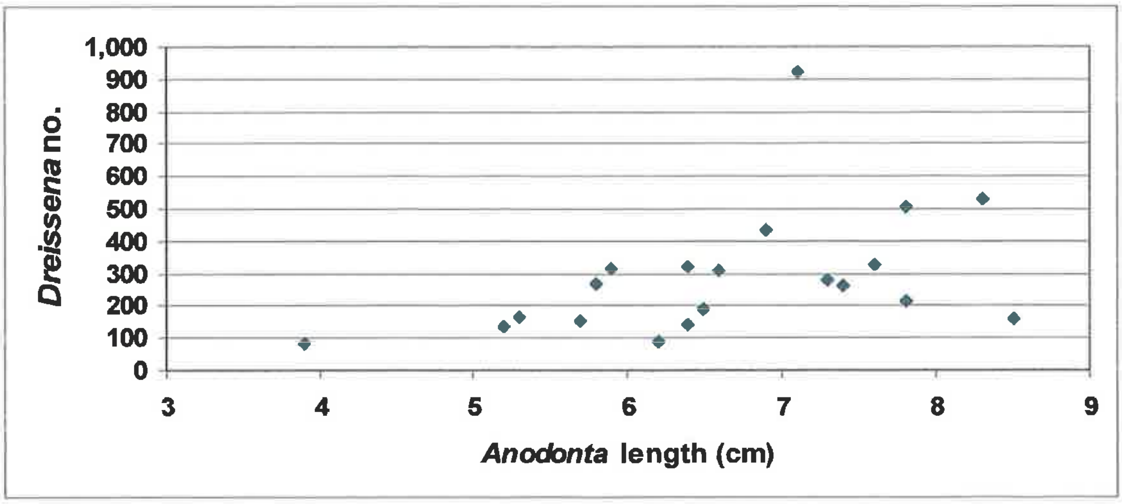


Fig 6.4 Zebra mussel loadings on living *A. anatina*, Lough Key, July 1999

Fig 6.5 shows that these attached zebra mussels were mainly young of the year (< 3mm) or 1+ specimens, although 2+ mussels were also represented (≥ 19mm) in low numbers. It was common in 1999 to find small numbers of 2+ or older (34-36mm) zebra mussels attached to *Anodonta* (Appendix 9).

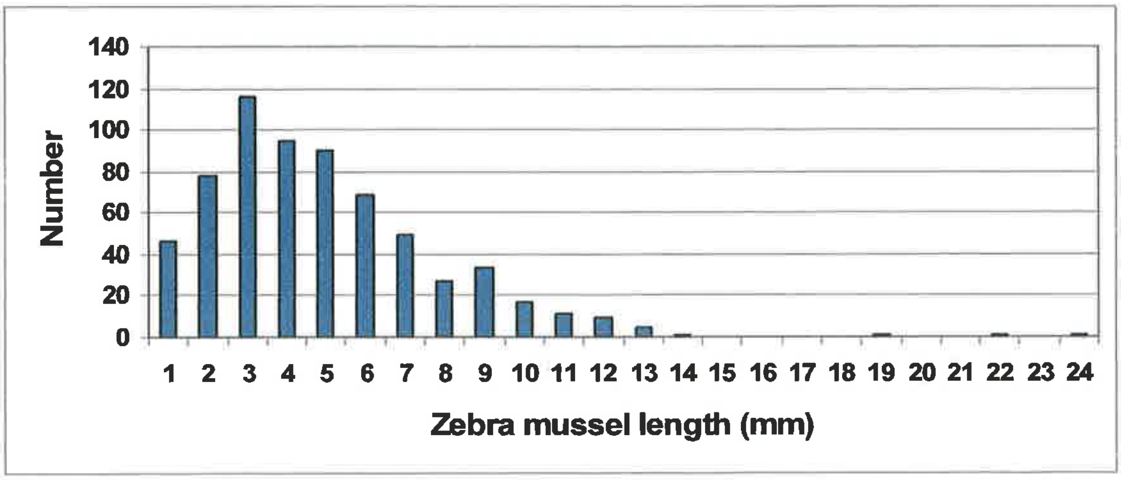


Fig 6.5 Zebra mussel size distribution on one living *A. anatina*, Site 8, July 1999

Appendix 9 outlines that fouling of living *Anodonta* was mainly on the outside of the shell at the posterior end but that sometimes zebra mussels had encroached into the inside of the shell. The smallest living *Anodonta* found was 26mm, with heavy fouling on one half of the shell. Another small *Anodonta* (41mm) was also found with similar fouling. Plate 6.1 shows a small living *Anodonta* with heavy fouling on posterior end.

Plate 6.1 *Anodonta* with zebra mussels attached

Maximum shell length of living *Anodonta* was 8.5 cm. Mean length for living *Anodonta* (6.3 ± 1.2cm) was significantly less than that for dead shell (7.8 ± 1.9cm) (t-test, $p < 0.05$). The length range for dead *Anodonta* shell was 29 to 101mm. Fouling of dead *Anodonta* usually covered the exterior of one half of the shell and often extended outwards from the shell as a druse (Plate 6.2). The other half of the shell was located below the substrate and therefore not exposed for settlement.

Plate 6.2 Fouling of one half of an *Anodonta* shell

No decaying flesh was present within the shell and it was not possible to ascertain whether these shells had been fouled prior to or after the death of the bivalves. Biomass of zebra mussels on dead shell (mean 19.2 ± 10.2g) was significantly higher than that on living *Anodonta* (mean 12.4 ± 6.2g) (t test, $p < 0.05$). The weights of faeces/pseudofaeces and other associated debris on the shell were often in excess of the actual biomass of attached *Dreissena* (mean 11.5 ± 6.1g) (Appendix 9). The proportional loading of zebra mussels on live *Anodonta* ranged from 0.24 to 3.48 (mean, 0.93) of the unionid biomass (Site 8, July 1999).

In November 1999, 36 *Anodonta* were sampled from Site 8, but only 6 were alive giving a live/dead ratio of 1:6. The mean biomass ratio of zebra mussels to living *Anodonta* was 0.45. Thirty dead *Anodonta* were removed, 4 of which had half shells only. The other 26 were still mostly buried in the substrate and fouled at the posterior end. This indicated that they had been fouled as living *Anodonta* and had presumably died during 1999. Zebra mussels were counted on 15 of the dead *Anodonta*, with an average of 745 zebra mussels (range 334 - 1,108) per shell, and a biomass of 31.6 ± 13.3 g per shell.

The maximum age estimates of 24 years made during this research (Site 5, 2001) agreed with those of Ross (1988), who aged *Anodonta* up to 27 years in Lough Key. It was often difficult to identify growth rings when shells became dull inside. Mean lengths of dead shell from Site 8 (2000, 8.4 ± 1cm; 2001, 8.7 ± 1.1cm; 2003, 9.2 ± 8.1cm) were highly significantly longer (t test, p <0.001) than living *Anodonta* collected in 1999 from this site. This suggests that in at least some cases zebra mussel have colonised empty shell of bivalves, which died of old age/natural causes prior to the recorded unionid extirpation.

Site 8 is close to the lake outfall (Appendix 12, aerial photo) where large quantities of shell were filmed entrained in the lock gates. Snorkel and video surveys also noted large amounts of *Anodonta* shell colonised at this site in 2001 (density estimate, 10 shells/m^2).

Several observations were made in terms of shell condition. Shells removed for sampling were nearly always paired because ligaments remained attached in most cases. This was the case, even in 2003 when these *Anodonta* had been dead for at least three years. An effort was made to estimate time of death by examining the nacre on the inside of the shell (dull/pearly) but although more shells were dull from 2001 onwards this proved to be inconclusive. Some shells which had remained tightly closed were found to be pearly or partially pearly inside even in 2003. No shell deformities were noted on any *Anodonta* (living or dead) during the course of these surveys (1998-2003) indicating that mortality was not due to physical damage to unionid shells.

6.3.3 *Anodonta anatina* shell as substrate, 2000-2003

No living *Anodonta* was recovered or viewed during groundtruthing, snorkel, dive, transect or video surveys from 2000 to 2003. One recently dead *Anodonta* was found at Site 2 in August 2000, length 56mm, age estimate of 3 years, shell weight 2g with a weight of 7g attached zebra mussels. This was the only decaying specimen found. Unless an undiscovered refuge exists within the lake, it is considered that the extirpation of *Anodonta* took place between November 1999 (last sample of that year) and August 2000.

From this time onwards *Anodonta* were considered as an abiotic hard substrate, classified as Category 3 in the habitat map. Substrate at the snorkel sites, are outlined in Appendix 7. In most cases *Anodonta* occurred on soft substrate in the midst of stone and rock. Site 8 had the highest proportion of stone and rock (90%) and *Anodonta* shell mainly occurred there wedged between stones. The density of *Anodonta* shells/m^2 and the percentage zebra mussel cover on exposed parts of shell at snorkel sites in 2001 and 2003 are given in Table 6.1.

Table 6.1 Density of *Anodonta* shells/m^2 and percentage zebra mussel cover on exposed parts of shell at snorkel sites in 2001 and 2003

	2001		2003	
	Density/m^2	**% zm cover**	**Density/m^2**	**% zm cover**
Site 1	2 to 3	75	<1	100
Site 2	3	75	3	80
Site 3	2	100	4	100
Site 4	3	100	3	100
Site 5	3	100	4	100
Site 6	7 to 9	90	4 to 5	100
Site 7	6	100	3	100
Site 8	10	100	3	100

By 2003 shells were sinking into the soft substrate at Sites 1-7 but remained upright in the hard substrate at Site 8. This is reflected by a reduction in estimates for number of shells/m^2 at some sites (Sites 1, 6 and 7).

Anodonta shell was frequently recovered during ground-truthing (Appendix 2). The greatest depths at which an *Anodonta* shell was recovered was at 10.6m, south of Hermit Island (Fig 2.2) It is unknown whether this shell had moved passively to this depth or was previously living there. A fouled *Anodonta* shell with recent settlement was sampled from 4.7m depth in an area close to Hog Island. The 2001 video survey (depths < 2m, around lakeshore and island perimeters) gave a range of 0–12 *Anodonta* shells per m^2 with a mean of 2 shells/m^2.

The average biomass and ranges of zebra mussel loadings on *Anodonta* for all sites from 2000 to 2003 are given in Table 6.2. By the year 2000 most *Anodonta* were found lying on their sides, with high loadings of zebra mussels covering the exposed side (outside and often inside) of one half of the shell. Druses often extended from the shell outwards onto the substrate. In 2001 byssal plaques were often noted at the posterior end of the shell side lying in the substrate. This was believed to have resulted from the *Anodonta* moving from a vertical position in life to a horizontal position in death. Zebra mussels attached to the shell half that fell into the substrate would suffocate in soft substrate unless they detached and moved. In either case byssal plaques would remain.

Table 6.2 Zebra mussel loadings (g) on *Anodonta* shells at the eight snorkel sites. Ranges are given in brackets, with mean values shown below (n=30)

Year	2000	2001	2003
Site 1	(5-75) 35	(<1-57) 24	(0-46) 17
Site 2	nd	(<1-67) 24	(1-35) 13
Site 3	(8-66) 35	(13-58) 32	(3-21) 9
Site 4	(7-125) 57	(20-103) 55	(3-38) 18
Site 5	(3-50) 24	(12-49) 28	(5-31) 16
Site 6	(8-56) 28	(6-56) 32	(1-26) 11
Site 7	(3-27) 11	(11-45) 23	(1-22) 8
Site 8	(2-57) 24	(19-55) 39	(25-106) 51
Mean	31	32	18

nd = no data

There was no significant difference in biomass of *Dreissena* on *Anodonta* shell between 2000 and 2001. There was a significant reduction in biomass at Sites 1-7 between 2001 and 2003 (t test, $p < 0.05$), with a significant increase at Site 8, where shells lay on top of hard substrate (t test, $p <0.05$) Reduction in shell loading in Sites 1-7 was usually due to sinkage into the substrate; these shells were coated in byssal plaques and often had loose druses of attached zebra mussels (Plate 6.3).

Plate 6.3 Byssal plaques and zebra mussels on *Anodonta* shell

Positive correlation was found at some sites (Sites 4 and 5) between shell length/mm of *Anodonta* and zebra mussel loading/g in 2000 and 2001 but this was not the case in 2003 (Table 6.3).

Table 6.3 Correlation between shell length/mm of *Anodonta* and zebra mussel loading (g) for the years 2000, 2001 and 2003

Year	2000	2001	2003
Site 1	0.55	0.01	0.16
Site 2	nd	-0.01	nd
Site 3	0.32	0.42	0.47
Site 4	0.7	0.71	0.24
Site 5	0.61	0.61	0.18
Site 6	0.56	0.035	0.31
Site 7	0.53	0.28	0.47
Site 8	0.77	0.25	0.32

nd = no data

Table 6.4 gives results for biomass of zebra mussels on stone (g/m^2) and *Anodonta* (g/shell) in 2001 and 2003. There was no correlation between the biomass on shell and stone in snorkel sites in 2001 ($r = 0.49$, $p = 0.33$). This correlation was however, highly significant in 2003 ($r = 0.96$, $p = 0.0007$).

Table 6.4 Biomass of zebra mussels on stone (g/m^2) and *Anodonta* (g/shell) in 2001 and 2003

Year	2001		2002	
Sites	Stone g/m^2	*Anodonta*/g	Stone g/m^2	*Anodonta*/g
Site 2	4064	24	3280	13
Site 3	6080	32	3232	9
Site 4	5280	55	6352	18
Site 5	4240	28	3872	16
Site 6	4400	32	3216	11
Site 7	4480	23	976	8
Site 8	nd	39	11536	51

The size distributions of zebra mussels on *Anodonta* were not significantly different to those on stones (Mann-Whitney test, $p > 0.05$). Fig 6.6 shows the size distribution on the two substrates at Site 4 in August 2001. The largest zebra mussels found in 2001 on *Anodonta* shells were 20mm.

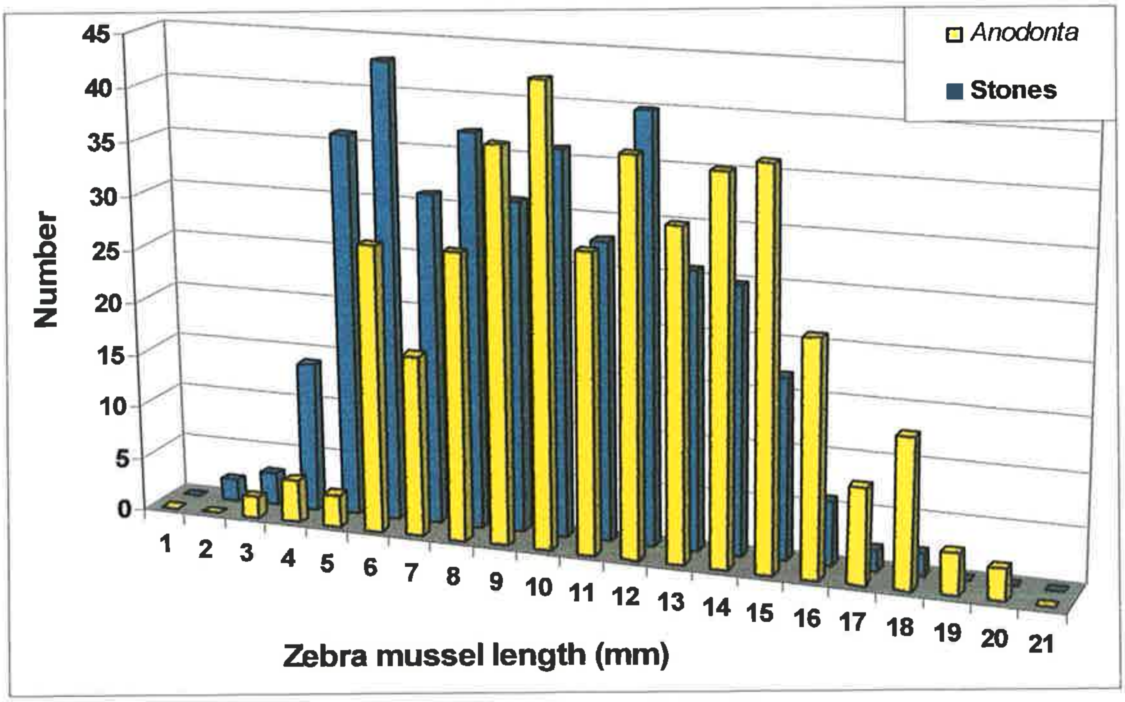


Fig 6.6 Size distributions of zebra mussels on *Anodonta* shells and stones, Site 4, August 2001

Fig 6.2 shows the size distribution of zebra mussels on *Anodonta* shell at Site 8 in 2003. The sample shows possible early settlement (3-4mm) but is mainly comprised of 1+ and 2+ individuals, with the largest being 22mm in length. This contrasts with the sample from the same site taken in July 1999, which had higher numbers of 0+ individuals and was mostly comprised of 1+ zebra mussels (≤ 13mm) with very few 2+ dreissenids.

6.4 Discussion

Unionid populations decline or disappear when lakes are invaded by zebra mussels. In both European and North American lakes infested by zebra mussels, other factors have also had a hand in reduction of unionid numbers, i.e. various types of environmental degradation (Nalepa *et al.*, 1991; Williams *et al.*, 1993) including the effects of eutrophication to which many unionids are sensitive (Arter, 1989). *Anodonta* are known eutrophication to which many unionids are sensitive (Arter, 1989). *Anodonta* are known to be less sensitive than other unionids to the impacts of eutrophication (Arter, 1989). In fact the abundance of *Anodonta* has been noted as higher in lakes with increased trophic status (Agrell, 1948; Okland 1963). *Anodonta* can also withstand a considereable degree of organic pollution (Lucey, 1997) As increased trophic status (mesotrophic/eutrophic) was the only known environmental problem in Lough Key prior to 1998 (Bowman, 2000 reviewed in Chapter 8) the arrival of *Dreissena* is alone culpable for the mass extirpation of *Anodonta* in the lake. The duration from no observed mortality (April 1998) to total extirpation (August 2000) was only 28 months. The live: dead ratio changed dramatically with the postlarval settlements of 1998 and 1999, resulting in extirpation of the species from the lake. If 1996 is considered the year of introduction then zebra mussels exterminated the Lough Key *Anodonta* population in a four year period.

It appears from size distribution data that the first significant settlement of zebra mussels on *Anodonta* in Lough Key took place in summer 1997 (Lucy and Sullivan, 2001). The two large specimens (34 and 36mm) found on a unionid at Site 8 in July 1999 were larger than any other specimens and may represent secondary settlement from boat drop-offs or localised spawning from *Dreissena* attached to boat-hulls in 1996. These occasional large individuals were also noted on stone substrates in jetty areas in 1998.

The exposed posterior ends of *Anodonta* provided a substrate for zebra mussel settlement. It is not possible to definitely assess whether *Anodonta* was a preferential substrate or just an alternative hard substrate to stone. It seems likely that settlement was selective because there was an average settlement of 78 zebra mussels/*Anodonta* in November 1998, with at an estimated *Dreissena* density of only 1,100m^2 (approximately 11% cover) on stone (Ni Chonmhara, 1998). Unfortunately density and biomass methodology for this research was developed subsequent to the demise of *Anodonta* in the lake and hence could not be used. In any case the high settlement rates and subsequent survival of juveniles in 1998 and 1999 determined that densities on the three main substrates (stone, *Anodonta* and aquatic plants) would increase. Loadings rose from a maximum of 5 per *Anodonta* in April 1998 to 78 by November 1998 and averaged 294 by July 1999. By

November of that year numbers on dead shells of a single *Anodonta* were often in excess of 1,000.

From the perspective of the unionid, the mass of the zebra mussels and the ratio of the zebra mussel mass to that of the *Anodonta*, are probably more important than actual numbers (Karatayev *et al.*, 1997) in terms of impairing metabolic activity and locomotion. The average mass proportion of 0.93 dreissenid to *Anodonta* mass in July 1999 could probably be doubled if associated debris was taken into account. At this point, loadings were approaching critical levels as the ratio of live to dead changed from 3.8:1 in July to 1:7.2 in November of that year.

The increase in the mass ratio between July and November 1999 (0.93 to 1.24) may have resulted from three factors. The principal factor was probably the loss of the living tissue in the *Anodonta* resulting in a loss of weight. Secondary factors were the growth of 0+, 1+ and 2+ zebra mussels present in July and also any additional settlement (during the August peak period) and subsequent growth. This critical mass ratio level is below some of the data quoted in European literature in lakes where zebra mussels and unionids co-exist (0.43-1.93 in Mikolajskie Lake, Lewandowski (1976); 1.2 in Lukomskoe Lake, Karatayev and Tishchikov (1983); 1.8 in Drozdy Reservoir and 1.13 in Lake Volchin, Burlakova *et al.*(2000)). In these eastern European waterbodies these bivalves co-exist after the early invasive period and initial peaks in zebra mussel abundance cause a dramatic decline in unionid abundance (Sebesteyen, 1937; Dussart, 1966; Karatayev and Burlakova, 1995b reviewed in Karatayev *et al.*, 1997). In other studies of the relatively recently infested Lake Naroch biomass ratios have changed from 2.8 to 1.1 in a two year period, with 100% colonisation and high mortalities (< 10% alive) in each year (Burlakova *et al.*, 2000). In other waterbodies, biomass ratios have been found at considerably lower levels (0.73 in Lake Lepelskoe, 0.81 in Lake Bolduk and 0.53 in Lake Dolzha, Burlakova *et al.*, 2000). Lewandowski (1976) indicates a direct relationship between non-lethal infestation intensites (< 200/unionid) and substrate densities below about 2,000/m^2. Those densities could relate to lakes with stabilised populations, e.g. the Belorussian waters mentioned above, but in contrast would be considered highly damaging to *Anodonta* in the early invasive stages of the colonisation of Lough Key (November 1998). The evolutionary history of co-occurrence of unionids and *Dreissena* in Europe is suggestive of a semi-parasitic relationship at least in terms of early stage colonisation, although Lewandowski (1976) suggests one of neutrality or commensalism. The notion of zebra mussels as parasites on unionids is somewhat ironic as the glochidial larvae of this family are parasitic on fish species (Ellis, 1978).

It is believed that there are no populations of *Anodonta* left in any of the infested Shannon lakes (Minchin *et al.*, 2002b), although some populations are known to co-exist with *Dreissena* in at least two Irish lakes. In England, increased fouling of bivalves has been noted with the recent spread of *Dreissena* (Aldridge *et al.*, 2004); it will be interesting to see whether this results in extirpation of their four vulnerable unionids (two each of *Unio* and *Anodonta* species) in zebra mussel colonised waters.

The short duration of time taken from colonisation of *Anodonta* to their extirpation in Lough Key compares well with North American studies on greater than 90% decline/extirpation in unionid populations of waterways (Table 6.4).

Table 6.4 A comparison of Lough Key vs North American lakes - decline of unionids

Location	**Approximate years for a 90% *Anodonta* decline**	**Peak *Dreissena* density/m^2**	**Reference**
Lough Key	4 (extirpated)	7,500	Lucy, 2005
L. Erie (western basin)	4	342,000	Schloesser and Nalepa, 1993
L. Erie (Presque Isle Bay)	4	342,000	Maleski and Masteller, 1994
Upper St Lawrence River	<5	4,000-20,000	Ricciardi *et al.*, 1996
Rideau River	4 (extirpated)	383,100	Martel *et al.*, 2001

In North America heavy mortality and extirpation in lakes are often associated with mean infestation in the order of 100 zebra mussels per unionid (Ricciardi *et al.*, 1995).

By July 1999, average density per *Anodonta* was 294 zebra mussels in Lough Key, most of which were <5mm in length. Schloesser *et al.* (1996) showed that mussel densities > 5,000-6,000/m^2 and infestation intensities of >100-200 zebra mussels/unionid results in near total mortality of unionids when heavy zebra mussel recruitment is present – these density factors are more appropriate for Lough Key than Lewandowski's (1976) data mentioned previously. Ricciardi *et al.* (1998) claimed that in North American lakes and rivers which support high densities (>3,000m^2) of zebra mussels, native unionid populations are extirpated within 4-8 years following invasion. The transect survey on Lough Key showed that the average number of zebra mussel/m^2 varied considerably at different depths and on various substrates but that the mean density between 0-3m depth was in excess of 5,000m^2 (Chapter 5) thus supporting both Schloesser *et al.* (1996) and Ricciardi *et al.*(1998) hypotheses.

Biomass ratio data is rarely available for North American studies but when mentioned is noted to exceed 4 or even 8.5 (Hebert *et al.*, 1991; Schloesser and Kovalak, 1991: Nalepa, 1994). In the Rideau River, mass ratios ranged from 0.37 to 1.81 during peak fouling (1995-1997), with two unionid species extirpated by 1997 (Martel *et al.*, 2001). Karatayev *et al.*, 1997 state that overwinter mortality of 0+ and 1+ mussels is typically very high in North America and that it lead to a reduction in biomass ratio during the early infestation of western Lake Erie (Schloesser and Nalepa, 1994). This over-wintering mortality has not been noted in Lough Key, presumably due to the annual ambient temperature regime. Hence the relatively low biomass ratio measured in July 1999 (0.93) lead swiftly to extirpation by the following summer due to extra settlement, continued growth and increased survival of zebra mussels in the interim. Only limited numbers of live *Anodonta* were present for sampling in November 1999 and these appeared to have survived due to the presence of a low mass ratio (0.35 – 0.7) as they somehow managed to evade the heavy settlement in 1998 and 1999. The growth of mussels already present on these surviving unionids, eventually lead to an increase in zebra mussel biomass and to the *Anodonta*'s demise by the following summer.

The presence of juvenile zebra mussels (less than 3mm) in July 1999 indicates that settlement took place from relatively early in the summer (June). This was also noted on stones but was not picked up on the settlement plates as they were not placed in the lake early enough in the season. This reinforces the need to research all available substrates in the course of zebra mussel population studies. In the case of lakes with surviving unionid populations, e.g. Naroch Lakes, variation in successful settlement and recruitment on unionids may explain temporal differences in biomass ratios. As zebra mussels generally have a short life cycle, poor settlement in a single year could significantly reduce the ratio by the following year subsequent to the demise of the 2+ zebra mussel population.

The position of the *Anodonta* shell in the lake dictated the level of zebra mussel attachment from the start of colonisation. In life the partially buried *Anodonta* was fouled only on its exposed posterior end. As expected there was no correlation between the length of the shell and the number of attached zebra mussels (November 1998 and July 1999), since most of the living vertically positioned *Anodonta* was under the substrate with varying amounts exposed for colonisation. In death the *Anodonta* became detached from the substrate, assuming a horizontal position and the biofouling generally spread over the surface of the shell, with dead *Anodonta* having a higher biomass of attached zebra mussels than their living vertical counterparts. The extended biofouling may possibly have involved those zebra mussels at the posterior end, which found themselves lying 'face-down' between the unionid and the substrate when the *Anodonta* keeled over horizontally. The shells were also exposed for settlement of juveniles from 2000 onwards and for secondary settlement of *Dreissena* (Schloesser and Kovalak, 1991; Martel, 1993). In some sites on Lough Key this colonisation of the exposed shell resulted in a positive correlation between length and biomass in the years 2000 and 2001. On soft substrates these shells provided the only substrates for settlement as they had done as living unionids, while in heterogenous substrates they provided an additional substrate in the midst of stone.

By the year 2003 many of the burdened shells were sinking into the soft substrate. One hundred percent zebra mussel cover was recorded underwater by the snorkel survey but shell collection revealed that the exposed area of shell cover had been severely diminished due to sinkage. This was reflected in the significantly reduced biomass on *Anodonta*, in that year and in fewer shells/m^2 recorded at some sites. When hard objects become silted-over or buried they become sub-optimal for zebra mussels (Toczylowski *et al.*, 1999). The only site which recorded an increase was Site 8. This site has a very stoney substrate presumably preventing sinkage of the shells. There was no correlation between shell length and biomass of zebra mussels at any site in 2003. The strong correlation between zebra mussel biomass on stone and *Anodonta* in 2003 reflects the drop in overall biomass at most sites, reflecting poor settlement in 2002 but also takes account of the reduced availability of *Anodonta* shells as substrates. Biomass remained high on stone at Site 8. This may reflect entrainment of larvae or higher food availability, as this site is close to the lake outfall to the River Boyle.

In terms of size distributions there is no indication that zebra mussels survive any longer than 2 years on *Anodonta* shells, with the exception of the two large ones found in July 1999. The occasional large 2+ zebra mussels recorded on *Anodonta* in 1999 represented the founding population on unionids (recorded in April 1998) and these were far outnumbered by the subsequent settlements of 1998 and 1999. These 2+ specimens achieved larger sizes than their contemporaries in subsequent years as noted in other studies (Nalepa, 2001; Gillis and Mackie, 1994) and also on other substrates (stone and plants) in this study (Fig 6.6 and Chapters 5 and 7). This was probably due to diminishing food supply in the lake because of sustained increased populations in the lake (Chapter 8).

In essence heavy *Anodonta* mortality occurred due to increasing biomass of zebra mussels because of high levels of recruitment in 1998 and 1999 and subsequent growth during the exponential phase of the initial dreissenid colonisation of Lough Key. This resulted in the extirpation of *Anodonta anatina* in Lough Key due to one or many of the zebra mussel related factors reviewed in the introduction, with the exception of shell deformity, which did not occur.

It is also possible that reduced levels of phytoplankton in the lake may have exacerbated the filter feeding problems associated with the biofouling of zebra mussels. The extirpation of *Anodonta anatina* in Lough Key is a clear cut example of how an invasive species can impact on native biodiversity. There may well be a case for *Anodonta* joining the pearl mussel (*Margaritifera margaritifera*) on the list of protective species in Ireland (EPA, 2004a). This extirpation impact is also an important reason to include zebra mussels in the alien species risk analysis (EPA, 2004b) for the Water Framework Directive.

Many factors may be involved in determining the critical biomass ratio in Lough Key and other lakes including the physiology, age, health and behaviour of the unionid species and the dreissenids, water quality, trophic status and food availability in the lake and habitat substrate. For example specific behaviour may favour the co-existence of those unionids as many are adapted to burrowing. By burrowing in silt, unionids can clean incrusted mussels from their shells (Arter, 1989: Nichols and Amberg, 1999; Burlakova *et al*., 2000) but this behaviour is dependant on the substrate available in the habitat with soft substrate facilitating burrowing. *Anodonta* only partially buries itself and in European studies zebra mussels were found more frequently and in higher densities than on *Unio tumidus*, which is normally almost completely buried (Kuchina, 1964; Lewandowski, 1976; Arter, 1989). This inability to cover the posterior end was a disadvantage to the survival of unionids, subsequent to zebra mussel invasion in Lough Key and other infested Irish lakes.

The various environmental constraints mentioned above make it difficult to compare impacts on unionids between lakes in different countries and even between sites within a particular lake. It is possible that in addition to burrowing strategies, there are other reasons why unionids, including *Anodonta anatina* can co-exist long term with *Dreissena* in European waters. Firstly there may be refuges within these waterways where unionids can exist without *Dreissena* (Zanatta *et al.*, 2002); secondly there could be uninfested populations in connecting tributaries, canals or feeder streams. The glochidia could be transported into the waterbody by fish travelling through the catchment. As young unionids are rarely found in limnological research there is little knowledge about the early stages of their life cycle. This makes it very difficult to understand the relationship between unionids and *Dreissena*. It is quite possible that fish may reintroduce *Anodonta* to Lough Key from other parts of the Boyle catchment and that without intensive sampling it could take years to detect whether this has happened. In such a case, the rapid extirpation of *Anodonta anatina* following dreissenid colonisation could actually be reversed by a natural reintroduction to the lake. Mass mortality of unionids is characteristic of periods of rapid population growth, subsequently these populations are not only preserved but can maintain high densities (reviewed in Karatayev *et al.*, 1997). Since *Dreissena* populations have stabilised in Lough Key, it is possible that reintroduction of unionids could result in sustained populations in the lake.

CHAPTER 7

THE ASSOCIATION BETWEEN ZEBRA MUSSELS AND AQUATIC PLANTS

7.1 INTRODUCTION

Hard substrates (stone and unionid bivalves) for zebra mussels have been researched extensively in both North America and Europe (including Stanczykowska, 1964; Lewandowski, 1976; Stanczykowska, 1964; Mackie, 1991; Schloesser and Kovalak, 1991; Hunter and Bailey, 1992; McIssac *et al.*, 1992; Haag *et al.*, 1993; Nalepa, 1993; Tucker *et al.*, 1993; Dorgelo, 1993; Mellina and Rasmussen, 1994; Gillis and Mackie, 1994; Tucker, 1994; Nalepa *et al.*, 1995; Ricciardi *et al.*, 1995; Schloesser *et al.*., 1996; Strayer and Smith, 1996; Strayer *et al.*, 1996; Karatayev *et al.*, 1997; Burlakova, 1998; Ricciardi *et al.*, 1998; Nalepa *et al.*, 1999; Strayer *et al.*, 1999, Lucy and Sullivan, 2001). Far less has been written specifically about the use of aquatic plants as substrates for zebra mussel settlement (Sozka, 1975; Shapkarev and Angelovski, 1978; Lewandowski, 1982, 1983, 1991; Grigorovich and Babko, 1996; Horvath and Lamberti, 1997; Karatayev *et al.*, 1997). Research on patterns of zebra mussel spread *via* recreational boating and fishing vectors may refer indirectly to aquatic plants and many management programmes that aim to prevent the spread of zebra musels to other water bodies have mentioned the importance of clearing infested weed from boats and trailers (Johnson and Padilla, 1996; Johnson et al., 2001; www.sgnis.org)

In 1999 survey work revealed the presence of 0+ and 1+ zebra mussels on aquatic plants in Lough Key. Further research was carried out between 2000 and 2003 to address the role played by various aquatic plants as zebra mussel substrates. The specific aims for this section were to:

- Identify and research the significance of different aquatic plants as zebra mussel substrates. Calculate statistically whether significant differences occurred in the size distribution and/or biomass of zebra mussels utilising specific aquatic plants between 2001 and 2003

- Provide information on seasonal colonisation patterns in terms of primary settlement and secondary movement of adult zebra mussels using a seasonal video survey Discover whether there was any correlation between stem length and zebra mussel loading
- Determine whether any differences occurred between size distributions on plants *vs* stones or *Anodonta*

7.2 MATERIALS AND METHODS

Plants were surveyed by two methods (a) snorkel surveys (Section 2.2.5.3) and (b) by reed bed video survey (Sections 2.2.5.3 and 3.3.1). Where necessary, the position of zebra mussels on plant stems was measured using a tape measure and observations made. Reed-beds were assessed by underwater video around the lake perimeter as part of the initial substrate survey (summer 2001). A seasonal video reed-bed survey was undertaken close to Sites 4 and at Site 8 in July 2001, October 2001, February 2002, October 2002 and May 2003 and at Site 1 in February 2002 and May 2003. Snorkel surveys concentrated on new and old *Phragmites australis* and on *Schoenoplectus lacustris,* since these were recorded as having zebra mussel colonisation in 1999 and were also the most conspicuous plants in reed-beds.

Sampling focused on the outer section of reed beds as there appeared to be a baffle effect in the reed bed, restricting the dispersal and settlement of zebra mussels shorewards. The reeds on the outer 1 metre periphery supported the greatest biomass of zebra mussels (maximum 579g/stem), while at 5 metres inshore from the outer reed bed margin, zebra mussel burden dropped to <1g/stem. This baffle effect was also noted by Lewandowski, 1982b and by Grigorovich and Babko, 1996).

Size distribution and biomass results were compared statistically using t-tests, ANOVA and post-hoc Tukey HSD test ($p<0.05$) where data were normal and variances were homogenous (Levene statistic, $p>0.05$). When data were not normally distributed and the variances were heterogeneous (Levene statistic, $p<0.05$), Kruskal-Wallis and post-hoc Mann-Whitney test tests ($p<0.05$) were applied.

7.3 RESULTS

7.3.1 Distribution of Relevant Aquatic Plants in Lough Key

There were numerous reed beds about the perimeter of the lake and islands, consisting of two dominant plant species, the common reed *Phragmites australis* and the common club rush *Schoenoplectus lacustris. P. australis* has strong woody rigid stems, while *S. lacustris* has typically rounded, smooth, light, pith filled stems. Both species occurred together in mixed reed beds, but also in monospecific stands of their own. *P. australis* was usually found growing from the shoreline to depths of 1.5 m. *S. lacustris* was commonly found in deeper water than *P. australis*, growing at depths from approximately 0.3m-2m. Both these plants are perennials with extensive rhizomes that may be exposed above the substrate. Lateral rhizome spread which occurs in all directions, was recorded in Britain as 3.3 to 6.6 feet (1m-2m) per year (Haslam, 1973). Emergence of new stems occurs in spring (March/April) with foliage persisting until late Autumn (October/November). The soft stems of *S. lacustris* usually die back by the end of the year, but old flaccid stems may persist in sheltered locations after the new season's growth. The dead hollow rigid stems of *P. australis* persist for a second year and are important as oxygen diffuses down them to the rhizome (Preston and Croft, 1997). Reed beds containing *P australis* are therefore comprised of both new and old stems. *Phragmites australis* was found at Sites 1, 2, 4 and 8 at densities between 25 and 50 plants m^{-2}. *Schoenoplectus lacustris* occurred at Sites 1 – 8 at densities between 15 and 80 plants m^{-2}.

The water horsetail, *Equisetum* fluviatile, also a rhizomatous perennial was found in association with *P. australis* and *S. lacustris* in some Lough Key' reed-beds. Yellow water lily, *Nuphar lutea* and pondweeds (*Potamogeton* spp.) were typically found in the deeper water in the outer fringes of reed beds. Other macrophytes included the submerged unbranched bur-reed, *Sparganium emersum*; Canadian pondweed, *Elodea canadensis*; arrowhead, *Sagittaria sagittifolia*; spiked water-milfoil, *Myriophyllum spicatum* and duck weed, *Lemna trisulca*. The benthic alga blanket-weed, *Cladophora* sp. was also common on substrates in the littoral zone. Charophytes were occasionally present as was the aquatic moss *Fontanalis antipyretica*. Records of plant occurrences at the eight snorkel sites vary according to presence, absence and densities (Appendix 7).

7.3.2 Preliminary Results and Observations – 1999

In 1999 on Lough Key, it was estimated that zebra mussels associated with reed-beds accounted for only 0.03% of the total zebra mussel population in the lake (Lucy and Sullivan, 2001). Results for that year cannot be compared with other years because zebra mussel numbers were estimated on reeds and rushes rather than biomass (2000, 2001 and 2003). Some data relevant to the exponential increase of zebra mussels should however be considered in this thesis. *S. lacustris* removed from Site 4 had a mean number of 1 zebra mussel per stem in August 1999; by November 1999 this had increased to 364 zebra mussels. New *Phragmites* stems had a mean of 3 zebra mussels per plant at Site 1 but old *Phragmites* had 16 per stem. Size distribution data show that these were comprised mainly of 0+ and 1+ individuals (Fig 7.1). The smallest (1-2mm) specimens probably represent early settlement of 1999 0+ cohort; plate data show that settlement was well established by the end of July (Appendix 6). Fig 7.2 shows a similar size distribution on *Equisetum* stems taken at Site 8. At Site 7 the mean density per stem was 51 individuals for old *Phragmites*. This trend of old *Phragmites* stems having greater numbers and hence higher biomass than new stems continued throughout the plant survey period (1999-2003).

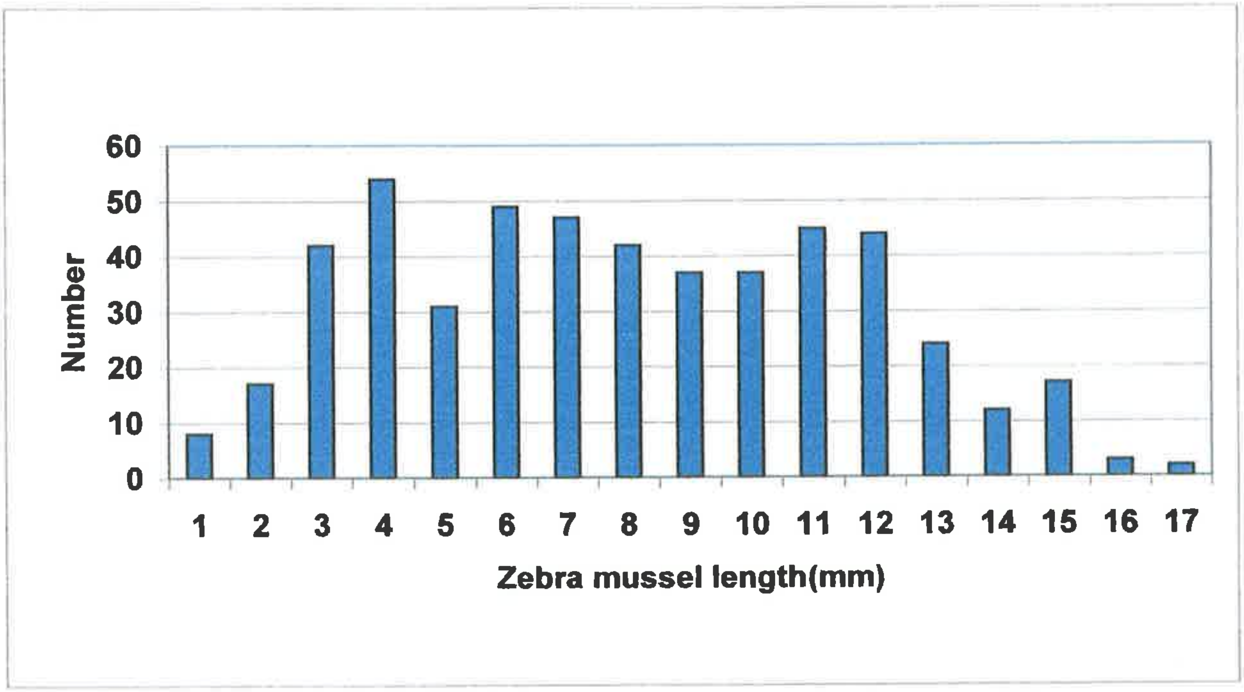


Fig 7.1 Size distribution of zebra mussels on old *Phragmites*, Site 1 August 1999

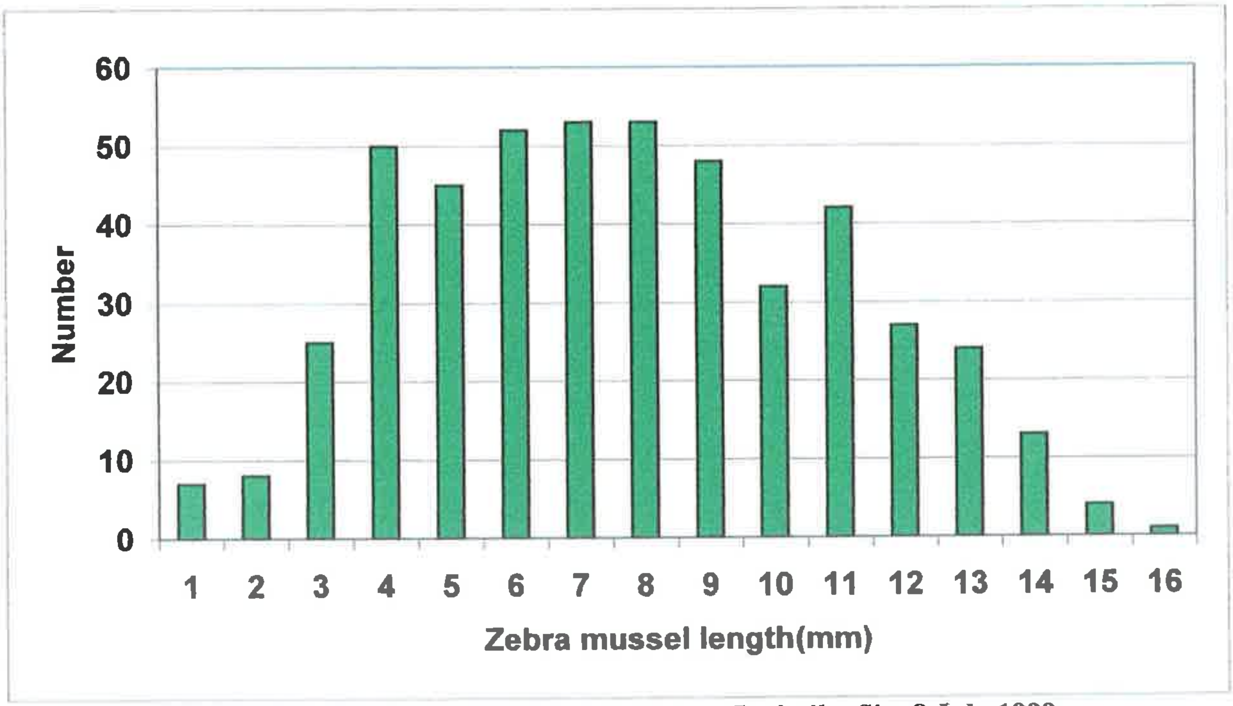


Fig 7.2 Size distribution of zebra mussels on *Equisetum fluviatile*, Site 8 July 1999

Zebra mussels were noted on exposed rhizomes of *P. australis*, *S. lacustris*, *E. fluviatile* and *N. lutea*. They were also observed distributed apparently at random along the submerged stems of new and old *P. australis*. On new *S. lacustris*, zebra mussels were most commonly found on the first underwater emergent leaf of the plant.

Early zebra mussel colonisation on the horsetail *E. fluviatile* was arranged largely in cluster format, with high concentrations around the whorled notches of the stem (generally occurring 2-3cm apart). These notches have toothed bracts that favour zebra mussel attachment. As the clusters increased, the inter-notch area also became colonised. The bulk of the zebra mussels occurred consistently around the notches and up to as much as 76cm from the base, with biomass then tapering towards the surface (Plate 7.1). Other plants were observed with zebra mussel attachment, *Nuphar lutea*, *Sparganium emersum*, *Lemna trisulca* and *Elodea canadensis,* but these were not assessed for number or biomass in 1999.

Plate 7.1 *Dreissena* on *E. fluviatile*

7.3.3 Diversity of Aquatic plants settled by Zebra Mussels in Lough Key

All aquatic species listed in Section 7.3.1 were observed in snorkel surveys (2000, 2001, 2003) with zebra mussels attached. In the case of most plants, the biomass of zebra mussels was ≤2g/plant. The stems of old *P. australis* usually had greater densities than this, with occasional densities in excess of 2g/stem found on new *P. australis*, *S. lacustris* and *E. fluviatile*. The rhizomes of *P. australis*, *N. lutea*, *S. lacustris* and *E. fluviatile* were often 100% covered by zebra mussels. The multi-faceted rhizome of *N. lutea* provided a relatively high surface area for attachment.

Plate 7.2 *N. lutea* rhizome with zebra mussels attached (Photo, D. Minchin)

Cladophora was observed to attach to zebra mussels previously settled on hard substrate. No biomass was taken, as it was not possible to separate different 'plants'.

Plate 7.3 Zebra mussels attached to *Cladophora* (Photo, D. Minchin)

7.3.4 Reed-bed Video Survey Work (2001-2003)

Appendix 3 indicates the widespread presence of the various aquatic plants listed in 7.3.1 around the shallow areas of the lake (< 2m) as mapped by video survey during the substrate survey (Chapter 3). It also includes analysis of the seasonal reed- bed surveys.

7.3.5 Zebra mussels on *Phragmites australis*

7.3.5.1 Old *Phragmites australis*

Table 7.1 shows the cumulative biomass of zebra mussels on ten old *P. australis* stems at Sites 1, 4 and 7 in 2000, 2001 and 2003. The maximum biomass on an individual stem was 579g (Site 1, 2001). There was no significant difference between overall biomass (combined sites) in 2000 and 2001 (t-test, $p > 0.05$) but decrease was significant in 2003 (t-test, $p>0.05$).

Table 7.1 Biomass of zebra mussels (g) on ten old *P. australis* at Sites 1, 4 and 7, 2001 and 2003

Year	Site 1 zebra mussels(g)	SD	Site 4 zebra mussels(g)	SD	Site 7 zebra mussels(g)	SD
2000	278	170	97	38	51	26
2001	351	135	94	77	64	34
2003	5	5	2	3	3	2

Increase in biomass may relate to the size of zebra mussels present on the stems (Fig 7.3, Table 7.2) in 2001. There was a significantly higher mean size in 2001 (Mann-Whitney test tests, $p < 0.05$, Site 1).

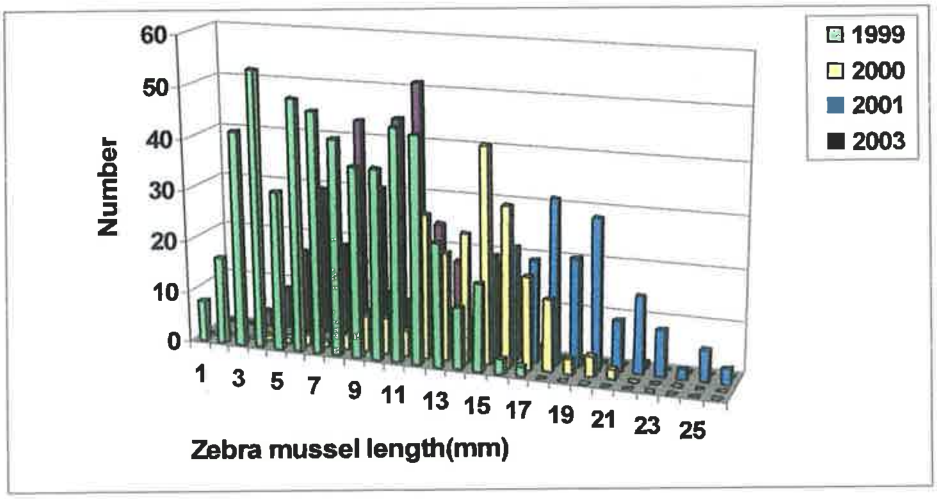


Fig 7.3 Size distribution (mm) of zebra mussels on old *P. australis*, Site 1, August 2000, 2001, 2003

Table 7.2 Summary statistics for Fig 7.3

Year	N	Mean	Std Deviation
1999	511	7.76	3.6
2000	261	11.45	3.31
2001	215	14.24	2.89
2003	323	9.76	3.11

It appears that 1999 stems were colonised by 0+ and 1+ zebra mussels; 2000 stems by 0+, 1+ and some 2+ zebra mussels; 2001 stems by 0+, 1+ and 2+, with a higher proportion of 2+ zebra mussels; 2003 stems had low colonisation of mostly 1+ individuals.

There was a significant decrease in the loading of zebra mussels on old *P. australis* in 2003 from that in 2001 (t-test, $p < 0.05$), particularly noticeable at Site 1, where previous high biomass had resulted in a 'corn on the cob' appearance on stems in 2000 and 2001 (Plates 7.4, 7.5).

Plate 7.4 *P. australis* (transverse sections) clockwise from left; Old *P. australis* stems with zebra mussels attached , new *P. australis* with no attachment and old stem removed from substrate (Photo, Dan Minchin)

Plate 7.5 Old *P. australis* covered with zebra mussels

A separate survey at Site 4, in 2000, found no correlation between length of old *P. australis* stem and the biomass of zebra mussels attached ($r = 0.374$, $p = 0.29$).

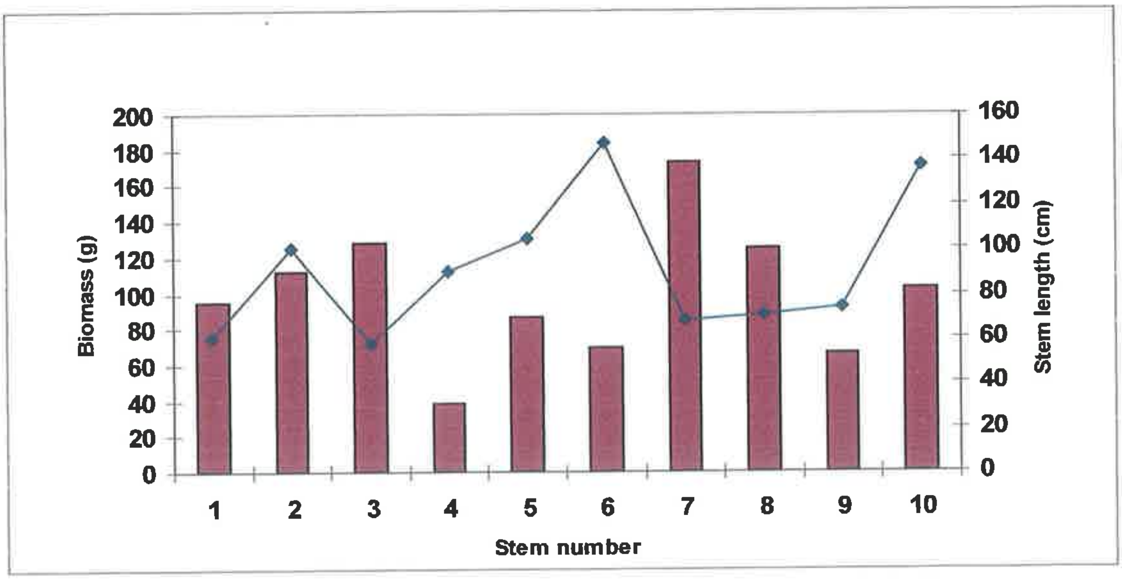


Fig 7.4 Length of old *P. australis* stems *vs* biomass of zebra mussels/g, Site 4 2000

7.3.5.2 New *Phragmites australis*

Biomass of zebra mussels on new *P. australis* in 2000 was not determined but the mean number per stem was 12, with a maximum of 135, compared to in excess of 1,000 zebra mussels on old stems (Site 7). In 2000 the size distribution of *Dreissena* on old *P. australis* (mean = 14.24mm) was found to be significantly different to that on new *P. australis* (mean = 11.12mm) (Mann-Whitney test, $p < 0.001$). In 2001 loadings of zebra mussels on new *P. australis* stems were significantly lower than on old *P. australis* stems (Mann-Whitney test, $p < 0.05$). In summary new *Phragmites* stems had smaller zebra mussels attached and at lower biomass than old *Phragmites* stems. The highest site biomass on new *P. australis* was at Site 7 in 2001 (maximum = 12g), but this had reduced to < 1g in 2003 (Appendix 7). Other Sites had <2g zebra mussels per stem in 2001 and 2003. Zero biomass was commonly recorded on new *P. australis* in both 2001 and 2003 (Appendix 7).

A survey was carried out to determine the position of zebra mussels on old *vs* new stems of *P. australis* (Site 7, 2000). On old stems zebra mussels were found 90cm above the lake bottom, whereas the highest point at which they were recorded on new stems was at 40cm above the substrate (Fig 7.5).

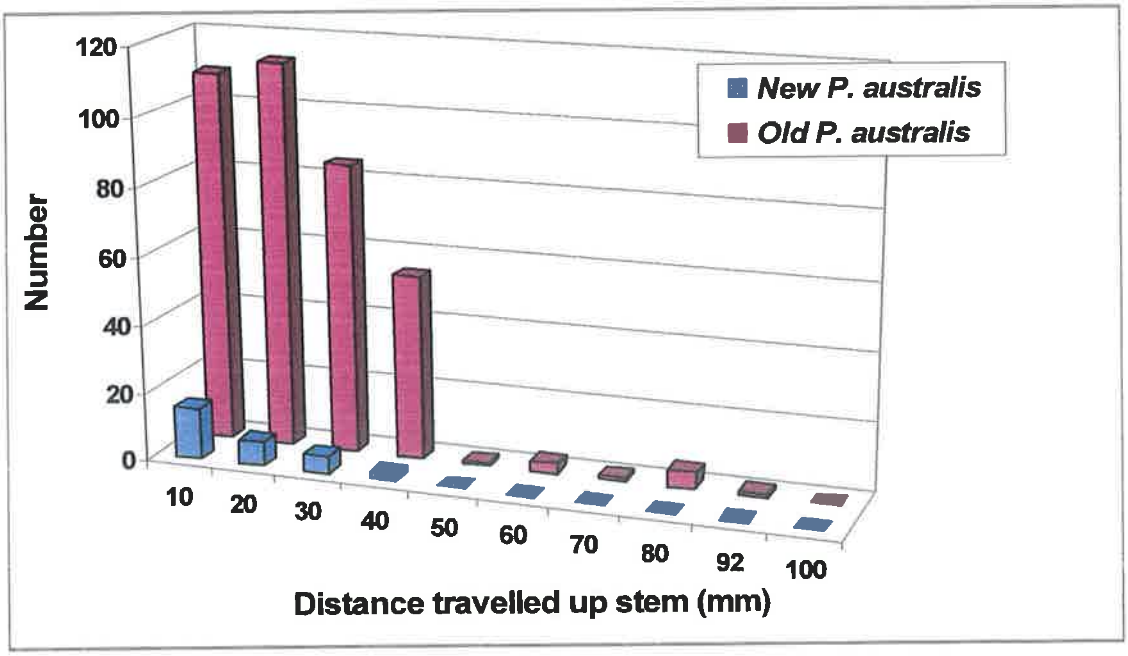


Fig 7.5 Distribution of zebra mussels on stems of old and new *P. australis*

Fig 7.6 shows *Dreissena* size distributions on old and new *Phragmites australis* in August 1999. No *Dreissena* greater than 16mm were found on new *Phragmites* stems and most were <10mm. Zebra mussels up to 19mm were found on old stems of *Phragmites*.

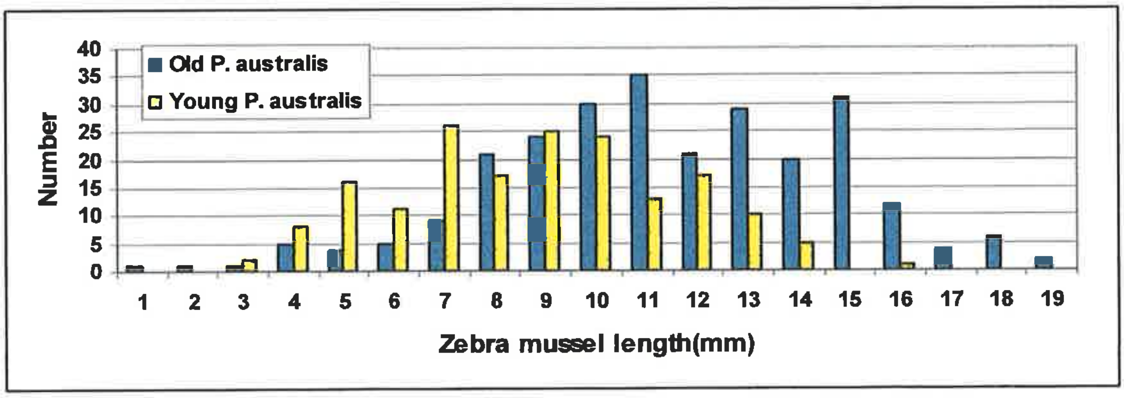


Fig 7.6 *Dreissena* size distributions on old and new *Phragmites australis*, August 1999

7.3.5.3 Zebra mussels on old *P. australis* *vs* other substrates

In 2001 and 2003 a significant difference was found in size distribution between *Dreissena* on old *P. australis* and *Anodonta* and also between *Dreissena* on old *P. australis* and stones (Mann-Whitney test, $p < 0.05$). In 2001 and 2003 the mean size of zebra mussel on old *P. australis* was larger than on the other two substrates (Table 7.4).

Table 7.4 Mean length (mm) of zebra mussels on different substrates, Site 7, 2001 and 2003

Substrate	Old *P. australis*		Stone		*Anodonta*	
Size (mm)	Mean	SD	Mean	SD	Mean	SD
2001	14.1	4.8	9.6	2.7	9.6	2.7
2003	11.9	4.1	10.2	2.6	10.1	2.2

7.3.6 Zebra mussels on *Schoenoplectus lacustris*

Several old stems of *S. lacustris* were examined for zebra mussel colonisation in 2000 at Sites 1, 3 and 7 (Table 7.5). The highest loads were on new stems at Site 3 and on a few old stems from the previous year at Site 1. No data on *Dreissena* biomass is available for these samples, but based on a 1g average per mussel, these loads were higher than those obtained in the 2001 and 2003 surveys (0-<1g/stem). The low colonisation in 2001 and 2003 was corroborated by the results from the video survey.

Table 7.5 *S. lacustris* stems examined in 2000 for presence of zebra mussels

Site	Plants	No. of plants examined	Mean no. zebra mussels per plant (no. range)
Site 1	*S. lacustris*(new)	11	1 (0-5)
	S. lacustris (old)	2	19 (13-25)
Site 3	*S. lacustris*(new)	10	6 (0-35)
Site 7	S. *lacustris* (new)	10	4 (0-8)

In 2001 there was a significant difference in the biomass of zebra mussels on old *P. australis* vs new *S. lacustris* ($p < 0.05$); there was no significant difference however between biomass on new *P. australis* and new *S. lacustris* ($p > 0.05$) (Sites 1, 4 and 7).

7.3.7 Zebra mussels on other aquatic plants

The presence of zebra mussels on other aquatic plants in 2001 and 2003 is recorded in Appendix 7. Biomass was low, with the exception of a *N. lutea* rhizome (52g) at Site 7 in 2001. Other plants showed 0 -<1g / plant. Colonisation on stems and leaves of these plants was by 0+ zebra mussels. Occasional *E. fluviatile* plants were noted with higher levels of colonisation, but were not sampled due to location outside the snorkel sites.

7.4 DISCUSSION

Plants studied included submerged forms, e.g *E. canadensis*, *M. spicatum*, *S. emersum* and *Potamogeton* spp.; floating forms, *N. lutea*, whose stems die back each year; and emergent forms, *S. lacustris*, *E. fluviatile* and *P. australis* whose stems may persist for a year or more after emergence. Zebra mussel size distributions have shown the presence of 0+ individuals on the stems and leaves of submerged and floating forms indicating that these plant parts have been used for primary settlement in the littoral zone by zebra mussel postveligers. This has also been recorded by other scientists (Stanczykowska and

Lewandowski, 1980, 1993; Lewandowski, 1982b; Garton and Johnson, 2000). The eventual fate of these zebra mussels appears, from Irish studies to depend on plant anatomy and the substrate below the plant. Plants with exposed rhizomes may provide a suitable substrate for the zebra mussel once the leaves and stem die back in Autumn. The video survey showed a *Nuphar lutea* plant emerging from a zebra mussel covered rhizome in springtime. This association allowed colonisation of the developing plant by zebra mussels attached to the rhizome. A study carried out on another Shannon lake, Lough Ree, examined zebra mussel size distributions on submerged leaves, stems and rhizomes of *N. lutea* in late August (Lucy, Minchin and Sullivan, unpublished data). Young of the year were found on submerged leaves; this relates to the usage of these surfaces for juvenile settlement and the temporary nature of this substrate due to decay of these leaves at the end of the growing season.

Rhizomes can provide a year round substrate as indicated by broad size distributions of *Dreissena*, including individuals of up to 25 mm (2 to 3 year olds) and this phenomenon was noted in Lough Key seasonal video work. While the stems and leaves were colonised by settling *Dreissena*, the presence of some larger individuals there probably resulted from byssal creep from the rhizomes, nearby stones or *Anodonta* shells. The greatest biomass of zebra mussels was recorded on the rhizoids, with decreasing mass on stems and leaves (Sullivan *et al.*, 2002). Both studies show that *N. lutea* provided a settlement substrate and was also a 'highway' for movement of zebra mussels from the rhizome.
The extensive use of rhizomes of *P. australis*, *S. lacustris*, *E. fluviatile* and *N. lutea* for zebra mussel settlement was noted by video and snorkel surveys at sites with both soft and hard substrate. As well as providing an alternative hard substrate for initial settlement, it also gave the adult mussel the possibility of migrating up the plant stem from the rhizome. The stem may provide a better environment for growth and feeding. Zebra mussels on old *P. australis* stems were significantly larger than those on the lake-bed. They may have had a better chance to filter maximally than those present in druses on hard substrates. It is possible that zebra mussels moved upward on the stem over time as distance travelled up old stems was greater than that traversed on new ones. This may also relate to feeding strategies. The greatest numbers were found between 10 and 50 cm

above the rhizome, which is a similar range (20-50cm) to that found in Lake Dojran, Macedonia (Sapkarev and Angeloski, 1978). No correlation was found between stem length and biomass and this movement from the rhizomes may be one reason why the lower parts of the stem tended to have the greatest biomass. Most of the zebra mussel settlement occurred after the stems' first summer as noted by the significant increase of *Dreissena* biomass on old *vs* new *P. australis* stems.

The size frequency of zebra mussels on a new *E. fluviatile* stem shown at Site 8 was very similar to that on old *P. australis*, clearly showing that 1+ zebra mussels had migrated from the rhizome up the stem of the *E. fluviatile* plant to settle on the nodes. The video surveys also showed that most of the zebra mussels associated with new *P. australis* plants were at the very base of the stem, and hence associated with the rhizome. The videos also showed that in general, settlement on emergent macrophytes was visually noticeable only in areas where zebra mussels were present on the substrate. This could also explain why there was no clear correlation between stem length of old *P. australis* and biomass of zebra mussels due to a complex combination of primary settlement and secondary movement upwards from the rhizome during the course of the stems existence.

Some plants may have provided fewer opportunities for zebra mussels attachment on account of their small lamina area (*Lemna trisulca*) or rapid growth (*Elodea canadensis*). The fate of annual plants with small root stocks is not clear. In the case of growth from soft substrates it is most likely that when the stems died back in autumn the zebra mussels would suffocate and die (Lewandowski, 1982b, Karatayev *et al.*, 1998). In situations where these plants grow over hard substrate, e.g. *S. erectum* and *L. trisulca* at Site 8 near the lake outfall, they may have survived on the substrate after sinking or possibly floated to the surface and were carried downstream in the Boyle River (Appendix 12, aerial photo of Site 8, Clarendon Lock and lake outfall). Drifting macrophytes as a mechanism for zebra mussel spread have been previously reviewed in the literature (Horvath and Lamberti, 1996, Minchin *et al.*, 2002a). *Cladophora,* common at Site 8, becomes buoyant during decay and floats to the surface in late summer; this could easily float downstream. As zebra mussels are already present downstream in this catchment, there was no cause for concern about spread of the species by this mechanism.

S. lacustris stems did not provide as suitable a substrate as *P. australis*; even though it was more common in reed beds and found at greater depths throughout the lake. Initial survey work in 1999 and 2000 showed some usage of stems and underwater leaves but this declined significantly from 2001 onwards. The high overall recruitment of post-larvae in 1999 and 2000 probably contributed to this early settlement. Low subsequent colonisation may relate to the smoothness of the stems, which did not provide a suitable substrate for byssal attachment. Any attached zebra mussels were extremely easy to remove during sample processing, this could also happen due to natural disturbances. The plant also generally dies back after the first autumn and so is limited in terms of providing a long term substrate. The video work revealed that the rhizomes of this plant and of *Equisetum fluviatile* were actually far more important than the stems in terms of providing a constant year-round substrate for zebra mussels.

In terms of biomass it was not surprising that old *P. australis* had the highest biomass relative to other plants during the survey period. This relates to its persistence for at least a year after emergence and to the factors relating to primary and secondary settlement mentioned above. Also, because Irish lakes rarely freeze in winter, survival is high. In contrast the size distribution of zebra mussels on *P. communis* (*australis*) in Lake Dojran, Macedonia had a very low component of 1+ zebra mussels relative to the 0+ population (Sapkarev and Angelovski, 1978). This is probably due to freezing conditions, as the waters of Lake Dojran are known to freeze over in wintertime (S. Trajanovski, 2005, pers. comm.).

The change in biomass and size distribution on old stems between 1999 and 2003 is very informative in terms of the invasion history of the zebra mussel. The first year of significant zebra mussel reproduction in Lough Key is considered to have occurred in 1998. Settlement on stems of old *P. australis* in 1999 showed the presence of 0+ to 1+ individuals (up to 17mm). No 2+ individuals were present, reflecting that no movement of these relatively rare larger zebra mussels (Chapter 5) had occurred from the rhizomes in the samples taken for the study. The distribution in 2000 clearly indicated the presence of some 2+ individuals (20-21mm), which had migrated up the stem either in that year or in 1999. Old stems in 2001 showed the greatest spread of sizes (0-2+ age cohorts), with greater representation of 2+ individuals. The shells of these larger mussels (up to 26mm) were all in the same condition (colour and hardness) and appeared to constitute a single 2+ age cohort. The large biomass and size distributions in 2000 and 2001 indicated the high survival of larvae in 1999 and 2000 to the settlement stage, which was also observed on other substrates.

Size distributions of *Dreissena* in 2003 showed the presence of one single 2+ individual, with all other zebra mussels < 17mm in length; shells were in good condition representing 0+ and 1+ age cohorts. Although size distributions were different, the same year classes were present on stone and *Anodonta,* in contrast to Lewandowski's study (1982b) in Polish lakes, where older zebra mussels (up to 6 years) were present on the lakebed but only 0 – 3 year olds were found on macrophytes. In contrast to that research, *P. australis* stems in Lough Key carried the same age classes as those found on the substrate presenting a more likely scenario in Irish waters where zebra mussels generally only survive to the 2+ stage. These datasets from old *P. australis* strengthen the hypothesis that most zebra mussels only survive for two years in Lough Key.

The biomass and size distribution data from 2001 and 2003 indicate a significant drop in the usage of old *P. australis* as a zebra mussel substrate for settlement and migration in 2002. Settlement rates on settlement plates were significantly lower in 2002 (Chapter 4). A decline in overall settlement may have affected the usage of *P. australis* as a settlement substrate in 2002. The video survey in spring 2003 indicated a drop in usage of stems and rhizomes of different plant species, although there was still 100% cover on stoney substrates. At Site 1 (soft substrate) film footage indicated that old stems lying on the bottom were free from zebra mussels. This site had the highest biomass of zebra mussels on old *P. australis* in both 2000 and 2001, providing an alternative substrate in the absence of stones. The overall data suggests that colonisation of aquatic plants may be a phenomenon associated with the early stages of this species invasion due to high successful levels of recruitment.

Differences in biomass of zebra mussels on old *P. australis* between different sites in the same year could indicate several possibilities.

- Differences occurred between sites in the timing and extent of postlarval settlement in that and the previous summer due to variation in gonadal development and wind patterns. Size differences and biomass of zebra mussels on substrate/rhizomes varied between sites
- Food availability varied between sites
- Position on stem with regard to other zebra mussels might have compromised growth due to crowding within druses and may have increased growth due to positive positioning relative to flow.

These factors indicate the complex environment in which the zebra mussels live; this is probably one reason why many scientists choose to carry out growth experiments under controlled laboratory conditions. Lake fieldwork may not provide definitive answers about association between zebra mussels and aquatic plants but the questions raised are fundamental to studying the ecology of zebra mussels. Although macrophytes are considered to be an insignificant substrate in terms of zebra mussel biomass, they are easy to sample and may be used in long-term monitoring of zebra mussel invasive stages in a lake. They may also be a significant factor in the spread of zebra mussels to other angling lakes in the vicinity due to boat and tackle movement, which may result in colonised weed being moved to other waterbodies (Johnson *et al.*, 2001; Minchin and Lucy, 2003). In fact three lakes within a fifteen km radius of Lough Key have been newly recorded with zebra mussel colonisation since 2002.

This research clearly showed that density of *Dreissena* was lower both on annual plants and on new *Phragmites australis* than on annual plants. Annual plants were colonised by 0+ *Dreissena* whereas the perennial *Phragmites australis* also had larger *Dreissena* (0+, 1+ and 2+) attached to plants.

CHAPTER 8

ZEBRA MUSSELS AND TROPHIC STATUS IN LOUGH KEY

This chapter deals with the ecosystem impacts of zebra mussel populations and lake water in terms of water quality, phytoplankton and trophic status. Filtration of Lough Key by zebra mussels is also assessed. Potential changes in Lough Key' water quality due to the provision of a new phosphate removal system in Boyle Sewage Treatment Plant are also addressed.

SECTION A LAKE WATER QUALITY AND TROPHIC STATUS

8.1.1 INTRODUCTION

One focus of this thesis was to assess the relationship between changes in lake water quality and the zebra mussel population in Lough Key from 1998 to 2003 to assess impacts of the *Dreissena* population on water quality and also examine possible effects of water quality on *Dreissena*. The impacts of zebra mussels on the pelagic measures of water quality used to assess trophic status have been well documented (Stanczykowska *et al.*, 1993; Holland *et al.*, 1994; Johengen *et al.*, 1995; Binelli *et al.*, 1997; Nalepa *et al.*, 1999; Nicholls *et al.*, 1999; Maguire *et al.*, 2003). Zebra mussels have been described as ecosystem engineers altering both ecosystem structure and function including nutrient cycling (Karatayev *et al*, 2002). Lake water quality changes in total phosphorus levels in Lough Key could occur due to the introduction of the zebra mussel. In addition, if phosphorus became a limiting nutrient in the lake, phytoplankton stocks would diminish thus affecting the major food source for zebra mussels. In this way the population could be ultimately self- limiting.

An additional hypothesis, made by the Irish EPA inferred that the implementation, in late 2000, of the new Boyle sewage treatment plant, complete with a phosphate removal system would result in a reduced phosphorus load and subsequently lead to a decrease in total phosphate levels in the lake. This in turn could also result in a decrease in the Lough Key zebra mussel population.

Specific water parameters (transparency, chlorophyll *a,* total phosphorus and orthophosphate) were selected to assess any changes to water quality in terms of trophic status (OECD, 1982). These were either monitored in Lough Key between 1998 and 2003, or collated from other sources for this project (1995 onwards). A review of long term phosphorus data-sets (1995-2003) aimed to determine whether changes first occurred following the arrival of zebra mussels and whether subsequent trends in water quality could have been affected by the implementation of the new treatment plant.

The traditional way of assessing trophic status (OECD, 1982) by using chlorophyll *a* as an indicative parameter is not viable when zebra mussels are removing phytoplankton by filter-feeding from the water column. The chapter aims to explain why using this classification is problematical for Lough Key.

8.1.2 METHODS

Information on laboratory procedures used for analysis was given in Chapter 2. Data-sets for total phosphorus and orthophosphate for Lough Key were obtained from seasonal EPA sampling data-sets. These data-sets were also occasionally consulted for other parameters, e.g. colour and dissolved oxygen. Data for the Boyle River was obtained from the Lough Ree-Lough Derg monitoring programme (Roscommon County Council).

Statistical testing using the package SPSS 11, was carried out to determine whether significant difference occurred between data-sets. Data were found to be non-parametric so Kruskal-Wallis tests ($p < 0.05$) were used to determine significant difference, with Mann-Whitney tests ($p < 0.05$) providing results for differences between specific data-sets. All data-sets were used for statistical analyses whereas only mean values for specific periods were included in figures. It was decided not to use error bars in figures to prevent visual confusion due to overlap.

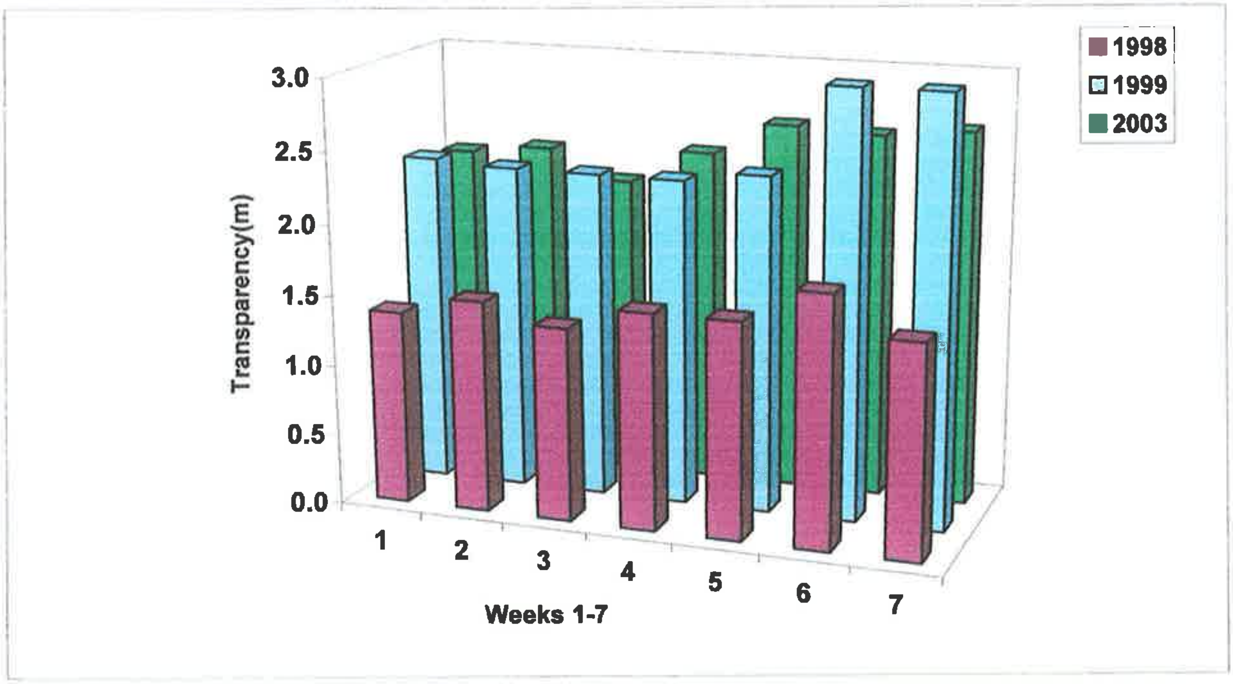
8.1.3 RESULTS

8.1.3.1 Transparency

The zebra mussel population in Lough Key began to increase rapidly in 1998 and a corresponding increased water transparency has been recorded since 1999 (Bowman, 2000; Lucy and Sullivan, 2001). Appendix 10 gives the Lough Key transparency dataset for 2000-2003.

Figs 8.1 shows transparency results from three sites (Sites A, B and C) for seven weeks from mid-July to the end of August in 1998, 1999 and at the end of thesis sampling in 2003. Mean transparency in 1998 was 1.5m, in 1999 it had increased by 1m to 2.5m, a highly significant increase (Mann-Whitney, $p < 0.001$).

Fig 8.1 also shows mean transparency from the same sites in 2000, 2001 and 2003. There was a slight drop in mean readings in 2000 but this was not statistically significant (mean 2.1m). Mean transparency in 2001 was 2.7m, with a maximum value of 3.4m recorded. Mean values were higher in 2001 than in other years (1998-2003). Mean transparency in 2002 was 2m. Water transparency was typically low during the early part of 2003 with levels increasing during June due to drier, calmer weather conditions. There was a highly significant increase in overall transparency in 2003 (Mann-Whitney, $p < 0.001$), transparency increased over the summer season (mean, 2.4m) and results taken in late October averaged 3.8m, the highest recorded between 1998 and 2003. This corresponded with dry weather and low colour in the lake (Appendix 11). Trends in transparency levels for this study are also generally reflected in data collected by the EPA for these years (Appendix 11).



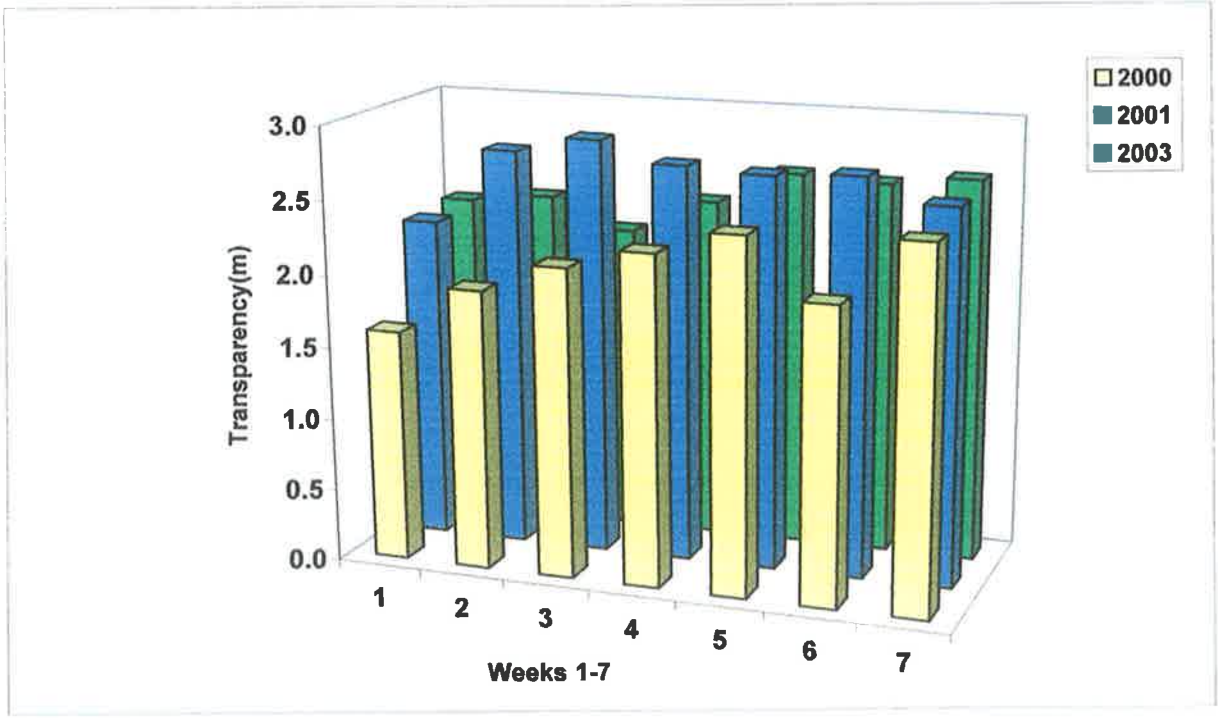


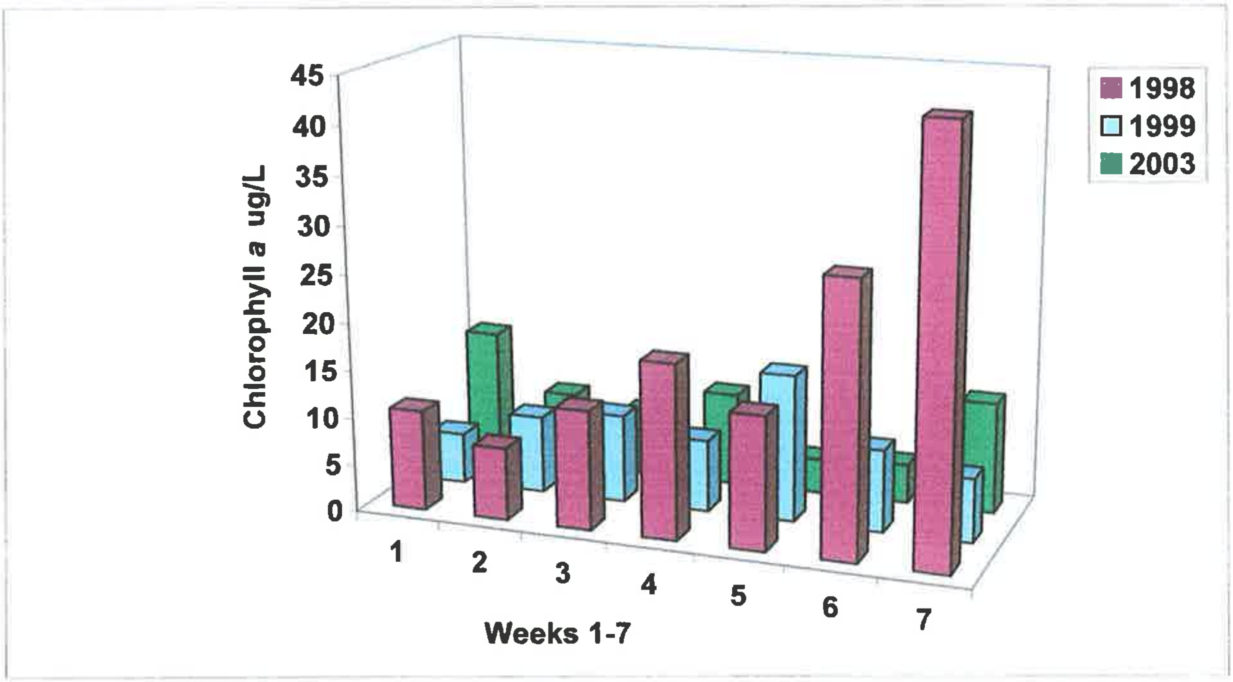
Fig 8.1 Mean transparency levels (m), Lough Key 1998-2003

8.1.3.2 Chlorophyll *a*

The results for chlorophyll *a* are dealt with in chronological order, from 1998 to 2003. Complete chlorophyll *a* results from this survey are shown in Appendix 10, with EPA data from the same years shown in Appendix 11. Peaks in chlorophyll *a* concentrations occurred during annual algal blooms, which typically occurred in late summer. Fig 8.2 shows mean chlorophyll *a* levels from Sites A, B and C during seven weeks (mid July to end of August) from 1998 to 2003. Table 8.1 shows mean values (Sites A-C) and associated standard deviations for chlorophyll *a* levels from July to September (1998-2003).

Table 8.1 Mean chlorophyll *a* levels (1998-2003), Sites A-C, Lough Key

Year	Mean chlorophyll *a*	Standard deviation
1998	19.36	16.69
1999	8.9	4.08
2000	7.72	4.77
2001	7.36	5.99
2002	5.30	2.35
2003	8.06	4.48



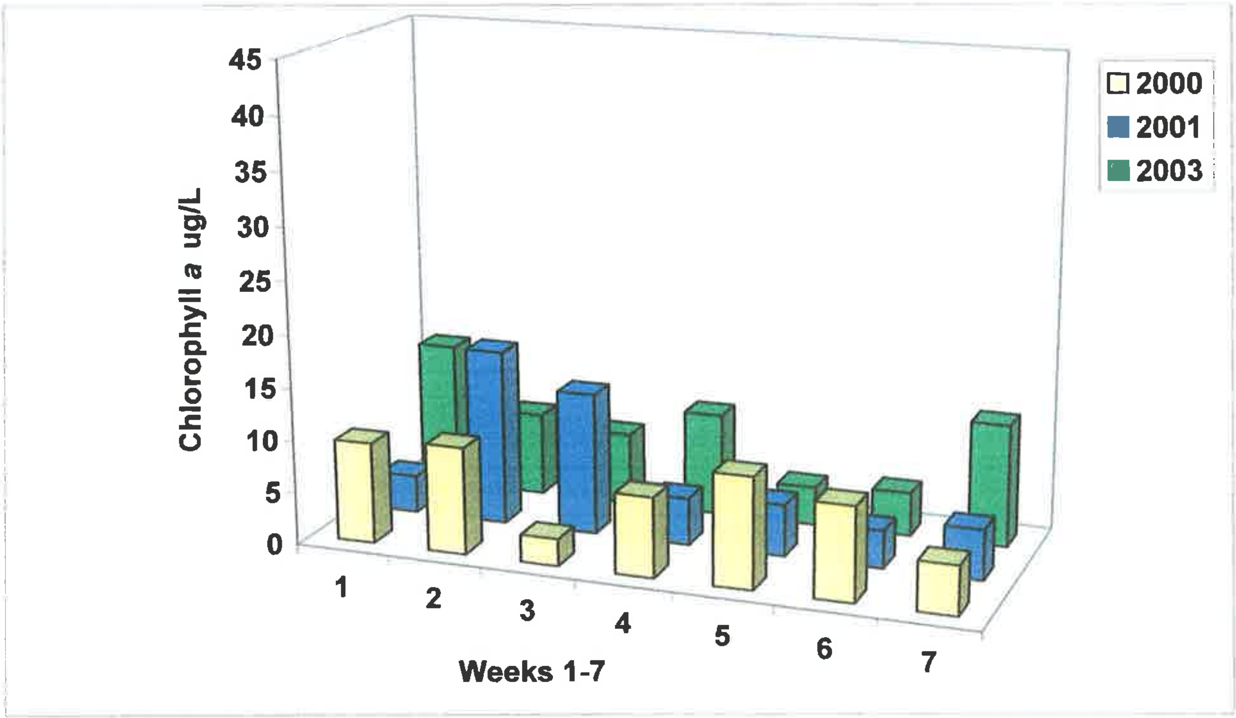


Fig 8.2 Mean chlorophyll *a* levels (µg/L), Lough Key, 1998-2003

1998 and 1999: Chlorophyll *a* levels were significantly lower in 1999 than in 1998 (Mann-Whitney, $p < 0.05$), particularly in the case of weeks 6 and 7, during the presence of an algal bloom (Fig 8.2). A similar bloom event occurred in 1999 on weeks 5 and 6. This bloom appeared to be less concentrated than in the previous year, giving lower chlorophyll *a* levels. On the basis of these maximal data, Lough Key was categorised as being on the threshold of moderately eutrophic status in 1998 (25-35µg/L) in 1998. All data from 1999, with the exception of one sample, fit within mesotrophic levels (8-25µg/L).

2000 and 2001: Fig 8.2 also shows trends in chlorophyll *a* concentrations between 2000 and 2003 (July-September). Most individual values outside the summer period fell within the oligotrophic category (<8µg/L). The 2001 bloom occurred during late July (week 3), a month earlier than the seasonal norm. In general, levels between mid June and late August 2000 and 2001 were mesotrophic (8-25µg/L) (OECD, 1982) with elevated values corresponding with seasonal algal blooms.

2002: Chlorophyll *a* results for the sampling period were low, with a maximum level of 9.73µg/L recorded at Site A on 22/8/02 during a bloom. With the exception of two other similar results (9.24µg/L at site A, Week 1 and 9.63µg/L at Site C, Week 2) all other results during the sampling period were <8µg/L. These results indicate that Lough Key could be classified as almost oligotrophic during 2002 on the basis of traditional OECD classification, although results were not significantly lower than in 2001 (Mann-Whitney, $p > 0.05$).

2003: March/April results for Chlorophyll *a* were low as seasonally anticipated with a maximum level of 7.49µg/L recorded at Site B on April 11. June results were higher than those obtained in 2002, with mesotrophic levels recorded on June 15 at Sites C and D (11.18 and 10.99µg/L respectively). A level of 10.22µg/L was recorded at Site E on June 30. Chlorophyll *a* results for the 2003 sampling period were not significantly higher overall than in 2002 (Mann-Whitney, $p > 0.05$) but reached a maximum level of 22.38µg/L, recorded at Site C on Week 1, during an algal bloom. From 54 samples taken over an eleven week period (31/5/03 – 9/9/03), 31 were <8μg/L. These included all sites during two sampling weeks in mid/late August. As the rest of the sample results fell between 8 and 22.38 μg/L, Lough Key could be trophically classified as mesotrophic in terms of chlorophyll during 2003 (OECD, 1982). Fig 8.3 shows the chlorophyll *a* and transparency levels at Site 1 during 2003, there was no statistical correlation between these parameters ($r = 0.25$, $p = 0.32$).

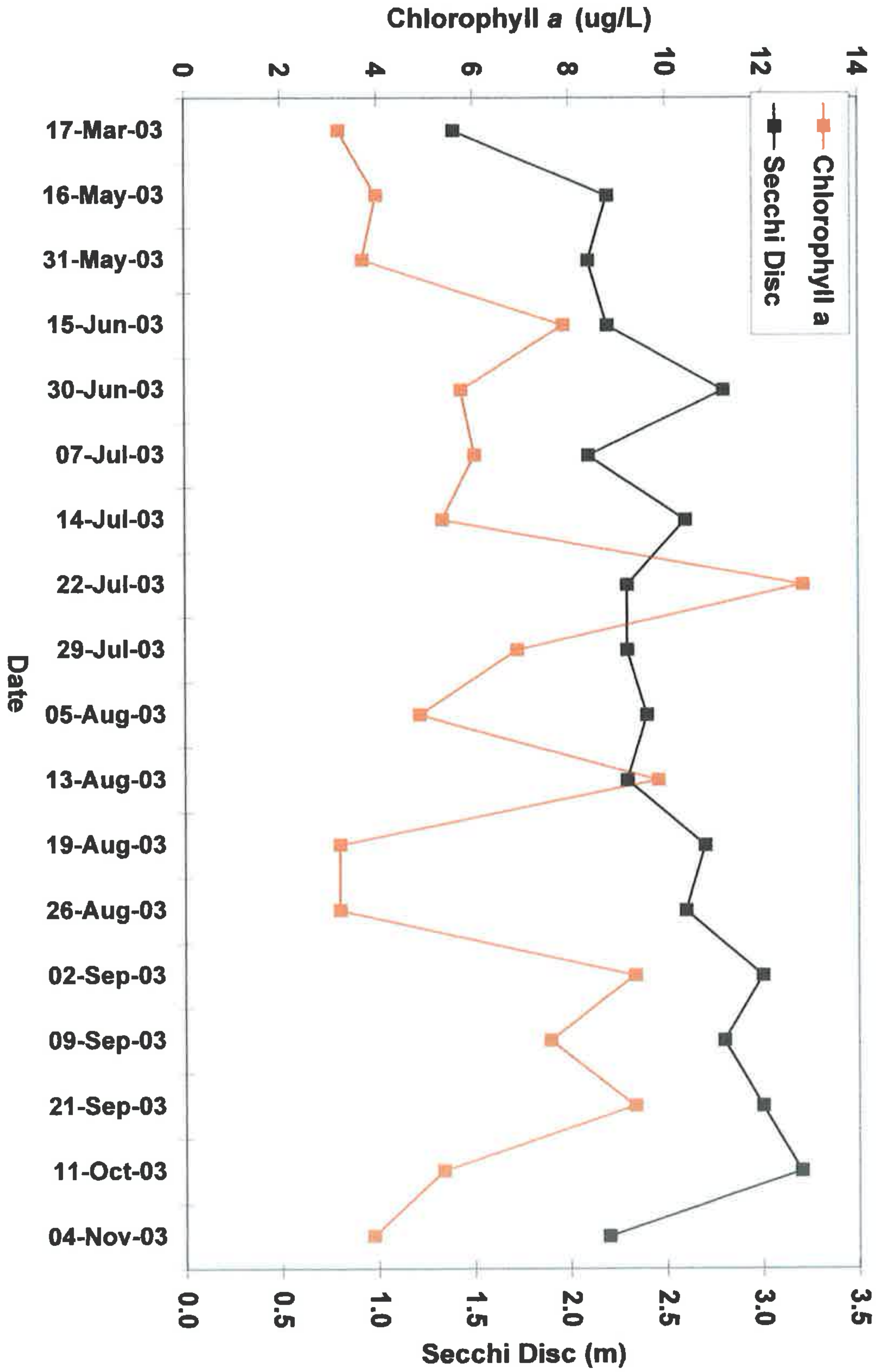


Fig 8.3 Chlorophyll *a* (µg/L) *vs* transparency (m) at Site A, March-November 2003

8.1.3.3 Phosphorus

Appendix 11 gives water quality data for Lough Key (EPA), the Boyle River (RCC/ Lough Ree-Lough Derg project data) and also shows effluent flow/m^3, total phosphorus (total P)concentration/mg/L and phosphate loadings/kg/year from Boyle sewage treatment plant in 2001, 2002 and 2003. These years were chosen as they followed commissioning of the new sewage treatment plant in spring 2000. Table 8.2 below shows trends in total P/µg/L levels in Lough Key from 1995 to 2003. Outlier results (occasional extremely high values obtained erroneously in analysis) have been removed prior to calculations (Appendix 11). Results show a decreasing trend in mean total phosphorus levels from 1996 onwards, with a highly significant decrease in phosphate between 1996 and 1997 (Mann-Whitney, $p < 0.01$). Although total phosphate levels dropped in the subsequent year, there was no significant difference in total phosphorus levels between 1997 and 1998 when zebra mussel densities were low in the lake (Mann-Whitney, $p > 0.05$). Despite the decrease in mean values there was no significant decrease in total phosphorus levels between 1997 and 2000 (Mann-Whitney, $p > 0.05$). The standard deviation decreased from 1997 onwards (exception, 2001) showing that total P levels were fairly uniform at different depths and between different sites among spring, summer and autumn sampling dates in 1998, 1999, 2000. The increase in levels in 2001, were mainly in the July sample at EPA Site A, the site closest to the lake inflow of the Boyle River. Levels in 2002 and 2003 were well within mesotrophic limits (10-35µg/L, mg/m^3 equivalent). There was a highly significant decrease in total phosphorus levels between 2001 and 2003 (Mann-Whitney, $p < 0.001$).

Table 8.2 Mean total P µg/L and range total P µg/L in Lough Key, 1995-2003

Year	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Mean total P µg/L	48	100	54	43	32	25	55	28	28
Range total P µg/L	24-136	34-350	25-198	28-77	24-44	13-56	20– 141	20– 44	14 – 61
Std deviation	30	76	21	15	6	6	35	7	8

Total phosphorus loadings/kg from Boyle sewage treatment plant for the project years 2001-2003 are outlined in Table 8.3. Weighted mean total phosphate concentrations for Boyle STP treated effluent were 0.82mg/L in 2001, 0.83mg/L in 2002 and 1.22mg/L in 2003. This sewage treatment plant is considered to be the main source of phosphorus in the Lough Key catchment (Jim Bowman, EPA, pers. comm) as agricultural in the catchment is marginal.

Table 8.3 Total phosphate loads (Boyle STP) P g/yr and total phosphate loads Pg/m^2/yr to Lough Key

Year	2001	2002	2003
TP kg/yr	2902	745	1011
TPg /m^2/yr	0.322	0.083	0.112

Fig 8.4 shows Vollenweider's relationship between annual phosphorus loading (g Pm^2/ yr) and ratio of mean depth (Z) to hydraulic residence time (τ_ω) for the 'permissible' and 'excessive' (eutrophic) steady state concentrations of phosphorus (0.01 and 0.02mg P m^3). Lough Key phosphorus loadings for 2001, 2002 and 2003 are represented alongside the 1976 EPA (An Foras Forbartha) estimated phosphorus load for the lake (Toner, 1979).

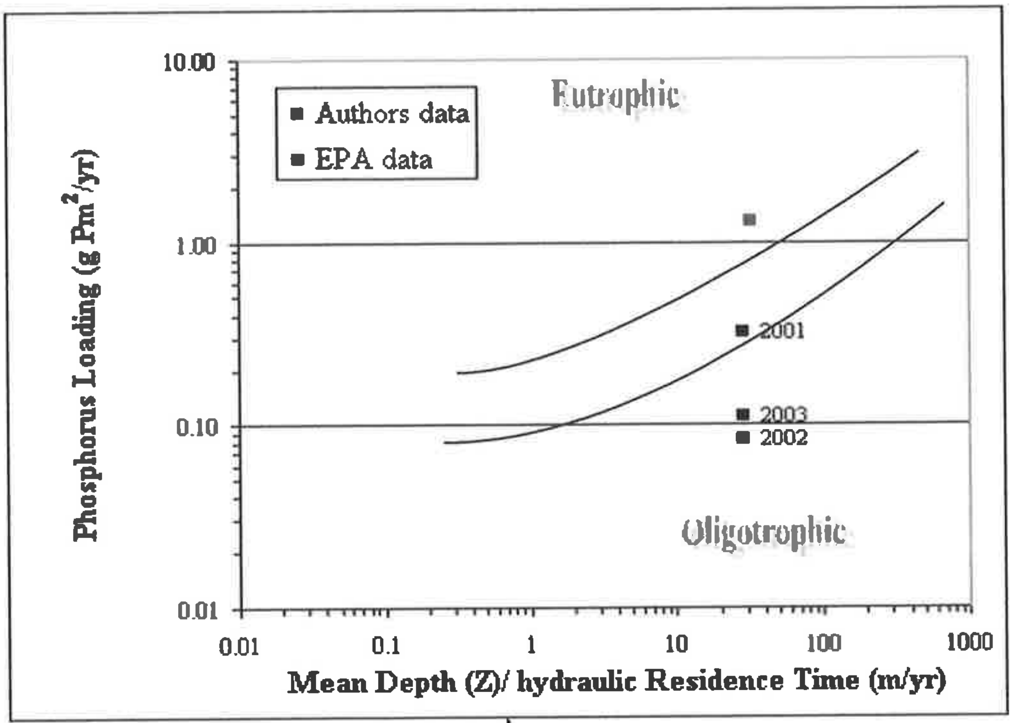


Fig 8.4 Vollenweider's relationship between annual phosphorus loading and ratio of mean depth (Z) to hydraulic residence time for mesotrophic state concentrations

This graph shows that the total P loadings in 2001 are within the mesotrophic range for Lough Key. In that year the EPA results for total P levels within the lake ranged between moderately mesotrophic and strongly eutrophic (OECD, 1982). The EPA 2001 data were significantly higher than results in both 2002 and 2003 (Mann-Whitney, $p < 0.05$). These data-sets are corroborated by the results shown in Fig 8.4 for those years, showing that TP loadings for Lough Key were within the oligotrophic range for those years.

Orthophosphate results for Lough Key are presented in Appendix 11. Lake orthophosphate (PO_4) levels were particularly low in July and September 2003 (<5µg/L), this probably reflects a high nutrient uptake by algae and plants due to an unusually long, warm summer by Irish standards.

Monthly Phosphorus sampling results from Boyle River stations upstream and downstream of the STP were consistently relatively low throughout the duration of the survey. Orthophosphate ranged from 1–26µg/L P upstream (mean = 11µg/L P) and from 2–25 µg/L P (mean = 15µg/L P) downstream. According to the Phosphate Regulations (S.I. 258 of 1998) both mean orthophosphate values fit into the unpolluted category for rivers. Total phosphorus values varied from 16–45µg/L P (mean = 32µg/L P) upstream and from 18–62 µg/L P downstream (mean = 39µg/L P). There were highly significant differences between both the total phosphorus levels and orthophosphate levels upstream and downstream of the sewage treatment plant during the sampling period, with results downstream significantly higher than those upstream of the plant (Mann-Whitney, $p < 0.05$).

8.1.4 DISCUSSION

8.1.4.1 Transparency

Zebra mussels remove a wide range of particulate matter from the water column when filter feeding and a corresponding increased water transparency related to the arrival of this invasive species has been recorded since 1999. By removing large amounts of suspended matter, populations of zebra mussels have the ability to alter transparency and plankton abundance (Holland, 1993). Although increases in water transparency are associated with decreased chlorophyll *a* levels due to a reduction in phytoplankton they may also reflect the removal of suspended solids, bacteria and other particulate matter by zebra mussels. Lough Key results obtained by Toner (1979) averaged 4.5m in August 1976, in excess of any values obtained in subsequent years' monitoring. Although phytoplankton levels were kept in check by the zebra mussel population from 1998 onwards, the previous high levels of transparency obtained in 1976 have not been repeated. In 1976 chlorophyll *a* levels were in the oligotrophic category, and relatively low nutrient levels were present in the lake. The difference in transparency levels may be a reflection of the deterioration in water quality in Lough Key from that time onwards. The marked increase in the total phosphorus and chlorophyll *a* levels in the lake between 1976 and 1997 was noted by Bowman, 1998. It may also relate to an increase in the release of humic acids due to ground disturbance in the catchment, notably the development of a new section of the main Sligo-Dublin road (N4) in the late 1990's.

A further section of the discussion will highlight that the 2003 high transparency values were not due to an increase in the zebra mussel population. Neither was it matched with decreasing chlorophyll *a* levels as in some cases, e.g. at the beginning of September as the increase in transparency was mirrored by a similar rise in chlorophyll *a* levels (Fig 8.3). Instead other environmental factors may be involved in these results, most notably the low rainfall and extremely calm conditions. Fig 1.3 shows the location of peatland in the catchment. Peaty soil is also common in the land surrounding Lough Key. The release of humic acid into lakes typically results in low water transparency due to its yellowish-brown colour (EPA, 2001). The high transparency and low colour readings (EPA data) in autumn 2003 were taken after a period of prolonged dry weather when there would have been little or no impact from peatland drainage. In fact 1976 was also a very dry summer and may have been partly responsible for the high Secchi disc reading obtained by Toner (1979). It is likely that the relatively low reduction in transparency relative to the drop in chlorophyll *a* levels, subsequent to zebra mussel invasion is due to high natural colour in the waters of Lough Key. In contrast, transparency in Lough Arrow, a largely spring fed lake 2km north-west of Lough Key, has increased from <2m to 7m following the introduction of zebra mussels (C. Jennings, NWRFB pers. comm.). The 2003 reduction in transparency in Lough Key is not believed to be a sustained trend as preliminary results from summer 2004 were 3m transparency or less. In other words dramatic changes in transparency levels have likely been prevented by the high Hazen values in Lough Key due to humic acid inputs. These high Hazen levels may explain why there was no correlation between transparency and chlorophyll a levels in 2003.

8.1.4.2 Chlorophyll *a*

Chlorophyll *a* levels reduced significantly from 1998 to 1999 (Mann-Whitney, $p<0.001$). The increase in population of zebra mussels in the lake is the only cause attributable to this change. The data-sets show that this decrease in chlorophyll *a* was maintained in 2000; most of the readings between 2000 and 2002 fall into the oligotrophic range with seasonal increases in late summer due to algal blooms. Somewhat higher levels obtained in summer 2003 are probably due to maximal water temperatures resulting in higher seasonal productivity of algae. The high standard deviations are indicative of seasonal changes during the summer months, with increased levels of chlorophyll *a* occurring during algal blooms.

Low chlorophyll *a* levels obtained during 2000-2003 cannot be attributed to limiting nutrients as mean total phosphate levels indicate at least mesotrophic levels. 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, typical of zebra mussel lakes. The zebra mussels stripped phytoplankton and Cyanobacteria from the water column by extensive grazing; these were then deposited as organic detritus (faeces and pseudofaeces) onto the benthos. In many other studies, high densities of mussels with high individual clearance rates (Fanslow *et al.*, 1995; Karatayev *et al.*, 1997; Horgan and Mills, 1997; Kotta *et al.*, 1998) have also 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. The phytoplankton taxa involved and the extent of this filtration in Lough Key will be dealt within Section B and C.

8.1.4.3 Phosphorus

The decline in total phosphorus levels in Lough Key water occurred in tandem with the reduction in chlorophyll *a* levels in 1999. It is believed that in common with many other studies (Stanczykowska and Planter, 1985; Mellina *et al.*, 1994; Johengen *et al.*, 1995; James *et al.*, 1997, 2001; Maguire *et al.*, 2003), the filtering activity of the exponentially increasing zebra mussel population removed total phosphorus both directly from the water column and also from the biomass of plankton consumed. Unlike the chlorophyll *a* levels, however, which were mostly within the oligotrophic range, Lough Key phosphorus levels were consistently mesotrophic in 1999, 2000, 2002 and 2003 according to the OECD classification suggesting a constant input of phosphorus from the catchment area. It is presumed due to the low intensity of agriculture surrounding the lake, that a high percentage of this was entering *via* the Boyle River as suggested by data from 2001. As there are significant differences between upstream and downstream phosphorus levels, the major point source has been indicated as Boyle sewage treatment plant. 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 Vollenweider model by Toner (1979) is useful in showing phosphorus loadings for Lough Key because it incorporates mean depth, flushing rate and lake area specifically for the lake. The model was slightly changed from the original because in this study, a new mean depth (4.5m) had been calculated from the bathymetric survey. The phosphorus removal system was put into operation in 2002. Plotting the 2001-2003 annual loadings from Boyle sewage treatment plant suggested that the phosphorus load in the first year of commissioning (without operating the phosphorus removal) would lead to a mesotrophic status in the lake, while the latter two years (with the phosphorus removal system in operation) were within oligotrophic levels. This should lead to long-term improvement in lake water quality if levels are kept within this margin and if the treatment plant continues to be the only major source of phosphorus input to the lake.

Orthophosphate results for Lough Key as expected were generally at their highest at spring sampling of each year, before uptake from algal/plant growth. The orthophosphate results for summer 2003 were very low (<5µg/L) (Appendix 11). This is probably due to increased uptake by phytoplankton and macrophytes during the extremely warm summer, as indicated by the temperature dataset shown in Fig 4.1.

There is always the possibility that phosphorus deposited from faeces and pseudofaeces 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) and phosphorus release from Irish lake sediments has been shown in laboratory experiments (Lough Ennell; Lennox,1984). Nutrient remineralisation may occur directly via excretion of soluble nutrients (Heath *et al.*, 1995) or indirectly *via* decomposition of zebra mussel faeces and pseudofaeces (Klerks *et al.*, 1996). In one study area (Saginaw Bay, Lake Huron) it was considered however, that resuspended phosphorus would not be in a form readily available for use by phytoplankton (Nalepa *et al*, 1999). Arnott and Vanni (1996) suggested, however, that enhanced soluble nutrient mineralisation by zebra mussels may be detrimental in promoting a shift in phytoplankton dominance to noxious Cyanophytes. In this study however, no increases were noted for either total phosphorus or orthophosphate levels in lake water during the project and these, as already stated, were in decline.

Raikow *et al.* (2004) found that in 61 Michigan lakes there was a positive influence of *Dreissena* invasion on Cyanobacteria in lakes with total phosphorus <25µg/L but not in lakes with levels >25 µg/L. These may not be directly comparable with the lake in this study as most were stratified during the summer. It is interesting to note that Lough Key was on the cusp of this range in 2000 (25µg/L), 2002 (28 µg/L) and 2003 (28µg/L). 1999 and 2001 had mean levels higher than 25µg/L; the chlorophyll *a* levels that year were not however, significantly different to other years apart from 1998, which was significantly higher (Mann-Whitney, $p>0.05$).

Trends in Lough Key' phosphorus results indicate that there are indeed two nutrient drivers in this system. Initial decreases in levels (1999 and 2000) were due to the zebra mussel populations alone, while an increase in 2001 was caused by higher phosphorus loadings from Boyle sewage treatment plant. It is not clear why the loading was higher as the population of Boyle has remained unchanged since the 1980's. It may result from problems associated with the operation of the phosphate removal system in the STP. Subsequent decreases in 2002 and 2003 may relate to improved performance of the sewage treatment plant.

It is considered from the preliminary results collated in this thesis that annual long term monitoring of total phosphorus (loadings and levels) in Lough Key would be required in tandem with zebra mussel population surveys to gain some understanding of trends in phosphorus levels.

8.1.4.4 Trophic Status of Lough Key

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

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

Using the normal OECD classification is not a satisfactory method when zebra mussels are present in a lake. As already noted the chlorophyll *a* levels and total phosphorus are at different trophic levels, whereas the transparency is limited by natural colour in the system. In Ireland, annual maxima are used by the EPA for chlorophyll *a* results. This is mainly due to the limitations of sampling programmes. In Section B of this chapter, the possibility of selective filtration by zebra mussels is discussed – this activity could also impact on trophic evaluation.

The total phosphorus results show that loadings to the lake from Boyle sewage treatment plant were reduced between 2001 and 2003, subsequent to commencing the operation of the new phosphorus removal system from 2002 onwards. There was also a 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 postulates that even without zebra mussels, total phosphorus loadings since 2002 are within acceptable levels for the lake. This dual reduction has not as yet resulted in phosphorus levels becoming limited. This is evident not alone from total phosphorus levels but more evidently from the increase in benthic algae and higher plants in the lake.

One major ecosystem impact has been the increase in the growth of *Cladophora* and benthic macrophytes in response to greater light availability. This response has been studied by in both American and European waters (Reeders and Bij de Vaate, 1990; Skubinna *et al*, 1995; reviewed in Karatayev *et al.*, 1997; Hecky *et al.*, 2004). Although measuring biomass of benthic algae, e.g *Cladophora* and macrophytes was not included in this thesis, fieldwork (snorkelling and camera work) did reveal an increase in growth during the 2000-2001 period. Increases in macrophytes (*Potamogeton* spp.) were noted as an increased sampling impedance during snorkel work. Video footage showed extensive growth of *Cladophora* on the substrate in many parts of the lake. This suggests that total phosphorus levels in the lake are not limiting and that the increase in light penetration due to zebra mussels is favouring the growth of both benthic algae and macrophytes.

Macrophytic biomass estimation techniques have been fine-tuned for the Water Framework Directive (2000/60/EEC). Since the phytoplankton are being stripped from the water column by the zebra mussels, sampling of benthic alga and macrophytes rather than chlorophyll could provide an alternative to assessing trophic status *via* plant productivity in *Dreissena* infested lakes.

If in subsequent years the total phosphorus levels diminish due to the dual action of the treatment plant and the zebra mussels, it is entirely possible that the zebra mussel population could be reduced in size. This was not the case however, during the course of this thesis and such an outcome could only be established by a long term monitoring programme.

SECTION B CYANOBACTERIA AND PHYTOPLANKTON

8.2.1 INTRODUCTION

One of the remarkable aspects of the lake environment is the large number of phytoplankton species present at any one time. In general lakes with a very high nutrient status have relatively low species diversity (Margalef, 1958). Between thirty and forty algal species may be routinely identified in mid summer samples from the water column of a temperate eutrophic lake (Sigee, 2005). The major seasonal changes that occur in phytoplankton biomass begin with a dominant spring expression of diatoms, which strip silica from the water column with extensive removal of phosphate and nitrate. Changes in the silica content of water are likely to follow diatom growth and abundance rather closely because few other freshwater organisms use it quantitatively (Hutchinson, 1975). Diatoms are non-motile plankton, which need water turbulence to stay in suspension. Species richness often increases during the summer period, with blooms dominated by Cyanophytes and/or Dinophyceae (dinoflagellates) occurring in the late summer/Autumn period. Noxious blooms of colonial Cyanobacteria such as *Microcystis*, *Anabaena* and *Aphanizomenon* are well known symptoms of eutrophication caused by excessive phosphorus loading (Smith, 1983). As eutrophication is the principal threat to the water quality of Irish lakes, the phenomenon of Cyanobacterial blooms is a common and widespread summer occurrence in many Irish waters.

Qualitative data-sets are available on seasonal phytoplankton and Cyanobacterial sampling in Lough Key between 1995 and 2003 The dominance of Cyanobacteria was noted in Lough Key in 1976 (Toner, 1979) and in 1995 before the arrival of zebra mussels to the lake (Bowman, 1998), with a strong summer expression also recorded in an earlier 1976 survey (Toner, 1979).

The objective of this section was to examine the Lough Key phytoplankton and Cyanobacterial data-sets to estimate whether any changes in relative abundance or biodiversity had occurred in the years following the zebra mussel invasion

8.2.2 METHODS

Methodology for phytoplankton analysis is included in Section 2.1.3. EPA data-sets were separated into three seasonal tables according to their sampling regime and available data; the first covered March/April (Spring) 1995-2003 (Table 8.4); the second July 1995-2002 (Summer) (Table 8.5); the third October (Autumn) 1995-September 2001 (Table 8.6).

A list of the common taxa of Phytoplankton and Cyanobacteria was compiled for each season with total numbers of taxa tallied. Relative abundance was gauged by the EPA standard method (Bowman 1998 and 2000) and indicated as:

+ + + = Dominant
+ + = Numerous
+ = Present
Blank = Absent

These results look at levels of relative abundance in samples. No total cell counts were available.

8.2.3 RESULTS

Tables 8.4, 8.5 and 8.6 list the common taxa of Cyanobacteria and phytoplankton encountered in qualitative examination of samples. The EPA list for Lough Key includes a total of 13 Cyanobacteria and 39 phytoplankton taxa for all seasons combined. Table 8.7 outlines different numbers of taxa for combined seasonal samples. These are divided into samples pre-1999 (1999, considered the first year with high densities of zebra mussels in the lake) and those from 1999-2003.

Table 8.4 Lough Key Phytoplankton, April/May 1995-2003. A list of the common taxa of planktonic algae and Cyanobacteria encountered in qualita examination of samples from various sampling dates.

Taxa	April 1995	May 1996	April 1997	April 1998	April 1999	March 2000	May 2000	April 2001	March 2002	March 2003
Cyanobacteria										
Anabaena circinalis										
Anabaena flos-aquae							+			
Anabaena scheremetievi	+									
Anabaena spiroides										
Anabaena sp.		+	+							
Aphanizomenon flos-aquae	+	+	+				+			
Aphanocapsa sp.										
Coelosphaerium naegelianum	+	+	+	+		+				
Lyngbya sp.										
Merismopedia sp.										
Microcystis aeruginosa										
Microcystis flos-aquae			+	+		+	++			
Oscillatoria sp.	+	+	+	+			+			
Chlorophyta (Green algae)										
Dictyosphaerium pulchellum										
Eudorina elegans			+		+	+				+
Kirchneriella obesa										
Mougeotia sp.										
Pandorina morum						+				
Pediastrum boryanum	+	+	+		+	++	+			+
Pediastrum duplex	+	+	+	+	+	+	+			
Scenedesmus quadricauda			+							
Sphaerocystis schroeteri			+		+					
Ulothrix spp.							++			+
Volvox sp.										
Chlorophyta (Desmidiaceae)										
Closterium aciculare		+	+	+						
Closterium spp.			+							
Staurastrum chaetoceras										
Staurastrum spp.		+	+	+	+	+	+			
Cosmarium spp										
Cymbella sp						+		+	+	
Bacillariophyceae (Diatoms)										
Asterionella formosa	+++	++		+		+++	++	++	++	++
Campylodiscus noricus var. hib		+		+			+			
Cymatopleura elliptica		+	+	+		++	+	+	+	+
Diatoma elongatum		+	+	++	+			+	+	+
Diatoma sp.	+		+	++	+	++			+	
Fragilaria crotonensis	+		+			+		+	+	+
Fragilaria sp.	+	+				++	+			+
Gyrosigma sp.			+			+	+	+	+	
Melosira granulata		+	+		+	+	+	+		+
Melosira italica		+	+			+	+	+	+	+
Melosira varians	+	++	+	++	+	++		++	++	++
Nitzschia sp.										
Stephanodiscus sp.		+	+					+		
Surirella sp.		+			+	+	+	+		+
Synedra acus	+	+	+	+	++	++		+	+	
Synedra ulna			+			+		+		+
Tabellaria spp.						+			+	
Dinophyceae										
Ceratium hirundinella		+	+	+		+	+	+		
Peridinium sp.							+			
Euglenophyta										
Phacus										+
Chrysophyceae										
Dinobryon spp.			+	+	+	++		+		+
Mallomonas sp									+	
Synura sp.									+	+

Relative abundance indicated thus: +++ = Dominant; ++ = Numerous; + = Present

Decreasing
Constant
Increase/seasonal

Table 8.5 Lough Key Phytoplankton, July 1996-2003. A list of the common taxa of planktonic algae and Cyanobacteria encountered in qualitative examination of samples from various sampling dates.

Taxa	1995	1996	1997	1998	1999	2000	2001	2002
Cyanobacteria								
Anabaena circinalis								
Anabaena flos-aquae	+++	+		+++	++	+	+	
Anabaena scheremetievi	+++		+					
Anabaena spiroides			+++	++		++	+	
Anabaena sp.								
Aphanizomenon flos-aquae	++	++	+++	+++	++	+	+	+
Aphanocapsa sp.		+						
Coelosphaerium naegelianum	+++	+	+	++				
Lyngbya sp.							+	
Merismopedia sp.								
Microcystis aeruginosa	+		+	+++	+			
Microcystis flos-aquae	+	+++			++	+	+	
Oscillatoria sp.	+		+				+	
Chlorophyta (Green algae General)								
Dictyosphaerium pulchellum		+						
Eudorina elegans	+			+		++	+	+
Kirchneriella obesa			+	+				
Mougeotia sp.	+							+
Pandorina morum						+++		
Pediastrum boryanum	+	+	+	+	+	+	+	+
Pediastrum duplex	+	+	+	+	+	++		
Scenedesmus quadricauda								
Sphaerocystis schroeteri	+	+	+	+	+			
Ulothrix spp.						+	+	+
Volvox sp.								+
Chlorophyta (Desmidiaceae)								
Closterium aciculare		+	+	+				
Closterium spp.						+	+	
Staurastrum chaetoceras	+	+	+					
Staurastrum spp.	+	+	+	+	+		+	
Cosmarium spp								
Cymbella sp								
Bacillariophyceae (Diatoms)								
Asterionella formosa	+	+	+	+	++	++	+	++
Campylodiscus noricus var. hib								
Cymatopleura elliptica				+	+	+	+	+
Diatoma elongatum								
Diatoma sp.								
Fragilaria crotonensis	+				+			
Fragilaria sp.	+						+	+
Gyrosigma sp.	+	+					+	+
Melosira granulata	++	+	+	+	+		++	+
Melosira italica		+				+		
Melosira varians				+	+	+	+	+
Nitzschia sp.								
Stephanodiscus sp.				+				+
Surirella sp.								+
Synedra acus								
Synedra ulna								
Tabellaria spp.					+			
Dinophyceae								
Ceratium hirundinella	++	+	++	+++	+	+	+	+
Peridinium sp.		+						
Euglenophyta								
Phacus								
Chrysophyceae								
Dinobryon spp.		+				+	+	+
Mallomonas sp								+
Synura sp.								

Relative abundance indicated thus: +++ = Dominant; ++ = Numerous; + = Present.

Decreasing

Constant

Increase/seasonal

Table 8.6 Lough Key Phytoplankton September/October 1995-2001. A list of the common taxa of planktonic algae and Cyanobacteria encountered in qualitative examination of samples from various sampling dates.

Taxa	Oct 95	Oct 96	Oct 97	Sept 98	Sept 99	Oct 99	Sept 00	Sept 01
Cyanobacteria								
Anabaena circinalis	+		+	+				
Anabaena flos-aquae	++			+	+	++	+	+
Anabaena scheremetievi				+				
Anabaena spiroides				+	+	++	+	+
Anabaena sp.		+						
Aphanizomenon flos-aquae	++	++	+	++	++	++	+++	+++
Aphanocapsa sp.								
Coelosphaerium naegelianum	+++	+++	+++	+		+		
Lyngbya sp.								
Merismopedia sp.	+							
Microcystis aeruginosa	+++	+	+++	++	+	++	++	++
Microcystis flos-aquae	+++	+			+++	+++	+	+
Oscillatoria sp.		+	+				+	+
Chlorophyta (Green algae General)								
Dictyosphaerium pulchellum	+			+				
Eudorina elegans				+	+	+	++	++
Kirchneriella obesa						+		
Mougeotia sp.								
Pandorina morum								
Pediastrum boryanum	+	+	+	+	+	+	+	+
Pediastrum duplex	+	+	+	+	+	+		
Scenedesmus quadricauda								
Sphaerocystis schroeteri			+	+	+	+		
Ulothrix spp.							+	+
Volvox sp.								
Chlorophyta (Desmidiaceae)								
Closterium aciculare	+	+	+++					
Closterium spp.			+	+	+			
Staurastrum chaetoceras	+	+						
Staurastrum spp.	+		+++	+	+	+		
Cosmarium spp						+		
Cymbella sp								
Bacillariophyceae (Diatoms)								
Asterionella formosa	+	+	+		+	++	+	+
Campylodiscus noricus var. hib			+		+			
Cymatopleura elliptica		+		+	+	+	++	+
Diatoma elongatum							+	
Diatoma sp.							+	
Fragilaria crotonensis	+				+	+	+	+
Fragilaria sp.	+						+	
Gyrosigma sp.	+	+	+		+	+		
Melosira granulata	++	+	+	+++	++	+	+++	
Melosira italica		+		+			+	
Melosira varians	+		+		+	+		+
Nitzschia sp.						+		+
Stephanodiscus sp.		+	+	+		+	+	
Surirella sp.					+	+		+
Synedra acus	+					+		+
Synedra ulna						+		
Tabellaria spp.			+					
Dinophyceae								
Ceratium hirundinella			+	+	+	+	+	
Peridinium sp.								
Euglenophyta								
Phacus								
Chrysophyceae								
Dinobryon spp.					+	+		
Mallomonas sp								
Synura sp.								

Relative abundance indicated thus: +++ = Dominant; ++ = Numerous; + = Present.

Decreasing — Increase/seasonal

Constant

Table 8.7 Total numbers of taxa sampled/season for Cyanobacteria and other phytoplankton in Lough Key (1995-2003)

	Cyanobacteria			**OtherPhytoplankton**		
	Pre 1999	**1999-2003**	**Total**	**Pre 1999**	**1999-2003**	**Total**
Spring	6	5	**7**	25	30	**33**
Summer	9	7	**10**	20	23	**29**
Autumn	11	7	**11**	22	27	**31**

Numbers of cyanobacterial taxa decreased in each season since 1999, whereas phytoplankton diversity has increased slightly. There was often similarities but some difference occurred in taxa present prior to and after zebra mussel invasion, this is reflected in the total numbers given. As each date reflects a single preserved sample, some caution must be applied to the interpretation of these results.

Tables 8.4 to 8.6 outline some of the taxa listed, which appear to have increased in occurrence (tan), remained the same (blue) and those, which decreased in samples taken (yellow). These will be dealt with seasonally, to take into account different natural patterns of succession. Cyanobacteria, particularly *Aphanizomenon flos-aquae*, *Coelosphaerium naegelianum* and *Oscillatoria* sp. show reduced occurrence from Spring 1999 onwards. There appeared to be no changes in Chlorophyta, apart from *Closterium aciculare*, which was not found in spring samples after 1998. The Bacillariophyceae (diatoms) exhibited a steady, seasonally natural dominance in the Spring plankton from 1995-2003.

Cyanobacterial occurrence in July samples also showed a reduction from dominant/numerous to numerous/present in the case of *Anaebena flos-aquae* and *Aphanizomenon flos-aquae*. *Coelosphaerium naegelianum* was not found in July samples following 1998. In the Chlorophyta, *Sphaerocystis schroeteri* was last recorded in 1999 samples; *Staurastrum chaetoceras* was not present in samples after July 1997. It should be noted that other unidentified *Staurastrum* species remained present in samples after 1998.

The diversity of the Bacillariophyceae (diatoms) appeared to have increased since 1998, with the presence of *Cymatopleura elliptica* and *Melosira granulata* in each July sample following that year. *Ceratium hirundella*, which was numerous to dominant in July samples 1995-1998, was reduced to 'present' in samples 1999-2002.

Autumn samples were generally taken during or closely following the annual late summer/Autumn blooms and this is reflected in the plankton samples taken. *Aphanizomenon flos-aquae* while numerous before the invasion, appeared to have increased in dominance from 1999 to 2001. This species formed plankton blooms with the *Microcystis* genera. The latters' combined occurence remained relatively similar between 1995 and 2001. Within the chlorophyta, *Eudorina elegans* was found in samples from 1998, was numerous in September 2000 and 2001 and is commonly associated with algal blooms; *Pediastrum boryanum* remained similarly 'present' from 1995 to 2001. *Closterium aciculare* was not found in samples after October 1997.

8.2.4 DISCUSSION

It must be prefaced that as noted in the methods section, these results look at levels of relative abundance in samples and are not total cell counts. The drop in chlorophyll *a* levels between 1998 and 1999, demonstrate the gross reduction of Cyanobacteria and phytoplankton from the waters of Lough Key. 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*, 1997; Maguire, 2003).

Lough Key is a small lake, which is well mixed except in rare periods of calm weather in summertime, which rarely last more than a week. This mixing brings phytoplankton in repeated contact with zebra mussels, particularly in the shallow areas of the lake where the highest dreissenid densities occur. As noted in the previous section, seasonal increases in chlorophyll levels and decreases in transparency levels occurred during plankton blooms in late summer.

The natural pre-invasion spring dominance of Bacillariophyceae (diatoms) has not been affected by the presence of zebra mussels. Many phytoplankton taxa would have doubling times in the order of less than 2 days. This doubling time may be fast enough to withstand zebra mussel clearance rates depending on favourable environmental conditions, their own densities and zebra mussel population size.

Silica levels were particularly low in July 2003 (Appendix11), this may be due to high uptake by diatom growth. Unfortunately the phytoplankton dataset for July 2003 was not available in time for this thesis to see whether there were any changes in relative concentrations of diatoms. In any case this may not have been apparent due to their consumption by zebra mussels. As the zebra mussel population remained relatively stable during the project period it indicates that although phytoplankton were still being produced as an abundant food supply, they were quickly stripped from the water column by filtering activity as suggested for a western Lake Erie study (Holland *et al.*, 1995).

Zebra mussels are known to filter at high rates from 10^0C upward (Reeders and Bij de Vaate, 1990). Spring water temperatures exceed this level from the start of April onwards (datalogger results, spring 2002, 2003 and 2004) and it is likely that diatom stripping takes place in tandem with the high reproduction rate of these phytoplankton. Similarly in Smith *et al.* (1998) several diatom genera (also present in Lough Key) i.e. *Asterionella*, *Melosira* and *Fragilaria* were shown to be indifferent in terms of relative abundance to the zebra mussel invasion of Hudson River survey, while *Diatoma* had benefited.

In terms of other phytoplankton taxa, the disappearance of *Ceratium hirundinella* and *Closterium* were also recorded by Smith *et al.* (1998).

The apparent increased diversity of phytoplankton species, particularly diatoms, in samples following zebra mussel invasion may relate to improvements in transparency and also to a reduction in overall biomass of Cyanobacteria and phytoplankton in the waters of Lough Key. This is very difficult to interpret for two reasons. Firstly, only qualitative phytoplankton data are available. Secondly, many other environmental factors including patchy distribution of phytoplankton, diurnal migration and weather conditions may effect diversity of phytoplankton obtained in samples.

Cyanophyta such as *Microcystis* have a relatively slow growth rate (Bastviken *et al.*, 1998). This could result in the lower relative abundance of Cyanophyta in spring and summer samples. This assumes at least some grazing pressure from zebra mussels; this consumption of Cyanobacteria by *Dreissena* is a very contentious issue in the literature. The situation in Lough Key is very different to some studies, e.g. in Lake Huron (Vanderploeg *et al.*, 2001) or in Oneida Lake (Horgan and Mills, 1997) because these blooms are not a post-*Dreissena* phenomenon. Late summer Cyanophyte blooms have occurred in Lough Key for many years during periods of calm weather (Toner, 1979; Bowman, 1998; local information). It is likely that many different environmental factors e.g. light intensity, mixing, nutrient ratios, water temperature all promote the development of these blooms. The main constitutents of the blooms in Lough Key since 1998 are *Microcystis aeruginosa*, *Microcystis flos-aquae* and *Aphanizomenon flos-aquae* (Bowman, 1998 and 2000). Between 1995 and 1997, another species *Coelosphaerium naegelianum* was present in Lough Key, but this has not appeared in summer or autumn samples since 1998 and possibly has been filtered out by zebra mussels or is present in very low levels.

The success of *Microcystis* and *Aphanizomenon* results in competitive superiority over other species of Cyanophyta and phytoplankton. This superiority may be affected in some way by the extensive filtration by zebra mussels in Lough Key and this must be considered.

Statistics on the chlorophyll *a* levels during algal blooms indicate an overall decrease in biomass of *Microcystis* and *Aphanizomenon* since the invasion of the zebra mussel. This is in contrast to the selective rejection theory proposed by Vanderploeg *et al.* (2001) but concurs with Dionisio Pires *et al.* (2004) who found that zebra mussels did not discriminate against Cyanobacteria. It is possible that in the well-mixed waters of Lough Key rejected or non-digested plankton trapped in pseudofaeces could be resuspended to return to the pelagial and survive in the long run. This would result in similar chlorophyll levels during blooms to pre-invasion levels, but this has not been the case.

There is however, the potential for development of toxic strains of *Microcystis* should these prove unpalatable to zebra mussels. This has consequent risk factors in terms of public health. The *Microcystis* colonies that often appear during the summer/autumn blooms in Lough Key may or may not contain toxic strains. The lake is used for a range of leisure pursuits. There has however, been no known increase in health issues relating to algal blooms since the arrival of zebra mussels in Lough Key. As such the zebra mussel does not appear to have engineered any increased toxicity in algal blooms since the species arrived in Lough Key.

One major physiological advantage that *Microcystis* has is the possession of gas vacuoles, which may keep them buoyant during quiescent periods and make them less susceptible to zebra mussel grazing. Gas vesicles also allow for vertical migration to greater depths at night-time (Sigee, 2005). During blooms, Cyanobacterial colonies were visible throughout the water column, while using the Secchi disc for transparency measurement.

Large colonial forms may be inaccessible to zebra mussels; in *Microcystis aeruginosa* spherical cells form elongated or clathrate colonies, often >1mm in diameter; *Aphanizomenon* exhibits filament clumping and so both can achieve a total particle size larger than the incurrent siphon of a zebra mussel. A combination of relatively lower consumption rate and a concomitant low replication rate may result in the continuation of algal blooms, albeit at a lower level, following the invasion of zebra mussels.

Long term changes in the occurrence of blooms may also be linked to declining nutrient levels in the lake following the upgrade of the sewage treatment plant in Boyle and the implementation of the phosphorus removal system in 2002. The mean total phosphorus level was 55µg/L in 2001 but lower at 28µg/L in 2002 and 2003.

Evaluating the available datasets emphasises the need for regular monitoring of waters during the spring to autumn period to assess statistically valid means rather than occasional maximum levels of Cyanobacteria and phytoplankton. Determination of bloom species is also important in case toxic *Microcystis* strains begin to dominate. Early identification of these strains would assist the public health management of leisure activities in Lough Key.

SECTION C: FILTRATION OF LAKE WATER BY ZEBRA MUSSELS

8.3.1 INTRODUCTION

The transect survey undertaken in 2002 provided an overall population size and biomass for the zebra mussel population in Lough Key. Combining this data with an estimated filtration rate provided the time estimate required for the zebra mussels in the lake to filter the lake volume. This data is unique to each lake system as it is dependant on population density and lake size. The aim was to use the data to create a more cohesive understanding of the changes in water quality due to the arrival of zebra mussels to Lough Key.

8.3.2 METHODS

The transect survey (Chapter 5) provided the wet biomass of zebra mussels in the lake. Most North American scientisits have calculated filtering rates of *Dreissena polymorpha* ranging from 49-100 ml/g WTM^{-1}(wet tissue mass, shell plus tissue) per hour, similar to European results; averaged results from a number of North American, FSU and European studies produced a mean of 58 ml/g WTM^{-1} per hour (Karatayev *et al.*, 1997).

In this study, a filtering rate of 44.4 ml/g WTM^{-1} h^{-1} was chosen by taking the mean of five independent East European surveys carried out at similar summer temperatures (Kondratiev, 1962; Stanczykowska, 1968; Lvova, 1977; Karatayev and Burlakova, 1993; Karatayev and Burlakova, 1995 all reviewed in Karatayev *et al.*, 1997). 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 the theoretical time taken in days for the *Dreissena* population to filter the entire lake during the summer period.

8.3.3 RESULTS

Filtration Capacity of zebra mussels in lake

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

Filtration rate = 44.4 ml/g zebra mussel/hr

Filtration rate/hr Lough Key = 1.95×10^8 L

Filtration rate/day = 4.7×10^9 L

= 4.7×10^6 m^3

Lake volume = 46×10^6 m^3

Time required to filter Lough Key = 9.8 days

Therefore the zebra mussel population in Lough Key filters a volume of water equivalent to the entire volume of Lough Key approximately every ten days at ambient summer temperatures.

8.3.4 DISCUSSION

From 10^0C upwards zebra mussels have been shown to filter at their peak capacity up to temperatures of at least 20^0c (Reeders and Bij de Vaate, 1990; Fanslow *et al.*, 1995). In Lough Key water temperatures exceed 10^0C for seven months of the year (March-November) of the year as shown by the temperature data. Zebra mussels were observed to be open during all seasonal video surveys.

The filtration rate as calculated assumes maximum filtration rates and may be excessive for periods of lower water temperature. As many of the zebra mussels in the lake are found in dense druses, it is likely that the filtration capacity of many larger zebra mussels (2+) located towards the centre of a druse may be compromised by the surrounding settlement of younger (0-1+) zebra mussels. Laboratory experiments on clearance rates and filtration activity of different size classes of zebra mussels in the literature researched for this thesis have not in general taken into account this 3-D factor of the druse and the location of zebra mussels within. Tuchman *et al.* (2004) however, found ingestion rates of individual mussels located at the surface to exceed those at the bottom of a 6cm thick colony by up to 75%. The filtration rate calculated also only takes into account filtration by zebra mussels >1mm; it is likely that veligers and juvenile zebra mussels also contribute substantially to the overall filtration of Lough Key.

The 10 day lake filtration time calculated for Lough Key is considerably shorter than the overturn rate of 58 days (0.16 year) (Toner, 1979). On this basis alone the Vollenweider model and OECD classification seem too simplistic to assess the trophic status of Lough Key. It is suggested that the calculation provided is as important as knowing the natural lake overturn rate and that this factor could be built into a trophic model for the lake.

The literature is conflicting in terms of whether zebra mussels filter more efficiently when algal concentrations have diminished. Horgan and Mills (1997) found that filtering activity declined as food availability decreased, whereas Sprung and Rose (1988) found maximum filtration rates at low food concentration. As these were laboratory based studies caution should be expressed in terms of extrapolation to a true lake ecosystem.

One study also found filtration efficiency was higher in deeper (>5m) water, rather than in shallower (<2.5m) areas (Kotta *et al.*, 1998).

As the highest biomass of zebra mussels are found on hard substrates near the mainland and island shores of Lough Key, maximum filtration occurs in these areas and not in the open waters of the lake. So can it be determined whether the lake water is well mixed? The EPA data-sets show that there was very little difference in parameter values (e.g. temperature, dissolved oxygen, chlorophyll *a*, total phosphate) at different depths during the calm summer of 2003; EPA stations B, D and E (surface and 6m depths) and at station C (surface and 18m depth) showed very similar results (Appendix 11). Although a slight thermocline has been observed in summer at station C during this study and in other monitoring (Bowman, 2000), this is believed to be a transient phenomenon lasting no more than a week. Results between lake sites were also similar in most of the project and EPA data-sets throughout 2001-2003, indicated that the water in Lough Key was well mixed in both pelagic and profundal layers. In addition the similarity of size distributions between zebra mussels at 0-1m and 12-13m depth indicated that food was available in the aphotic, profundal zone due to adequate mixing of water. The most probable scenario is that water in near shore areas of high zebra mussel density is simultaneously mixed and filtered, except on extremely calm days when it may be filtered to a high degree before it is overturned by wind induced currents to mix with other waters in the lake. Thus it can be considered that the water throughout the lake is well filtered by the *Dreissena* populations present in Lough Key.

CHAPTER 9

CONCLUSIONS

In less than a decade after their arrival in Ireland, zebra mussels have successfully colonised Lough Key. The introduction, most probably in 1996, of this invasive species was followed by a typically fast exponential rise in population size. This research study thoroughly investigated all life stages of *Dreissena* from the initial stages of the invasion to the phase where this species had reached their maximum density. *Dreissena* populations had stabilised in Lough Key by 2001 and research continued to 2003, with no significant change in population biomass. This thesis is the first comprehensive study of zebra mussels in southern Ireland and provides important information on reproduction, distribution and ecological impacts of *Dreissena.*

A variety of different techniques are required for comprehensive limnological studies. The inclusion of hydroacoustic and video surveys in this research provided valuable datasets, which were used as scientific tools for dive and snorkel monitoring work. These technical surveys also provided essential total area datasets for different depth intervals for Lough Key. Substrate analysis and ground-truthing determined that suitable stoney substrate was, with few exceptions, present only in the littoral zone of mainland and islands. Both the bathymetric and substrate maps are available in electronic format and can be used to provide detail on any lake section. As well as providing information for zebra mussel surveys, these maps would also be useful for future linked research on macrophytes, macroinvertebrates or fish in Lough Key.

In early life stages different patterns were observed annually in seasonal larval densities, size distributions and settlement patterns from 1998 to 2003. Although larval density was relatively low in 1998 and 1999, high levels of recruitment in this early stage of colonisation lead to an exponential rise in the adult zebra mussel population. This high recruitment was noted on the three main zebra substrates, stone, *Anodonta anatina* and aquatic plants. The impact of poor recruitment, noted in 2002 was minimised by successful survival of 2001 and 2003 cohorts. Variation in settlement between sites emphasised the need for multiple site monitoring even within a small lake system. Density variations were also observed in adult zebra mussel sampling both at snorkel and transect sites. Size distributions from different substrates throughout the survey period indicated that the majority of zebra mussels in Lough Key die before reaching three years of age.

In 2002 the transect survey determined total density and biomass of zebra mussels at different depth intervals in the lake. These were used to calculate the total number (33×10^9) and biomass (4.4×10^6 kg) of *Dreissena polymorpha* in Lough Key. Snorkel survey results suggested that the biomass of zebra mussels remained similar between 2001 and 2003. This indicated relative stability of population size within the lake but regular survey work would be required to monitor population dynamics over a longer time scale.

The direct ecological impact of zebra mussel invasion in Lough Key was the extirpation of *Anodonta anatina* populations in the lake by summer 2000. This native species, once plentiful in the lake was extirpated with four years of the invasion due to heavy colonisation by *Dreissena*. Aquatic plants, particularly the perennial *Phragmites australis* were noted as substrates for settlement of zebra mussels in the early years of invasion (1999-2001). By 2003 densities on reeds had reduced significantly and this may be linked to a reduction in overall recruitment of zebra mussels in 2002.

Once temperatures exceed 10^0C, the Lough Key zebra mussel population is estimated to be capable of filtering the entire lake volume in 10 days. This has had consequent effects on transparency and chlorophyll *a* levels in Lough Key, increasing the former and decreasing the latter due to filtration of phytoplankton. On this basis the OECD classification, which incorporates chlorophyll *a*, transparency and total phosphorus thresholds, seems too simplistic to assess the trophic status of Lough Key. The filtration calculation should be built into a trophic model for the lake.

In terms of total phosphorus levels it was not possible to separate the two main drivers in the system – Boyle sewage treatment plant and the zebra mussel population in Lough Key. While phosphorus levels in the lake had decreased, this nutrient was within mesotrophic levels and hence not limiting. Zebra mussels had not prevented the occurrence of summer algal blooms. Careful monitoring should be carried out due to public health concerns associated with the presence of *Microcystis aeruginosa* toxic strains.

River basin district (RBD) monitoring programmes for the Water Framework Directive (wfd) need to include zebra mussels as a biological pressure in dreissenid infested waters. Zebra mussels impact on all three elements of water quality noted in the directive (Table 9.1). According to the directive good water quality must be achieved in Irish waters by 2015. This thesis highlights that zebra mussel colonisation changes water quality elements. Changes in these elements will occur within less than five years in newly colonised lakes where water parameters are suitable for zebra mussel colonisation. Assessment of wfd water quality in dreissenid colonised lakes is a difficult task but must be developed due to these changes. Lakes should be monitored to assess whether zebra mussels are present so that invasion impacts can be taken into scientific account.

Table 9.1 Water framework elements changed by zebra mussel colonization of Lough Key

Biological	**Physico/chemical**	**Hydromorphological**
Anodonta	Transparency	Substrate changes due to high density of stone
Chlorophyll a	Total phosphorus	
Phytoplankton		
Macrophytes		
Phytobenthos		

This intensive study of Lough Key shows that population variation can exist, temporally and spatially, even within a small lake system. This means in essence, that caution should be taken in interpreting data from sporadic spot sampling of large lake systems, e.g. the Great Lakes of North America. For the Lough Key ecosystem, continued annual zebra mussel population surveys are required, in tandem with water quality monitoring. This research is necessary to determine both the long term trends in population dynamics and any other further impacts on the lake ecosystem.

This intensive survey of *Dreissena polymorpha* in Lough Key through the sequence of invasive stages should benefit new research on other Irish lake systems. It is most important that research is carried out on the ecology and impacts of zebra mussels and also other aquatic invasive species in Irish waters. Otherwise it will not be possible to assess ecological changes due to exotic species in Ireland's freshwater ecosystems.

REFERENCES

Ackerman, J.D., Blair, S., Nichols, S.J. and Claudi, R., 1994. A review of the early life history of zebra mussels (*Dreissena polymorpha*): comparisons with marine bivalves. *Canadian Journal of Zoology* **72**, 1169-1177.

Aldridge, D.W., Payne, B.S. and Miller, A.C., 1995. Oxygen consumption, nitrogenous excretion, and filtration rates of *Dreissena polymorpha* at acclimation temperatures between 20^0C and 32^0C. *Canadian Journal of Fisheries and Aquatic Science* **52**, 1761-1767.

Aldridge, D.C., Elliott, P. and Moggridge, G.D., 2004. The recent and rapid spread of the zebra mussel (*Dreissena polymorpha*) in Great Britain. *Biological Conservation* **119(2)**, 253-261.

Alimov, A. F., 1981. *Functional Ecology of Freshwater Bivalve Molluscs*. Nauka Press, Leningrad. (in Russian).

Almada-Villela, P.C., Davenport, J. and Gruffydd, L.L.D., 1982. The effects of temperature on the shell growth of young *Mytilus edulis*. *L. J. Exp. Mar. Biol. Ecol.*, **59**, 275-288.

Agrell, I., 1948. The shell morphology of some Swedish unionids as affected by ecological conditions. *Arkiv for Zoologi* **41** , 1-30.

Aldridge, D.C., 1999. The morphology, growth and reproduction of Unionidae (Bivalvia) in a fenland waterway. *Journal of Molluscan Studies* **65**, 47-60.

APHA, AWWA, WPCF, 1999. *Standard methods for the examination of water and wastewater*. APHA. Washington.

Arnott, D.L and Vanni, M.J., 1996. Nitrogen and phosphorus recycling by the zebra mussel (*Dreissena polymorpha*) in the western basin of Lake Erie. *Canadian Journal of Fisheries and Aquatic Science* **53**, 646-659.

Arter, H.E., 1989. Effect of eutrophication on species composition and growth of freshwater mussels (Mollusca, Unionidae) in Lake Hallwil (Aargau, Switzerland). *Aquatic Sciences* **51/2**, 87-99.

Astanei, I., Gosling, E., Wilson, J. and Powell, E., 2005. Genetic variability and phylogeography of the invasive zebra mussel, *Dreissena polymorpha* (Pallas). *Molecular Ecology* **14**(6), 1655-1666.

Bacchetta, R., Mantecca, P and Vailati, G., 2001. Reproductive behaviour of the freshwater *mussel Dreissena polymorpha* in Italy: a comparison between two populations. *Arch Hydrobiol.* **151**, 247-262.

Baker, S.M. and Hornbach, D.J., 2000. Physiological status and biochemical composition of a natural population of unionid mussels (*Amblema plicata*) infested by zebra mussels (*Dreissena polymorpha*). *American Midland Naturalist* **143**(2), 443-452.

Bastviken, D.T.E., Caraco, N.F. and Cole, J.C., 1998. Experimental measurement of zebra mussel (*Dreissena polymorpha*) impacts on phytoplankton community composition. *Freshwater Biology* **39**, 375-386.

Beekey, M.A., McCabe, D.J. and Marsden, J.E., 2004. Zebra mussel colonization of soft sediments facilitates invertebrate communities. *Freshwater Biology* **49**, 535-545.

Berkman, P.A., Haltuch, M.A. and Tichich, E., 1998. Zebra mussels invade Lake Erie muds. *Nature* **393**, 27-28.

Berkman, P. A., Garton, D.W., Haltuch, M.A., Kennedy, G.W. and Febo, L.R., 2000. Habitat shift in invading species: zebra and quagga mussel population characteristics in shallow soft substrates. *Biological Invasions* **2**: 1-6.

Bij de Vaate, A., 1991. Distribution and aspects of population dynamics of the zebra mussel, *Dreissena polymorpha* (Pallas) in the Lake Ijsselmeer area (The Netherlands). *Oecologia* **86**, 40-50.

Bij de Vaate, A, Jazdzewski, K., Ketelaars, H.A.M., Gollasch, S. and Van der Velde, G., 2002. Geographical patterns in range extension of Ponto-Caspian macroinvertebrate species in Europe. *Canadian Journal of Fisheries and Aquatic Science* **59**, 1159-1174.

Binelli, A., Provini, A. and Galassi, S., 1997. Modifications in Lake Como (N. Italy) caused by the zebra mussel (*Dreissena polymorpha*). *Water, Air and Soil Pollution* **99**, 633-640.

Boon, P., 2003. Alien species and the water framework directive. Ecological change in Lough Erne; Proceedings of Queens University workshop, Co. Fermanagh.

Borcherding, J., 1991. The annual reproductive cycle of the freshwater mussel *Dreissena polymorpha* Pallas in lakes. *Oecologia* **87**, 208-218

Borcheding, J., 1992. Morphometric changes in relation to the annual reproductive cycle in *Dreissena polymorpha* – a prerequisite for biomonitoring studies with zebra mussels. *In*: Neumann, D. and Jenner, H.A. (eds) *The zebra mussel Dreissena polymorpha*. Gustav Fischer Verlag, New York, pp 87-99.

Borcherding, J. 1995. Laboratory experiments on the influence of food availability, temperature and photoperiod on gonad development in the freshwater mussel, *Dreissena polymorpha*. *Malacologia* **36** (1-2), 15-27.

Bowman, J.J., 1998. *River Shannon lake water quality monitoring 1995 to 1997.* Irish EPA, Wexford. 74pp.

Bowman, J.J., 2000. *River Shannon lakewater quality monitoring 1998 &1999.* Irish EPA, Wexford. 78pp.

Bunt, C.M., MacIssac, H.J. and Sprules, W.G., 1993. Pumping rates and projected filtering impacts of juvenile zebra mussels (*Dreissena polymorpha*) in Western Lake Erie. *Canadian Journal of Fisheries and Aquatic Science* **50**, 1017-1022.

Burlakova, L.E., 1998. *Ecology of Dreissena polymorpha (Pallas) and its role in the structure and function of aquatic ecosystems*. Candidate dissertation. Zoology Institute of the Academy of Science, Republic Belarus, Minsk.

Burlakova, L.E., Karatayev, A.Y. and Padilla, D.K., 2000. The impact of *Driessena polymorpha* (Pallas) invasion on unionid bivalves. *International Review of Hydrobiology* **85**, 529-541.

Carmichael, W.W., 1994. The toxins of cyanobacteria. *Scientific American* **270**, 78-86.

Chase, M.E. and Bailey, R. C., 1999. The ecology of the zebra mussel (*Dreissena polymorpha*) in the lower great Lakes of North America: I. Population dynamics and growth. *Journal of Great Lakes Research* **25**, 107-121.

Chorus, I. and Bartram, J., 1999. *Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management.* E and FN Spon, London.

Claudi, R. and Mackie, G.L., 1994. *Practical manual for zebra mussel monitoring and control*. Lewis Publishers, Boca Raton.

Cleven, E.J. and Frenzel, P., 1993. Population dynamics and production of *Dreissena polymorpha* (Pallas) in River Seerhein, the outlet of Lake Constance (Obersee). *Arch. Hydrobiol.* **127**, 395-407.

Council of the European Communities, 2000. *Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy.* Official Journal of the European Communities No L 327. 71 pp.

Commons, E., 2000. *The zebra mussel in Lough Key - veliger research 1999.* Unpublished BSc thesis. Institute of Technology, Sligo.

Conn, D.B., Lutz, R.A., Ya-Ping, H and Kennedy, V.S., 1993. *Guide to the identification of larval and postlarval stages of zebra mussels Dreissena spp. and the dark false mussel, Mytilopsis leucophaeata.* New York Sea Grant, New York.

Crowley, T.E., 1956. Age determination in *Anodonta*. *Journal of Conchology* **24**, 201-207.

CSO (Central Statistics Office), 2002. *Census of population, Volume 1.* CSO, Cork.

Dermott, R. and Munawar, M., 1993. Invasion of Lake Erie offshore sediments by *Dreissena,* and its ecological implications. *Canadian Journal of Fisheries and Aquatic Science* **50**, 2298-2304.

Dermott, R. and Kerec, D., 1997. Changes to the deepwater benthos of eastern Lake Erie since the invasion of *Dreissena*: 1979-1993. *Canadian Journal of Fisheries and Aquatic Sciences* **54**, 922-930.

Dionisio Pires, L.M., Jonker, R.R., Van Donk, E. and Laanbroek, H.J., 2004. Selective grazing by adults and larvae of the zebra mussel (*Dreissena polymorpha*): application of flow cytometry to natural seston. *Freshwater Biology* **49**, 116-126.

Doka, S.E., 1994. *Spatio-temporal dynamics and environmental predictions of recruitment in industrial and nearshore Dreissena populations of Lake Erie.* MSc dissertation, University of Guelph, Guelph, Ontario.

Dorgelo, J., 1993. Growth and population structure of the zebra mussel (*Dreissena polymorpha*) in Dutch lakes differing in trophic state. *In*: Nalepa, T.F. and Schloesser, D.W. (eds.) *Zebra mussels biology, impacts and control.* Lewis publishers, Boca Raton., pp 79-95.

Duggan, S., 2001. *An investigation of Dreissena polymorpha in Lough Key.* Unpublished BSc thesis. Institute of Technology, Sligo.

Dussart, B., 1966. *Limnologie*. Gauthier-Villars, Paris.

Effler, S.W., Boone, S.R., Siegfried, C.A., Walrath, L. and Ashby, S.L., 1997. Mobilisation of ammonia and phosphorus by zebra mussels (*Dreissena polymorpha*) in the Seneca River, New York. *In*: D'Itri, F. (ed.) *Zebra mussels and aquatic nuisance species*. Ann Arbor Press. Michigan, pp 187-209.

Ehrlich, P.R., 1989. Attributes of invaders and the invading processes: vertebrates. *In*: Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.J., Rejmanek, M. and Williamson, M. (eds.) *Biological Invasion: a global perspective, scope 37*. John Wiley and Sons. Chichester, pp. 315-328.

Einsle, U., 1973. Zur horizontal und vertikalverteilung der larven von *Dreissena polymorpha* Pallas im pelagial des Bodensee-Obersees (1971). *Gwf-wasser/abwasser* 114, 27-30.

Ellis, A.E., 1978. *British freshwater bivalve Mollusca. Synopses of the British fauna No. 11 (New Series)*. Academic Press for the Linnean Society. London.

EPA (Environmental Protection Agency), 2002. *Water quality in Ireland*. Irish EPA, Wexford. 128pp.

EPA (Environmental Protection Agency), 2004a. *Ireland's Environment*. Irish EPA, Wexford. 316pp.

EPA (Environmental Protection Agency), 2004b. *Alien risk analysis (Republic of Ireland). Guidance for the assessment of pressures and impacts in accordance with Article 5 of the water framework directive (WFD)*. Irish EPA, Wexford. 37pp.

Fahnenstiel, G.L., Bridgeman, T.B., Lang, G.A., McCormick, M.J. and Nalepa, T.F., 1995. Phytoplankton productivity in Saginaw Bay, Lake Huron: effects of zebra mussel (*Dreissena polymorpha*) colonization. *Journal of Great Lakes Research* **21(4)**, 465-475.

Fanslow, D.L., Nalepa, T.F. and Lang, G.A., 1995. Filtration rates of the zebra mussel (*Dreissena polymorpha*) on natural seston from Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* **21(4)**, 489-500.

Frahleigh, P. C., Klerks, P.L., Gubanich, G., Matisoff, G. and Stevenson, R.C. 1993. Abundance and settling of zebra mussel (*Dreissena polymorpha*) veligers in western and central Lake Erie. *In*: Nalepa, T.F. and Schloesser, D.W. (eds) *Zebra mussels, Biology, Impacts and Control*. Lewis Publishers. Florida, pp 129-141.

Franchini, D.A., 1978. Vertical distribution of *Dreissena polymorpha* (Pallas) in Garda Lake. *Boll. Zool.* **45(3)**, 257-260.

Garton, D.W. and Haag, W.R., 1993. Seasonal reproductive cycles and settlement patterns of *Dreissena polymorpha* in western Lake Erie. *In*: Nalepa, T.F. and Schloesser, D.W. (eds) *Zebra mussels, Biology, Impacts and Control*. Lewis Publishers. Florida, pp 111-128.

Garton, D.W. and Johnson, L.E., 2000. Variation in growth rates of the zebra mussel, *Dreissena polymorpha*, within Lake Wawasee. *Freshwater Biology* **45**, 443-451.

Gillis, P.L. and Mackie, G.L., 1994. Impacts of the zebra mussel, *Dreissena polymorpha*, on populations of Unionidae (Bivalvia) in Lake St. Clair. *Canadian Journal of Zoology* **72**, 1260-1271.

Gist, D.H., Miller, M.C. and Brence, W.A., 1997. Annual reproductive cycle of the zebra mussel in the Ohio River: a comparison with Lake Erie. *Archiv fur Hydrobiologie* 138, 365-379.

Gosling, E. 2004. *Bivalve molluscs: biology, ecology and culture*. Blackwell Science. Oxford.

Graczyk, T.K., Marcogliese, D.J., De Lafontaine, Y., DaSilva, A.J., Mhangami-Ruwende, B. and Pieniazek, N.J., 2001. *Cryptosporidium parvum* oocysts in zebra mussels (*Dreissena polymorpha*): evidence from the St. Lawrence River. *Parasitol. Res.* **85**, 518-521.

Graczyk, T.K., Conn, D.B., Lucy, F., Minchin, D., Tamang, L., Moura, L.N.S. and DaSilva, A.J., 2004. Human waterborne parasites in zebra mussels (*Dreissena polymorpha*) from the Shannon River drainage area, Ireland. *Parasitol. Res.* **93**, 385-391.

Greaney, N. 1999 *Environmental study of the zebra mussel, Dreissena polymorpha in Lough Key*. Unpublished BSc thesis. Institute of Technology, Sligo.

Griffiths, R., Schloesser, D., Leach, J. and Kovalak, W., 1991. Distribution and dispersal of the zebra mussel (*Dreissena polymorpha*) in the Great Lakes region. *Canadian Journal of Fisheries and Aquatic Science* **48**, 1381-1388.

Grigorovich, I.A., Babko, R.V., 1997. Sessile invertebrates in beds of aquatic macrophytes. *In* D'Itri, F. (ed.) *Zebra mussels and aquatic nuisance species*. Ann Arbor Press. Michigan, pp 87-97.

Haag, W.R. and Garton, D.W., 1992. Synchronous spawning in a recently established population of the zebra mussel, *Dreissena polymorpha*, in western Lake Erie, USA. *Hydrobiologia* **234**, 103-110.

Haag, W.R., Berg, D.J., Garton, D.W. and Farris, J.L., 1993. Reduced survival and fitness in native bivalves in response to fouling by the introduced zebra mussel (*Dreissena polymorpha*) in western Lake Erie. *Canadian Journal of Fisheries and Aquatic Science* **50**, 13-19.

Hallac, D.E. and Marsden, J.E., 2000. Differences in tolerance to and recovery from zebra mussel (*Dreissena polymorpha*) fouling by *Elliptio complanata* and *Lampsilis radiata*. Canadian Journal of Zoology **78**, 161-166.

Haslam, S. M., 1973. Some aspects of the life history and autecology of *Phragmites communis* Trin.: A review. *Polish Archives of Hydrobiology* **20(1)**, 79-100.

Heath, R.T., Fahnenstiel, G.L., Gardner, W.S., Cavaletto, J.S. and Hwang, S.J., 1995. Ecosystem-level effects of zebra mussels (*Dreissena polymorpha*): an enclosure experiment in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* **21**, 501-516.

Hecky, R.E., Smith, R.E.H., Barton, D.R., Guildford, S.J., Taylor, W.D., Charlton, M.N. and Howell, T., 2004. The nearshore phosphorus shunt; a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Science* **61**, 1285-1293.

Hebert, P.D.N., Muncaster, B.W. and Mackie, G.L. 1989. Ecological and genetic studies on *Dreissena polymorpha* (Pallas): a new mollusc in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Science* **46**, 1587-1591.

Hebert, P.D.N., Wilson, C.C., Murdoch, M.H., and Lazar, R., 1991. Demography and ecological impacts of the invading mollusc, *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Science* **49**, 405-409.

Hepworth Holland, C., 2001. *The Geology of Ireland.* Dunedin Academic Press. Edinburgh. 531pp.

Hillbricht-Ilkowska A., and Stanczykowska A. 1969. The production and standing crop of planctonic larvae of *Dreissena polymorpha* (Pall.) in two Mazurian lakes. *Pol. Arch. Hydrobiol.*, **16 (29)**, 193-203.

Holland, R.E., 1993. Changes in planktonic diatoms and water transparency in Hatchery Bay, Bass Island area, Western Lake Erie since the establishment of the zebra mussel. *Journal of Great Lakes Research* **19(3)**, 617-624.

Holland, R.E., Johengen, T.H. and Beeton, A.M., 1994. Trends in nutrient concentrations in Hatchery Bay, western Lake Erie, before and after *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Science* **52**, 1202-1209.

Horgan, M.J. and Mills, E.L., 1997. Clearance rates and filtering activity of zebra mussel (*Dreissena polymorpha*): implications for freshwater lakes. *Canadian Journal of Fisheries and Aquatic Science* **54**, 249-255

Hovarth, T.G., Lamberti, G.A., Lodge, D.M. & Perry, W.P., 1996. Zebra mussel dispersal in lake stream systems: source-sink dynamics? *Journal of the North American Benthologists' Society* **11**, 341-349.

Howitt, D. and Cramer, D., 2003. *A guide to computing statistics with SPSS11 for windows.* Revised edition. Prentice Hall, Harlow.

Hunter, R.D. & Bailey, J.F., 1992. *Dreissena polymorpha* (zebra mussel): colonisation of soft substrata and some effects on Unionid bivalves. *Nautilus* **106**: 60-67.

Hutchinson, G.E., 1975. *A treatise on limnology. Vol. 1. Part 2. Chemistry of lakes.* John Wiley and Sons, New York.

Jack, J.D. and Thorp, J.H., 2000. Effects of the benthic suspension feeder *Dreissena polymorpha* on zooplankton in a large river. *Freshwater Biology* **44**, 569-579.

James, W.F., Barko, J.W. and Eakin, H.L., 1997. Nutrient regeneration by the zebra mussel (*Dreissena polymorpha*). *Journal of Freshwater Ecology* **12**, 209-216.

James, W.F., Barko, J.W. and Eakin, H.L., 2001. Phosphorus recycling by zebra mussels in relation to density and food resource availability. *Hydrobiologia* **455**, 55-60.

Jantz, B. & D. Neumann. 1998. Growth and reproductive cycle of the zebra mussel in the River Rhine as studied in a river bypass. *Oecologia* **114**, 213-225.

Johengen, T.H., Nalepa, T.F., Fahnenstiel, G.L. and Goudy, G., 1995. Nutrient changes in Saginaw Bay, Lake Huron, after the establishment of the zebra mussel (*Dreissena polymorpha*). *Journal of Great Lakes Research* **21(4)**, 449-464.

John, J.D., Whitton, B.A. and Brook, A.J., 2002. *The freshwater algal flora of the British Isles*. University Press, Cambridge.

Johnson, L and Padilla, D.K., 1996. Geographic spread of exotic species: ecological lessons and opportunities from the invasion of the zebra mussel, *Dreissena polymorpha*. *Biological Conservation* **78**, 23-33.

Johnson L.E., Ricciardi, A. and Carlton, J.T., 2001. Overland dispersal of aquatic invasive species: A risk assessment of transient recreational boating. *Ecological Applications* **11**, 1789-1799.

Jones, C.G., Lawton, J.H. and Shachak, M., 1994. Organisms as ecosystem engineers. *Oikos* **69**, 373-386.

Jones, C.G., Lawton, J.H. and Shachak, M., 1997. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology* **78**, 1946-1957.

Juhel, G., Culloty, S.C., O'Riordan, R.M., O' Connor, J., De Faoite, L. and McNamara, R., 2003. A histological study of the gametogenic cycle of the freshwater mussel *Dreissena polymorpha* (Pallas, 1771) in Lough Derg, Ireland. *Journal of Molluscan Studies* **69**, 365-373.

Kachanova, A.A., 1961. Some data on the reproduction of *Dreissena polymorpha* Pallas in Uchinsk reservoir. *Trudy. Vses. Gidrobiol. Obsc.* **11**, 117-121.

Karatayev, A.Y, 1983. Ecology of *Dreissena polymorpha* Pallas and its effects on macrozoobenthos of the thermal power plant's cooling reservoir. Candidate Dissertation, Zoology Institute of Academy of Science Belarussian SSR, Minsk, Belarus, 153p. (in Russian).

Karatayev, A. Y. 1983. Effect of heated water on the lethality, growth and production of *Dreissena polymorpha* Pallas, pp. 21-29. *In:* Proceedings of the All Union

Conference on Model Species of Aquatic Invertebrates. Vilnius: VINITI Press. Paper 3494-84 Dep. (in Russian).

Karatayev, A.Y., Lyakhnovich, V.P. and Reznichenko, O.G., 1990. Quantitative study of the density, biomass and abundance dynamic. In:Shkorbatov, G.L. and Starobogatov, Y.I. (eds.) *Methods for study of bivalvian molluscs*. Trudy Zoologicheskogo Instituta **29**, 172-178 (in Russian).

Karatayev, A.Y., and Burlakova, L.E., 1993. The filtering activity of *Dreissena* and its influence on the trophic stucture of planktonic and benthic invertebrates.*In*: *Proceedings on the fourth international conference on the project: species and its productivity within their range*. Gidromiteoizdat Press, St Petersburg (in Russian), pp 211-213.

Karatayev, A. Y. & A. A. Lvova. 1993. The results of research of *Dreissena* within the framework of the project "Species and its productivity in the distribution area. pp. 213-215. *In: Proceedings of the 4th International Conference on the Project: Species and its Productivity Within their Range*. Gidrometeoizdat Press, St. Petersburg (in Russian).

Karatayev, A.Y. and Burlakova, L.E., 1995. The role of *Dreissena* in lake ecosystems. *Russian Journal of Ecology* **26**, 207-211.

Karatayev, A.Y., Burlakova, L.E. and Padilla, D.K., 1997. The effects of *Dreissena polymorpha* invasion on aquatic communities in Eastern Europe. *Journal of Shellfish Research* **16(1)**, 187-203.

Karatayev, A.Y., Burlakova, L.E. and Padilla, D.K., 1998. Physical factors that limit the distribution and abundance of *Dreissena polymorpha* (Pall.). *Journal of Shellfish Research* **17(4)**, 1219-1235.

Karatayev, A.Y., Burlakova, L.E. and Padilla, D.K., 2002. Impacts of zebra mussels on aquatic communities and their role as ecosystem engineers. *In*: Leppakowski, E., Gollasch, S. and Olenin, S. (eds.) *Invasive aquatic species of Europe. Distribution, impacts and management*. Kluwer Academic Publishers, Dordrecht., pp 433-447.

Kerney, M.,1999. *Atlas of the Land and Freshwater Molluscs of Britain and Ireland*. Harley Books, Colchester..

Kerney, M.P. and Morton, B.S., 1970. The distribution of *Dreissena polymorpha* in Britain. *Journal of Conchology* **27**, 97-100.

Kern, R., Borcherding, J. and Neumann, D., 1994. Recruitment of a freshwater mussel with a planktonic life-stage in running waters – studies on *Dreissena polymorpha* in the River Rhine. *Arch. Hydrobiol.* **131**, 385-400.

Kirk, McLure and Morton, 2001. *Lough Derg and Lough Ree catchment monitoring and management system. Final Report.* GPS, Cork. 223 pp.

Kirpichenko, M. J., 1964. Phenology, abundance and growth of *Dreissena* larvae in the Kujbysev reservoir. *In*: Sbornik (ed.) *Biologija Drejsseny I borba z nej*. Izat Nauka, Moskva.

Klerks, P.L., Fraleigh, P.C. and Lawniezak, 1996. Effects of zebra mussels (*Dreissena polymorpha*) on seston levels and sediment deposition in western Lake Erie. *Canadian Journal of Fisheries and Aquatic Science* **53**, 2284-2291.

Kondratiev, G.P., 1962. Features of filtration of *Dreissena polymorpha* Pallas. Tr. Sarat. Otd. Vses. Nauchno. Issled. Inst. Ozern. Rechn. Rybn. Khoz..**7**, 280-283 (in Russian).

Kondratiev, G. P., 1969. The influence of water temperature on the duration of filtering activity of some freshwater mussels. pp. 31-36. *In: The Species Composition, Ecology and Productivity of Hydrobionts in Volgogradskoe Reservoir.* Saratov University Press, Saratov (in Russian).

Kotta, J., Orav, H. and Kotta, I., 1998. Distribution and filtration activity of the zebra mussel, *Dreissena polymorpha*, in the Gulf of Riga and the Gulf of Finland. *Proceedings of the Estonian Academy of Science, Biology and Ecology* **47**, 32-41.

Kovaleva, A.A., 1969. Some data on the ecology of mollusks in the Volgogradskoe Reservoir. *In*: *The influence of economic activity on the animal world of the Saratov part of the Volga region.* Saratov University Press, Saratov, pp 42-44.

Kraft, C.E. and Johnson, L.E., 2000. Regional differences in rates and patterns of North American inland lake invasions by zebra mussels (*Dreissena polymorpha*). *Canadian Journal of Fisheries and Aquatic Science* **57**, 993-1001.

Lei, J., Payne, S. and Wang, S.Y., 1996. Filtration dynamics of the zebra mussel, *Dreissena polymorpha*. *Canadian Journal of Fisheries and Aquatic Science* **53**, 29-37.

Lennox, L.J., 1984. Lough Ennell: laboratory studies on sediment phosphorus release under varying mixing, aerobic and anaerobic conditions. *Freshwater Biology* **14**, 183-187.

Lewandowski, K. and Stanczykowska, A., 1975. The occurrence and role of bivalves of the family Unionidae in Mikolajskie Lake. *Ekologia Polska* **23**, 317-334.

Lewandowski, K., 1976. Long-term changes in the fauna of family Unionidae bivalves in the Mikolajskie Lake. *Ekologia Pol*ska **39**, 265-272.

Lewandowski, K., 1982a. The role of early developmental stages in the dynamics of *Dreissena polymorpha* (Pall.) (Bivalvia) populations in lakes I. Occurrence of larvae in the plankton. *Ekologia Polska* **30 (1-2)**, 81-109.

Lewandowski, K., 1982b. The role of early developmental stages in the dynamics of *Dreissena polymorpha* (Pall.) (Bivalvia) populations in lakes II. Settling of larvae and the dynamics of number of settled individuals. *Ekologia Polska* **30 (1-2)**, 223-286.

Lewandowski, K., 1983. Occurrence and filtration capacity of young plant dwelling *Dreissena polymorpha* (Pall.) in Majcz Wielki Lake. *Pol. Arch. Hydrobiol.*, **30(3)**, 255-262.

Lewandowski, K., 1991. The occurrence of *Dreissena polymorpha* (Pall.) in some mesotrophic lakes of the Masurian Lakeland. *Ekologia Polska*, **39(2)**, 273-286.

Littlejohn, C., Nixon, S., Casazza, G., Fabiani, C., Premazzi, G., Heinonen, P., Ferguson, A. and Pollard, P., 2002. *Guidance on monitoring for the water framework directive, final draft*. Working group 2.7, monitoring.

Lodge, D.M., 1993. Biological invasions: lessons for ecology. *Trends Ecological Invasions* **8**, 133-137.

Lohan, J., 2004. An investigation of the early life stages of the zebra mussel, *Dreissena polymorpha* in Lough Key, 2003. Unpublished BSc thesis. Institute of Technology, Sligo.

Lucy, F. and Sullivan, M., 2001. *The investigation of an invasive species, the zebra mussel Dreissena polymorpha in Lough Key, Co Roscommon, 1999*. Desktop study no. 13. Irish EPA, Wexford, 38pp.

Lucey, J., 1995. The distribution of *Anodonta cygnea* (L.) and *Anodonta anatina* (L.) (Mollusca:Bivalvia) in southern Irish rivers and streams with records from other areas. *Irish Naturalists Journal*. **25**, 1-40.

Lucey, J. and Caffrey, J., 2004. Invasive plant species in Irish aquatic habitats. 13th International |Aquatic Invasive Species Conference, Ennis, Ireland. www.icais.org.

Lvova-Kachanova, A. A. 1972. Growth and longevity of *Dreissena polymorpha* (Pall.). *Kompleksn. Issled. Kaspiyskogo Morya* **3**, 74-82 (in Russian).

Lvova, A.A., 1977. *The ecology of Dreissena polymorpha in Uchinskoe reservoir*. Candidate dissertation, Moscow University.

Lvova, A. A., 1980. Ecology of *Dreissena (Dreissena polymorpha* (Pall.). *Trudy Vserossijskogo gidrobiologicheskogo obshchestva* **23**, 101-119 (in Russian).

Lyakhnovich, V. P., A. Y. Karatayev, N. I. Andreev, S. I. Andreeva, S. A. Afanasiev, A. K. Dyga, V. P. Zakutskiy, V. I. Zolotareva, A. A. Lvova, M. Y. Nekrasova, V. F. Osadchikh, Y. V. Pligin, A. A. Protasov & G. M. Tischikov. 1994. Living conditions. pp. 109-119. *In:* J. I. Starobogatov (ed.). *Freshwater Zebra Mussel Dreissena polymorpha (Pall.) (Bivalvia, Dreissenidae). Systematics, Ecology, Practical Meaning*. Nauka Press, Moscow (in Russian).

Mackie, G.L., Gibbons, W.N., Muncaster, B.W. and Gray, I.M., 1989. The zebra mussel, *Dreissena polymorpha*: a synthesis of European experiences and a preview for North America. *Report prepared for Water Resources Branch, Great Lakes Section*. Ontario.

Mackie, G.L., 1991. Biology of the exotic zebra mussel, *Dreissena polymorpha*, in relation to native bivalves and its potential impact in Lake St. Clair. *Hydrobiologia* 219, 251-268.

Mackie, G.L. and Schloesser, D.W., 1996. Comparative biology of zebra mussels in Europe and North America: an overview. *American Zoologist*. **36**, 234-248.

MacDermot, C.V., Long, C.B. and Harney, S.J., 1996. *Geology of Sligo-Leitrim*. Geological Survey of Ireland. Sligo.

MacIssac, H., Sprules, W.G. and Leach, J.H., 1991. Ingestion of small-bodied zooplankton by zebra mussels (*Dreissena polymorpha*): can cannabalism on larvae influence population dynamics? *Canadian Journal of Fisheries and Aquatic Science* **48**, 2051-2060.

MacIssac, H.J., Sprules, W.G., Johannsson, O.E. and Leach, J.H., 1992. Filtering impacts of larval and sessile zebra mussels (*Dreissena polymorpha*) in western Lake Erie. *Oecologia* **92**, 30-39.

MacIssac, H.J., Lonnee, C.J. and Leach, J.H., 1995. Suppression of microzooplankton by zebra mussels: importance of mussel size. *Freshwater Biology* **34**, 379-387.

Maguire, C.M., Roberts, D. and Rosell, R.S., 2003. The ecological impacts of a zebra mussel invasion in a large Irish lake, Lough Erne: a typical European experience? *Aquatic Invaders* **14 (1)**, 10-18.

Maitland, P.S., 2004. *Keys to the freshwater fish of Britain and Ireland.* Freshwater Biological Association. Scientific Publication No. 62. Cumbria. pp 248.

Maleski, K.R. and Masteller, E.C., 1994. The current status of the Unionidae of Presque Isle Bay, Erie, PA. *Bulletin of the North American Benthological Society* **11**, 109.

Mann, K.H., 1964. The pattern of energy flow in the fish and invertebrate fauna of the River Thames. *Verh. Int. Verein. Theor. Angen. Limnol.* **15**, 485-495.

Mantecca, P., Vailati, G., Garibaldi, L. and Bacchetta, R., 2003. Depth effects on zebra mussel reproduction. *Malacologia* **45**, 109-120.

Margalef, R., 1958. Temporal succession and spatial heterogeneity in phytoplankton. In Buzzati-Traverso, A (Ed.) *Perspectives in Marine Biology*. University of California Press, Berkley. pp 323-349.

Marsden, J.E., 1992. Standard protocols for monitoring and sampling zebra mussels. *Illinois Natural History Survey, Biological Notes* 138.

Marshall, A., 2002. *An investigation of Dreissena polymorpha in Lough Key.* Unpublished BSc thesis. Institute of Technology, Sligo.

Martel, A., 1993. Dispersal and recruitment of zebra mussel (*Dreissena polymorpha*) in a nearshore area in West-central Lake Erie: the significance of postmetamorphic drifting. *Canadian Journal of Fisheries and Aquatic Science* **50**, 3-12.

Martel, A.L., Pathy, D.A., Madill, J.B., Renaud, C.B., Dean, S.L. and Kerr, S.J., 2001. Decline and regional extirpation of freshwater mussels (Unionidae) in a small river system invaded by *Dreissena polymorpha*: the Rideau River, 1993-2000. *Canadian Journal of Zoology* **12**, 2181-2191.

McCarthy, T.K, Fitzgerald, J., Cullen, P., Doherty, D. & Copley, L., 1997. *Zebra mussels in the River Shannon*. Zoology Department, University of Galway, November 1997. 49pp.

McCarthy, T. K, Fitzgerald, J. & O'Connor, W., 1998. The ocurrence of the zebra mussel *Dreissena polymorpha* (Pallas. 1771), an introduced biofouling freshwater bivalve in Ireland. *Irish Naturalists' Journal* **25**(11/12), 413-415.

McMahon, R.F., 1992. The zebra mussel – the biological basis of its macrofouling and potential for distribution in North America. Corrosion 92, *NACE Annual Conference and Corrosion Show*. Houston.

McMahon, R.F., 1996. The physiological ecology of the zebra mussel, *Dreissena polymorpha*, in North America and Europe. *American Zoologist* **36**, 339-363.

Mellina, E. and Rasmussen, J.B., 1994. Patterns in the distribution of zebra mussel (*Dreissena polymorpha*) in rivers and lakes in relation to substrate and other physicochemical factors. *Canadian Journal of Fisheries and Aquatic Science* **51**, 1024-1035.

Mellina, E., Rasmussen, J.B. and Mills, E.L., 1995. Impact of zebra mussel (*Dreissena polymorpha*) on phosphorous cycling and chlorophyll in lakes. *Canadian Journal of Fisheries and Aquatic Science* **52**, 2553-2573.

Mikheev, V. P., 1967a. The nutrition of zebra mussels (*Dreissena polymorpha* Pallas). Summary of the Candidate Dissertation. State Research Institute for Lakes and Rivers Fishery Industry, Leningrad, USSR (in Russian).

Mikheev, V. P., 1967b. Filter-feeding of *Dreissena*. *Tr. Vses. Nauchno. Issled. Inst. Prud. Rybn. Khos.* **15**, 117-119 (in Russian).

Minchin, D. & Moriarty, C., 1998 Zebra mussels in Ireland. *Fisheries Leaflet No 177*, Marine Institute. 11pp.

Minchin, D. & Moriarty, C., 1999 Distribution of the zebra mussel *Dreissena polymorpha* (Pallas) in Ireland, 1997. *The Irish Naturalists' Journal*, **26**, pp 38-42

Minchin, D., 2000 Dispersal of zebra mussels in Ireland. *Verhandlungen Internationale Vireinigung Limnologie,* **27**, 1576-1579.

Minchin, D. Lucy, F. & Sullivan, M., 2002 (a). Zebra mussel: Impacts and Spread. *In*: Leppakoski, E., Gollasch S. and Olenin, S. (eds) *Invasive Aquatic Species of Europe: Distribution, Impacts and Spread.* Kluwer Press, Dordrecht, pp 135-146.

Minchin, D., Lucy, F. and Sullivan, M., 2002 (b). *Monitoring of zebra mussels in the Shannon-Boyle navigation, other navigable regions and principal Irish lakes, 2000 and 2001*. Marine Environment and Health Series, No. 5. Marine Institute, Dublin.

Minchin, D., Maguire, C. & Rosell, R., 2002. The zebra mussel (*Dreissena polymorpha*) Pallas invades Ireland: human mediated vectors and the potential for rapid international dispersal. *Biology and Environment, Proceedings of the Royal Irish Academy,* Dublin.

Minchin, D. and Lucy, F., 2003. *Monitoring of zebra mussels in the Shannon-Boyle navigation and midland lakes*. Report to the Marine Institute, Dublin.

Molloy, D.P., Karatayev, A.Y., Burlakova, L.E., Kurandina, D.P. and Laruelle, F., 1997. Natural enemies of zebra mussels: predators, parasites and ecological competitors. *Reviews in Fisheries Science*. **5(1)**, 27-97.

Morton, B.S., 1969. Studies on the biology of *Dreissena polymorpha*. III. Population dynamics. *Proceedings of the Malacological Society of London,* **38**, 471-481.

Nalepa, T.F, Manny, B.A., Roth, J.C., Mozley, S.C. and Schloesser, D.W., 1991. Long-term decline in freshwater mussels (Bivalvia:Unionidae) of the western basin of lake Erie. Journal of Great Lakes Research. **17**, 214-219.

Nalepa, T.F., Cavaletto, J.F., Ford, M.,Gordon, W.M. and Wimmer, M., 1993. Seasonal and annual variation in weight and biochemical content of the zebra mussel, *Dreissena polymorpha*, in Lake Huron. *Journal of Great Lakes Research* **19**, 541-552.

Nalepa, T.F., 1994. Decline of native Unionid bivalves in Lake St. Clair after infestation by the zebra mussel, *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Science* **51**, 2227-2233.

Nalepa, T.F., Wojik, J.A., Fanslow, D.L. and Lang, G.A., 1995. Initial colonization of the zebra mussel (*Dreissena polymorpha*) in Saginaw Bay, Lake Huron: population recruitment, density and size structure. *Journal of Great Lakes Research* **21(4)**, 417-434.

Nalepa, T.F., Fahnenstiel, G.L. and Johengen, T.H., 1999. Impacts of the zebra mussel on water quality: a case study in Saginaw Bay, Lake Huron. *In*: Claudi, R. (ed.) *Nonindigenous freshwater organisms: vectors, biology and impacts.* CRC Press, Florida, pp 255-271.

Nalepa, T.F., Hartson, D.J., Fanslow, D.L. and Lang, G.A., 2001. Recent population changes in freshwater mussels (Bivalvia; Unionidae) and zebra mussels (*Dreissena polymorpha*) in Lake St. Clair, USA. *American Malacological Bulletin* **16 (1-2)**, 141-145.

Negus, C.L., 1966. A quantitative study of growth and reproduction of unionid mussels in the River Thames at Reading. *Journal of Animal Ecology* **35**, 513-532.

New York Sea Grant, 2003. Distribution map of zebra mussels in North America. *Aquatic Invaders*. **14 (4)**, 16-17.

Nicholls, K and Hopkins, G., 1993. Recent changes in Lake Erie (north shore) phytoplankton: cumulative impacts of phosphorus loading reductions and the zebra mussel introduction. *Journal of Great Lakes Research* **19**, 637-654.

Nicholls, K.H., Hopkins,G.J. and Standke, S.J., 1999. Reduced chlorophyll to phosphorus ratios in nearshore Great Lakes waters coincide with the establishment of dreissenid mussels. *Canadian Journal of Fisheries and Aquatic Science* **56**, 153-161.

Nichols, S.J., 1996. Variations in the reproductive cycle of *Dreissena polymorpha* in Europe, Russia and North America. American Zoologist **36**, 311-325.

Nichols, S.J. and Amberg, J., 1999. Co-existence of zebra mussels and freshwater unionids: population dynamics of *Leptodea fragilis* in a coastal wetland infested with zebra mussels. *Canadian Journal of Zoology* **77**, 423-432.

Ni Chonmhara, E., 1999. *The zebra mussel in Lough Key, 1998-1999*. Unpublished BSc thesis. Institute of Technology, Sligo.

OECD, 1982. *Eutrophication of waters monitoring assessment and control.* Organisation for Economic Co-operation and Development. Paris. 154 pp.

Okland, J., 1963. Notes on population density, age distribution, growth and habitat of *Anodonta piscinalis* (Nilss.) (Mollusca:Lamellibranchia) in a eutrophic Norwegian lake. *Nytt. Mag. Zool.* **11**, 19-43.

O' Mahoney, K., 2003. *An investigation of Dreissena polymorpha in Lough Key.* Unpublished BSc thesis. Institute of Technology, Sligo.

O'Neill, C. R., 1995. The zebra mussel – impacts and control. *Cornell Cooperative Extension Information Bulletin* 238.

Orlova, M. 2002. *Dreissena polymorpha*: Evolutionary origin and biological peculiarities as prerequisites of invasion success. *In*: Leppakoski, E., Gollasch S. and Olenin, S. (eds) *Invasive Aquatic Species of Europe: Distribution, Impacts and Spread.* Kluwer Press, Dordrecht. pp 135-146.

Orlova, M.I. and Panov, V.E., 2004. Establishment of the zebra mussel, *Dreissena polymorpha* (Pallas), in the Neva Estuary (Gulf of Finland, Baltic Sea): distribution, population structure and possible impact on local unionid bivalves. *Hydrobiologia* **514**, 207-217.

Ovchinnikov, I.F., 1933. Comtemporary spreading of *Dreissena polymorpha* PALLAS (Mollusca) in the BSSR – Zoogeographical essay. – *Tr. Inst. Zoologii Akad. Nauk SSSR* **1**, 365-373 (In Russian).

Panov, V.E., Alimov, A.F., Balushkina, E.V., Golubkov, S.M., Nikulina, V.M., Telesh, V.I. and Finogenova, N.P., 1997. Monitoring biodiversity in bottom and planktonic communities of the Neva Estuary. In: Sokolov, V.E., Reshetnikov, Y.S. and Shatunovski (eds) *Monitoring of biodiversity*. Pensoft, Moscow, pp. 228-294.

Parker, I., Simberloff, M.D., Lonsdale, W.M., Goodell, K., Wonham, M., Kareiva, P.M.,.Williamson, M.H., VonHolle, V., Moyle, P.B., Byers, J.E., and Goldwasser, L., 1999. Impact: Toward a framework for understanding the ecologicl effect of invaders. *Biological Invasions* **1**:2-19.

Pauly, D. and Caddy, J.F., 1985. *A modification of Bhattacharya's method for the analysis of mixtures of normal distributions.* FAO Fishery Circular. **781**.

Piers, H., 1682. *A chorographical description of the County of West-meath.* Published for Charles Vallency in 1786. Luke White, Dublin.

Pollux, B., Minchin, D., Van der Velde,G., Van Alen, T., Van der Staay, S and Hackstein, J., 2003. Zebra mussels in Ireland (*Dreissena polymorpha*), AFLP-fingerprinting and boat traffic both indicate an origin from Britain. *Freshwater Biology* **48**, 1127-1139.

Preston, C.D. and Croft, J.M., 1997. *Aquatic plants in Britain and Ireland.* Harley books. Colchester. 365 pp.

Ram, J.L., Fong, P.P. and Garton, D., 1996. Physiological aspects of zebra mussel reproduction: maturation, spawning and fertilization. *American Zoologist* **36**, 326-338.

Ramcharan, C. W., Padilla, D. K and Dodson, S. I., 1992. Models to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Sciences* **49**:2611-2620.

Rehmann, C.R., Stoeckel, J.A. and Schneider, D.W., 2003. Effect of turbulence on the mortality of zebra mussel veligers. *Canadian Journal of Zoology* **81**, 1063-1069.

Reed-Anderson, T.R., Carpenter, S.R., Padilla, D.K. and Lathrop, R.C., 2000. Predicted impact of zebra mussel (*Dreissena polymorpha*) invasion on water quality in Lake Mendota. *Canadian Journal of Fisheries and Aquatic Science* **57**, 1617-1626.

Reeders, H.H. and Bij de Vaate, A., 1990. Zebra mussels (*Dreissena polymorpha*): a new perspective for water quality management. *Hydrobiologia* 200/201, 437-450.

Reid, D.F. and Orlova, M.I., 2002. Geological and evolutionary underpinnings for the success of Ponto-Caspian species invasions in the Baltic Sea and North American lakes. *Canadian Journal of Fisheries and Aquatic Science* **59**, 1144-1158.

Reynolds, J.D., 1998. *Ireland's freshwaters.* SIL XXVII Congress, Dublin. ESB, Dublin. 130pp.

Rhee, G.Y. and Gotham, I.J., 1980. N:P ratios and co-existence of planktonic algae. *Journal of Phycology*, 486-489.

Ricciardi, A., Whoriskey, F.G. and Rasmussen, J.B., 1995. Predicting the intensity and impact of *Dreissena* infestation on native unionid bivalves from *Dreissena* field density. *Canadian Journal of Fisheries and Aquatic Science* **52**, 1449-1461.

Ricciardi, A., Neves, R.J. and Rasmussen, J.B., 1998. Impending extinctions of North American freshwater mussels following the zebra mussel (*Dreissena polymorpha*) invasion. *Journal of Animal Ecology* **67**, 613-619.

Roditi, H.A., Caraco, N.F., Cole, J.J and Strayer, D.L., 1996. Filtration of Hudson River water by the zebra mussel (*Dreissena polymorpha*). *Estuaries* **19(4)**, 824-832.

Rosell, R., McCarthy, T.K. & Maguire, K.,1999. First settlement of zebra mussels *Dreissena polymorpha* in the Erne system, Co Fermanagh. Northern Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* 98B(3) 191-193.

Ross, E.D., 1984. *Studies on the biology of freshwater mussels (Lamellibranchia: Unionacea) in Ireland.* MSc thesis. National University of Ireland, Galway.

Ross, E.D., 1988. *The reproductive biology of freshwater mussels in Ireland, with observations on their distribution and demography.* PhD thesis. National University of Ireland, Galway.

Sapkarev, J., 1975. Composition and dynamics of the bottom animals in the littoral zone of Dojran Lake. *Verhandlungen Internationale Vireinigung Limnologie* **19**,1339-1350.

Sapkarev, J.A. and Angelovski, P.J., 1978. Population dynamics of *Dreissena polymorpha* on *Phragmites communis* from Dojran Lake. *Godisen Zbornik* 31, 29-51.

Schloesser, D.W. and Kovalak, W.P., 1991. Infestation of Unionids by *Dreissena polymorpha* in a power plant canal in Lake Erie. *Journal of Shellfish Research* **10**, 355-359.

Schloesser, D. & Nalepa, T. & Mackie, G.L. 1996. Zebra mussel infestation of unionid bivalves (Unionidae) in North America. *American Zoologist* **36**, 300-310.

Sebestyen , O. 1938. Colonisation of two new fauna-elements of Pontus origin (*Dreissena polymorpha* (Pall.) and *Corophium curvispinum* (G.O. Sars forma devium Wundsch) in Lake Balaton. *Verhandlungen Internationale Vereinigung Limnologie* **8**, 169-181.

Sigee, D.C., 2005. *Freshwater microbiology*. John Wiley and Sons, Chichester. 524 pp.

Simberloff, D., and Gibbons, L., 2004. Now you see them, now you don't! – population crashes of established introduced species. *Biological Invasions* **6**, 161-172.

Skelly, A., 2000. *The impact of the zebra mussel on Anodonta populations in Lough Key.* Unpublished BSc thesis. Institute of Technology, Sligo.

Skubinna, J.P., Coon, T.G. and Batterson, T.R., 1995. Increased abundance and depth of submersed macrophytes in response to decreased turbidity in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* **21(4)**, 476-488.

Smit, H. and Dudok van Heel, E., 1992. Methological aspects of a simple allometric biomass determination of *Dreissena polymorpha* aggregations. *In*: Neumann, D. and Jenner, H.A. (eds.) *The zebra mussel Dreissena polymorpha: ecology, biological monitioring and first applications in the water quality management.* Gustav Fisher Verlag. New York, pp 79-86.

Smit, H., Bij de Vaate, A. and Fioole, A., 1992. Shell growth of the zebra mussel (*Dreissena polymorpha*) (Pallas) in relation to selected physicochemical parameters in the Lower Rhine and some associated lakes. Arch. Hydrobiol. **124**, 257-280.

Smit, H., Bij de Vaate, A., Reeders, H.H., van Nes, E.H. and Noordhuis, R. 1993. Colonisation, ecology and positive aspects of zebra mussels (*Dreissena polymorpha*) in The Netherlands. *In*: Nalepa, T.F. and Schloesser, D.W. (eds.) *Zebra mussels biology, impacts and control.* Lewis publishers, Boca Raton, pp 55-77.

Smith, V.H., 1983. Low nitrogen to phosphorus favours dominance by bluegreen algae in lake phytoplankton. Science (Washington, D.C.) **221**, 669-671.

Smith, T.E., Stevenson, R.J., Caraco, N.F. and Cole, J.J., 1998. Changes in phytoplankton community structure during the zebra mussel (*Dreissena polymorpha*) invasion of the Hudson River (New York). *Journal of Planktonic Research* **20(8)**, 1567-1579.

Sondergaard, M., Kristensen, P. and Jeppesen, E., 1992. Phosphorus release from resuspended sediment in the shallow and windexposed Lake Arreso, Denamrk. *Hydrobiologia* **228**, 91-99.

Soszka, G.J., 1975. The invertebrates on submerged macrophytes in three Masurian lakes. *Ekologia Polska*, **23(3)**, 371-391.

Sparre, P. and Venema, S.C., 1992. *Introduction to tropical fish stock assessment.* FAO Fishery Technical Paper **306**.

Sprung, M. and Rose, U., 1988. Influence of food size and food quantity on the feeding of the mussel *Dreissena polymorpha*. *Oecologia* **77**, 526-532.

Sprung, M., 1989. Field and laboratory observations of *Dreissena polymorpha* larvae: abundance, growth, mortality and food demands. *Archiv fur Hydrobiologie* **115**, 537-561.

Stanczykowska, A., 1968. The filtration capacity of populations of *Dreissena polymorpha* (Pall.) in different lakes, as a factor affecting circulation of matter in the lake. *Ecologia Polska* **14**, 265-270.

Stanczykowska,, A. 1977. Ecology of *Dreissena polymorpha* (Pall.) (Bivalvia) in lakes. *Pol. Arch. Hydrobiol.* **24**, 461-530.

Stanczykowska, A. and Lewandowski, K., 1993a. Effect of filtering activity of *Dreissena polymorpha* (Pall.) on the nutrient budget of the littoral of Lake Mikolajskie. *Hydrobiologia* **251**, 73-79.

Stanczykowska, A. and Lewandowski, K., 1993b. Thirty years of studies of *Dreissena polymorpha* ecology in Mazurian lakes of Northeastern Poland. *In*: Nalepa, T.F. and Schloesser, D.W. (eds) *Zebra mussels, Biology, Impacts and Control*. Lewis Publishers. Florida. pp 3-38.

Stanczykowska, A. and Lewandowski, K., 1995. Individual growth of the freshwater mussel *Dreissena polymorpha* (Pall.) in Mikolajskie Lake; estimates in situ. *Ekol. Pol.* **43(3-4)**, 267 – 276.

Stanczykowska, A. and Planter, M., 1985. Factors affecting nutrient budget in lakes of the R. Jorka watershed (Masurian Lakeland, Poland). Role of the mussel *Dreissena polymorpha* (Pall.) in N and P cycles in a lake ecosystem. *Ekologia Polska* **33(2)**, 345-356.

Stoeckel, J.A., Padilla, D.K., Schneider, D.W. and Rehmann, C.R., 2004. Laboratory culture of *Dreissena polymorpha* larvae: spawning success, adult fecundity and larval mortality patterns. *Canadian Journal of Zoology* **82**, 1436-1443.

Strayer, D.L. and Smith, L.C., 1996. Relationships between zebra mussels (*Dreissena polymorpha*) and unionid clams during the early stages of the zebra mussel invasion of the Hudson River. *Freshwater Biology* **36**, 771-779.

Strayer, D.L., Powell, J., Ambrose, L.C., Smith, M.L., Pace, M.L. and Fischer, D.T., 1996. Arrival, spread and early dynamics of a zebra mussel (*Dreissena polymorpha*) population in the Hudson River estuary. *Canadian Journal of Fisheries and Aquatic Science* **53**, 685-691.

Strayer, D.L., Caraco, N.F., Cole, J.J., Findlay, S.E.G. and Pace, M.L., 1999. Transformation of freshwater ecosystems by bivalves. A case study of zebra mussels in the Hudson River. *Bioscience* **49**, 19-27.

Sullivan, M., Lucy, F. and Minchin, D., 2002. The association between zebra mussels and aquatic plants in the Shannon River system, Ireland. *Aquatic Invaders* **13**, 6-9.

Ten Winkel, E.H. and Davids, C., 1982. Food selection by *Dreissena polymorpha*, Pallas (Mollusca: Bivalvia*)*. *Freshwater Biology* **12**, 553-558.

Toczylowski, S.A. and Hunter, R.D., 1996. Do zebra mussels preferentially settle on Unionids and /or adult conspecifics? *In*: D'Itri, F. (ed.) *Zebra mussels and aquatic nuisance species*. Ann Arbor Press. Michigan, pp 125-141.

Toczylowski, S.A., Hunter, R.D. and Armes, L.M., 1999. The role of substratum stability in determining zebra mussel loads on unionids. *Malacologia* **41(1)**, 151-162.

Todd Howell, E., Marvin, C.H., Bilyea, R.W., Kauss, P.B. and Somers, K., 1996. Changes in environmental conditions during *Dreissena* colonisation of a monitoring station in Eastern Lake Erie. *Journal of Great Lakes Research* **22(3)**, 744-756.

Toner, P.F., 1979. *The trophic status of Irish lakes, Lough Key*. An Foras Forbatha. WR/LIZ.

Tuchman, N.C., Burks, R.L., Call, C.A. and Smarrelli, J., 2004. Flow rate and vertical position influence ingestion rates of colonial zebra mussels (*Dreissena polymorpha*). *Freshwater Biology* **48**, 191-198.

Tucker, J.K., Theiling, C.H., Blodgett, K.D. and Thiel, P.A. 1993. Initial occurrences of zebra mussels (*Dreissena polymorpha*) on freshwater mussels (Family Unionidae) in the Upper Mississippi River system. *Journal of Freshwater Ecology* **8**, 245-251.

Tucker, J.K., 1994. Colonization of Unionid bivalves by the zebra mussel *Dreissena polymorpha*, in Pool 26 of the Mississippi River. *Journal of Freshwater Ecology 9* 129-134.

Vanderploeg, H.A., Johengen, T.H., Strickler, J.R., Liebig, J.R. and Nalepa, T.F., 1996. Zebra mussels may be promoting *Microcystis* blooms in Saginaw Bay and Lake Erie. *Bulletin of the North American Benthological Society*, **13(1)**, 181-182.

Vanderploeg, H.A., Liebig, J.R., Carmichael, W.W., Agy, M.A., Johengen, T.H., Fahnenstiel, G.L. and Nalepa, T.F., 2001. Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (lake Huron) and Lake Erie. *Canadian Journal of Fisheries and Aquatic Science* **58**, 1208-1221.

Walz, N., 1973. Studies on the biology of *Dreissena polymorpha* Pallas in the Lake of Constance. *Arch. Hydrobiol. Suppl.* **42**, 452-458.

Walz, N., 1975. Ruckgang der *Dreissena polymorpha* – population im Bodensee. *Gas-Wasserfach. Wasser Abwasser* **115**, 20-24.

Walz, N., 1978 The energy balance of the freshwater mussel *Dreissena polymopha* Pallas in laboratory experiments and in Lake Constance. IV. Growth in Lake Constance. *Arch. Hydrobiol./Suppl.* **55**, 142-156

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology* **30**, 377-392

Wiktor, J., 1963. Research on the ecology of *Dreissena polymorpha* (Pall.) in the Szczecin Lagoon. *Ekologia Polska* **A11**, 275-280.

Williams, J.D, Warren, M.L. Jr, Cummings, K.S., Harris, J.L. and Neves, R.J., 1993. Conservation status of freshwater mussels of the United States and Canada. *Fisheries* **18 (9)**, 6-22.

Wilson, A.E., 2003. Effects of zebra mussels on phytoplankton and ciliates: a field mecocosm experiment. *Journal of Plankton Research* **25(8)**, 905-915.

Zanatta, D.T., Mackie, G.L., Metcalfe-Smith, J.L. and Woolnough, D.A., 2001. A refuge for native freshwater mussels (Bivalvia: Unionidae) from impacts of the exotic zebra mussel (*Dreissena polymorpha*) in Lake St. Clair. *Journal of Great Lakes Research* **28(3)**, 479-489.

Websites

www.coillte.ie

www.epa.gov/grtlakes/lmmb/methods/chllabr2.pdf

www.sgnis.org

APPENDIX ONE: Development of Sediment and Depth Models for Lough Key Using Data Generated by an Acoustic Ground Discrimination System.

June 2001

Ivor Marsh, Monterrey Software
John Breslin, Seabed Surveys International Ltd

Background

The RoxAnn™ acoustic ground discrimination system (AGDS) was used to collect bathymetric and sediment data in Lough Key. This system allows the collection of large volumes of data, which are achieved remotely, with the result that there is no disturbance to the lakebed by the act of observation. The post-processed hydro-acoustic data from the survey of Lough Key was integrated with Geographical Information System (GIS) Technology, which was employed by Monterrey Software to develop sediment and depth models of the surveyed lake. These models can then be used to extract baseline data for use in scientific and spatial analysis. There is potential to combine information from dive and grab-sampling programmes with the sediment and depth models in order to investigate the relationship between sediment and depth on the distribution and abundance of zebra mussels within Lough Key.

Hydro-acoustic Survey

Prior to the survey of Lough Key, survey tracks were designed, using Microplot electronic charting software, which enabled the survey vessel to follow a pre-determined route. A systematic parallel survey design was implemented and transects were run in an East-West direction. Transects were set at two levels of intensity, using near shore transects spaced at 50 metres and offshore transects spaced at 100 metres, in order concentrate the sampling effort in shallow parts of the lake where highest zebra mussel densities are expected. The cruise track employed during the course of the survey is illustrated in Figure 1. Where sufficient depth allowed, the vessel followed this pre-determined track throughout the survey.

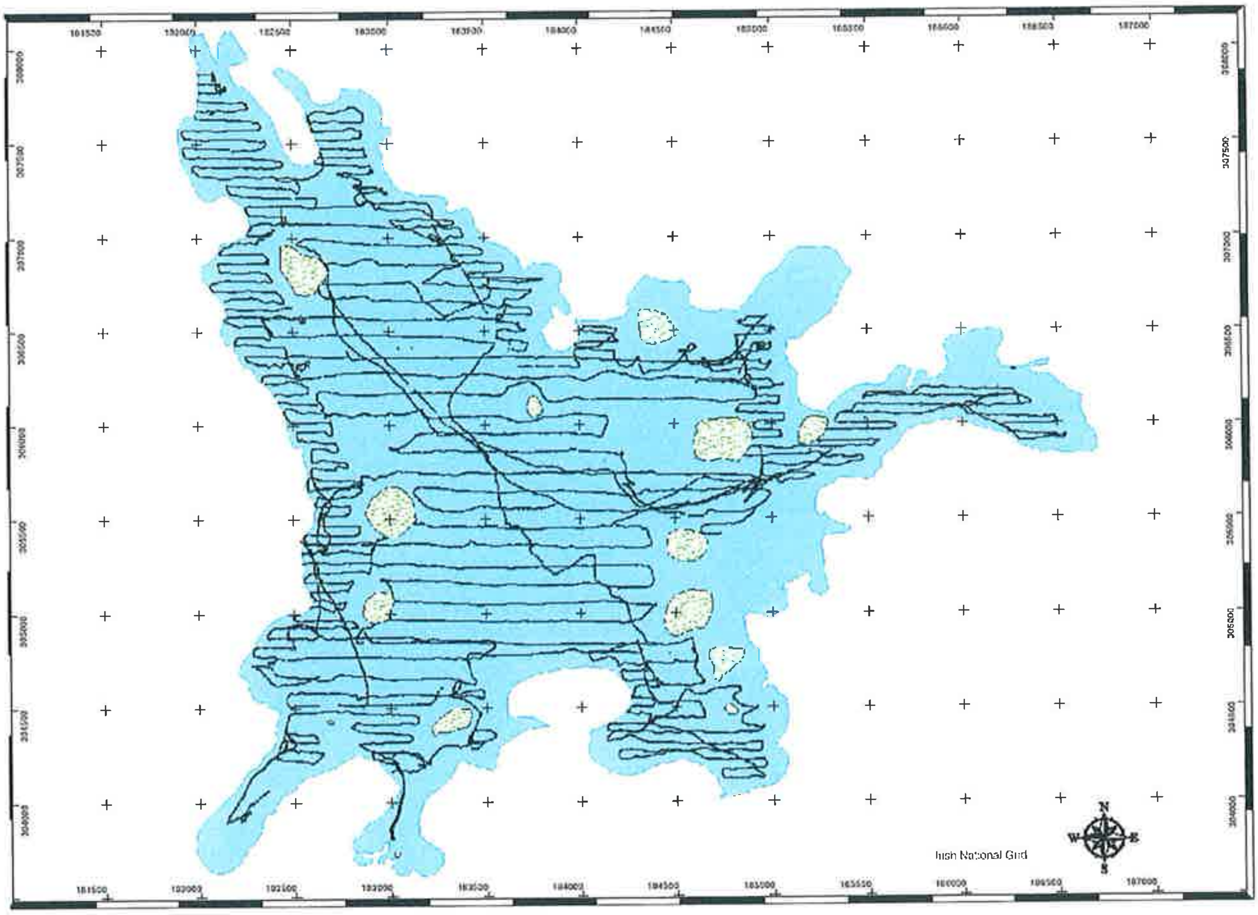


Fig 1 The Lough Key Roxann ™ survey track

The survey was carried out onboard a 17 ft cabin cruiser between the 26th May and the 5th of June 2001. The vessel was equipped with an inverter and batteries in order to produce a clean consistent power supply to allow the collection of acoustic data with minimal noise and interference. The transducer was mounted on a pole attached to the starboard side of the vessel, in order to minimise any signal attenuation due to aeration. A 200 kHz RoxAnn™ acoustic ground discrimination system (AGDS) was used for the collection of sediment type data. Positional accuracy was maintained throughout the survey using Koden Differential Global Positioning Systems (DGPS) set to output the WGS84 Datum.

Description of the Acoustic Ground Discrimination System

The RoxAnn™ hydro-acoustic processor was used to provide detailed discrimination between lakebed sediment types. RoxAnn™ operates as a passive receiver of acoustic signals generated by a standard single beam echo sounder. Using two digital indices generated from the first (E1) and second echoes (E2) observed via a dedicated parallel receiver, ground discrimination can be successfully achieved. E1 is an integration of the tail of the first echo, and provides an estimation of the evenness or roughness of the sediment, whilst E2 is an integration of the whole of the second echo and indicates the hardness of the substratum. Changes in E1 and E2 occur because different lakebed material types reflect sound from the transducer in different ways. These differences are reflected in the strength of the voltages of the returned echoes. Using the E1 and E2 values in combination allows the operator to identify the nature of the lakebed and to distinguish a wide range of sediment types ranging from, fine mud through sand and gravel, onto cobbles and bedrock

Ground-truthing

Prior to the collection of data the equipment was calibrated over a variety of sediment types in order to allow the creation of a "boxfile" based on an E1 versus E2 scatterplot. Various "box sets" can be applied to the data so that each box has a minimum and maximum E1 and E2, which relates to the acoustic signature produced by a particular sediment type. A 0.25 m^2 Van–Veen grab sampler and an underwater camera mounted on a drop frame were used to provide the ground-truthing information for the AGDS system.

The data was edited in real-time for the selection of appropriate ground-truthing sites by re-analysing the data to detect 'natural' clusters in E1 and E2 values. Once these clusters have been identified a grab or camera is employed to identify the sediment type that produces this acoustic response. Real-time visualisation using Microplot allows the operators to keep a constant check on variations in bottom type, consistency between tracks and sediment discrimination (with regard to *in situ* observations using the grab or camera).

Preliminary Data Treatment

Depth spikes were removed from the dataset using a Median programme designed to remove obvious outliers from the data-set prior to mapping. In certain deeper parts of the lake it was difficult to obtain satisfactory depth measurements due to sub-bottom penetration of the sound pulse in very soft sediments. When this occurs there is a fundamental confusion between seabed backscatter and sub-bottom reflection because they arrive back at the transducer at the same time. This problem is not specific to RoxAnn™ and will be shared by any acoustic system, which attempts to classify the lakebed, by the analysis of echosounder signals. Sound energy can penetrate the sub-bottom if the echo sounder is using low frequencies, high power or operating in very shallow water, and it is more likely to occur in soft substrates. In order to collect correct depth measurements it was necessary to re-survey these areas using a different hardware setting, which allowed the collection depth recordings over very soft substrates.

Mapping and Modelling of Acoustic Data

On completion of the survey, all ground-truthing sites were overlain onto the track data for the purpose of fine tuning the "boxfiles". New "boxfiles" were then created based on both ground-truth data and E1 and E2 clusters. Any clusters that were not backed up by the ground-truth data were included as unknowns. A numerical value relating to sediment or plant type was assigned to each of the "boxfiles". Plants on the lakebed produced characteristically high E1 values and were easily identified from bare sediment.

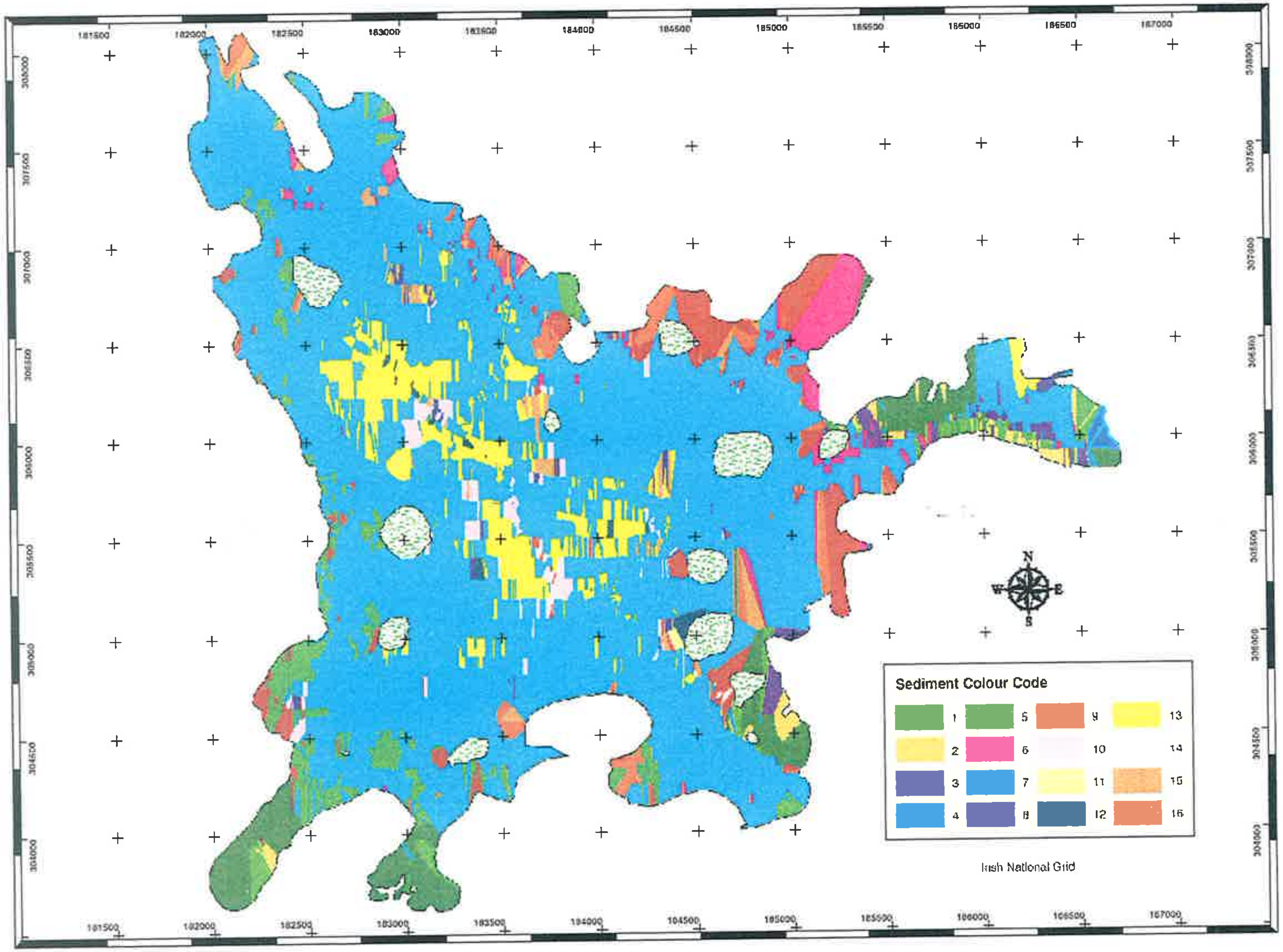
Logistically, it is not always possible to get exhaustive values of data at every desired point. Therefore, interpolation is important and fundamental to the generation of geo-statistical models. Kriging is a geo-statistical interpolation method that provides a means of interpolating values for points not physically sampled, by using knowledge about the underlying spatial relationships in the dataset. Kriging is based on regionalised variable theory and is superior to other means of interpolation because it provides an optimal interpolation estimate for a given coordinate location, as well as a variance estimate for the interpolation value. The kriging method uses a variogram to express the spatial variation and to minimise the error of predicted values. Ordinary kriging was the interpolation used to determine depth.

Bathymetric Map

The bathymetric chart is illustrated in Figure 3.2. Table 3.1 gives the estimated area (m^2) at different depth zones within Lough Key. The RoxAnn™ survey could only research lake areas >2m in depth. The total lake area <2m deep was extrapolated using the relevant Ordinance Survey Ireland (OSI) vector tiles. Substrate mapping of areas <2m depth were carried out by the ROV video survey.

Sediment Map

As sediment data is categorical and depth data is continuous a different method of interpolation i.e. nearest neighbour algorithm was used to generate the sediment model (Figure 2 and PDF file lough_key_sediment_model_2004). Sediment types obtained by ground-truthing and corresponding RoxAnn™ colour codes are presented in Table 3.2.



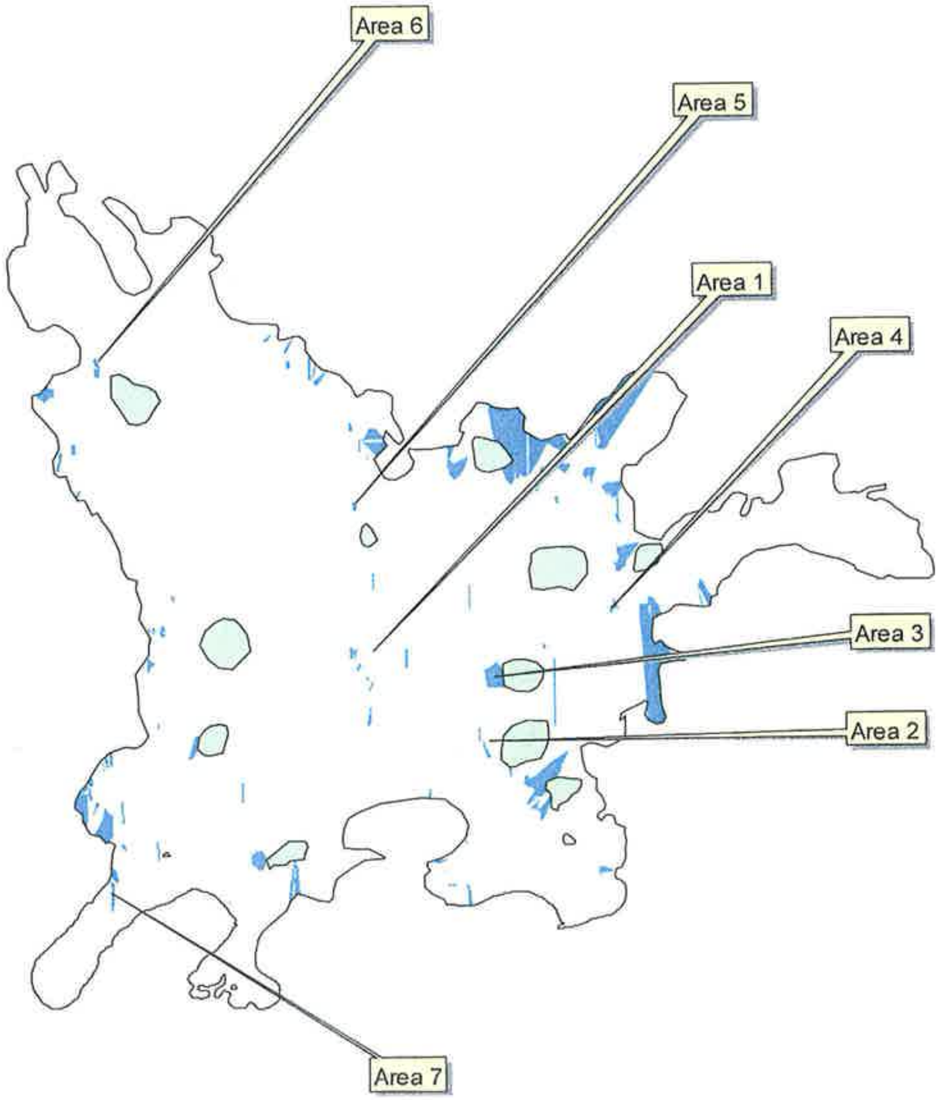
✓ Fig 2 Lough Key sediment types classified by RoxAnn™

Colour Code	Colour	Sediment Type	Observations
1 and 2	Deep Green and Deep Yellow	Algal beds on mud	Acoustic signature is definitely different than Colour 1 Camera footage looks the same as above Possibly different proportions of plant species or different underlying substrate
3	Magenta	Algal beds on mud	Same as 5 but lower E1 values
4	Electric Blue	Transition	Transition between different substrates. No definite cluster of E21 and E2
5	Green	Plants on mud	Sometimes zebra mussels attached to plant shoots Also found zebra mussels attached to small stones or dead Anodonta shells. These small stones were too small to generate an acoustic signature RoxAnn™ picked up a definite acoustic signature for plants over mud as opposed to mud
6	Pink	Sandy mud / Mud & Clay	Higher E2 values indicate harder substrate than mud alone
7	Cyan	Mud	Characteristic low E1 and E2 values
8	Purple	Transition Sediment	A few small clusters identified
9	Red	Stones & Rock	Characteristic high E1 and E2 values
10	Neon Red	Ridge or Peaks of hard bottom may be covered with mud or silt	A definite ridge shows up in the depth profile so it is likely that there is a hard ridge present. However, the ridge may be covered with liquid mud or silt which can cause the sound energy to penetrate the sub-bottom thus producing high E1 values.
11	Yellow	Gravel & Stones	Only one small cluster identified.
12	Blue	Unknown	Looks like something very hard as the E2 value went right off the scale
13	Gold	Liquid mud/silt but E1 and E2 values are False	This cluster indicates a lost depth reading over liquid mud or silt. In these circumstances the E1 and E2 values are affected, however, ground-truthing has shown these areas to contain mud/silt. Although the E1 and E2 values are abnormal repeatability is still maintained.
14	White	Possibly Mussels over Rock	Dense clusters of zebra mussels over rock may be resulting in lower E2 values. This is difficult to ascertain as there are only small patches of rocky areas in very shallow water and the mussels appear to aggregate in discrete clumps rather than extensive mats making it difficult if the mussels are resulting in lower E2 values.
15	Orange	Gravelly sand	A few small clusters identified.
16	Crimson	Transition / Plants on Mud	This cluster is found only in small areas. One cluster present near the Light Green Cluster (10) suggesting mud and weeds.

Table 1. RoxAnn™ colour codes and sediment descriptions for the Lough Key sediment model

APPENDIX 2

Additional "Stones and Rock " Ground Truthing Locations



Appendix 2. Lough Key Ground-truthing Survey

Grab Samples, Lough Key — **Date: 17/08/01**

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	*Dreissena* Yes/No	New Settlement	Sediment Category	Category Number
N. Boyle River	1	183	Tra	105	N 53.99091 W008.26791	2.2	N	-	Mud + plant debris + *Sparganium*	2
	2	183	Tra	106	N 53.99102 W008.26789	2.3	Y -1 only	N	Mud + Peat + Roots	2
	3	183	Tra	107	N53.99101 W008.26790	2.3	Y	N	Mud + *Anodonta* (*Dreissena*) + *Sparganium* + loose druse	2
East of Church	1	23	Tra 2	108	N53.99712 W008.25368	10.3	N	-	Mud (Silky)	1
	2	23	Tra 2	109	N53.99721 W008.25373	10.3	N	-	Mud + odd gastropod + odd dead *Dreissena*	1
	3	23	Tra 2	110	N53.99708 W008.25368	10.4	N	-	Mud (Silky)	1
N.NE Hog Isl.	1	59	Tra 3	111	N54.00448 W008.25664	11.3	Y	N	Small *Dreissena* druse	2
	2	59	Tra 3	112	N54.00451 W008.25663	11.5	N	-	Empty	2
	3	59	Tra 3	113	N54.00450 W008.25672	11.5	N	-	Empty	2
	4	59	Tra 3	114	N54.00450 W008.25672	11.4	Y	N	Mud, Gravel, gastropod + *Dreissena* druse	2
	5	59	Tra 3	115	N54.00438 W008.25704	12.3	Y	N	Gastropods + *Dreissena* druse	2
Near Hog Isl.	6	59	Tra 3	116	N54.00445 W008.25789	13.7	Y	N	Mud, Little gravel, plant debris	2
	7	59	Tra 3	117	N54.00454 W008.25818	13.4	N	-	Empty	2
	8	59	Tra 3	118	N54.00435 W008.25818	15.3	N	-	Empty	2
	9	59	Tra 3	119	N54.00438 W008.25824	14.5	N	-	Empty	2
100 m off Tra 3	10	59	Tra 3	120	N54.00442 W008.25830	14.3	N	-	Tripped early	2
120 m off Tra 3	11	59	Tra 3	121	N54.00444 W008.25848	14.7	Y	Y	Dreissena druse only	2
130 m off Tra 3	12	59	Tra 3	122	N54.00452 W008.25862	14.7	N	-	Tripped early	2
130 m off Tra 3	13	59	Tra 3	123	N54.00459 W008.25865	14.2	N	-	Mud only	2
50 m off Tra 3	14	59	Tra 3	124	N54.00407 W008.25706	16.5	Y	N	Mud, stone submerged in mud	2
	15	59	Tra 3	125	N54.00402 W008.25721	16.3	Y	N	Dreissena druse only	2
	16	59	Tra 3	126	N54.00402 W008.25743	17.3	N	-	Mud only	1
80 m off Tra 3	17	59	Tra 3	127	N54.00403 W008.25759	17.8	Y	?	Mud + small druse (3 *Dreissena*)	2
90 m off Tra 3	18	59	Tra 3	128	N54.00403 W008.25787	18.9	N	-	Mud	1
East Hog Isl.	1	59		129	N 53.9964 W008.25786	0.5	Y	Y	Sand/Mud/gravel + most druses stuck to a piece of gravel (Rocky shore)	3
East Hog Isl.	2	59		130	N 53.9964 W008.25786	1.0	Y	Y	*Dreissena* on ash + sally trees (branches and roots)	3
									Anodonta bed here with 100% *Dreissena*, density 7m2.	3
Centre Lake	1	1384	St-Roc	132	N53.99529 W008.24765	8.5	N	-	Empty	3
	2	1384	St-Roc	133	N53.99532 W008.24775	8.6	Y	Y	Druse only	3
	3	1384	St-Roc	134	N53.99536 W008.24786	10.6	Y	Y	Pebbles + *Dreissena* -not drused	3
	4	1384	St-Roc	135	N53.99536 W008.24773	9.6	Y	Y	Rock, Pebbles, druse	3

Grab Samples, Lough Key Date: 17/08/01

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	*Dreissena* Yes/No	New Settlement	Sediment Category	Category Number
Centre lake	1	1407	St-Ro2	136	N53.99678 W008.24730	11.2	Y	Y	Pebbles, druses	3
	2	1407	St-Ro2	137	N53.99690 W008.24800	12.5	Y	Y	Druse only	2
	3	1407	St-Ro2	138	N53.99683 W008.24752	12.7	Y	Y	Druse only	2
	4	1407	St-Ro2	139	N53.99686 W008.24754	12.4	Y	N	Single *Dreissena*	2
40 m from	5	1407	St-Ro2	140	N53.99647 W008.24706	13.2	Y	N	Mud + 1 *Dreissena*	2
50 m from	6	1407	St-Ro2	141	N53.99634 W008.24705	12.9	Y	Y	*Dreissena* druse	2
Centre lake	1	1415	St-Ro3	142	N53.99706 W008.24787	13.9	Y	N	*Dreissena* druse	2
	2	1415	St-Ro3	143	N53.99715 W008.24781	15.4	N	-	Empty	2
	3	1415	St-Ro3	144	N53.99723 W008.24802	15.8	Y	Y	*Dreissena* druse	2
	4	1415	St-Ro3	145	N53.99722 W008.24746	17.6	N	-	Mud (Silky)	1
Centre lake	1	1421	St-Ro4	146	N53.99776 W008.24846	13.8	Y	Y	Druse + Mud + rope	2
20 m from	2	1421	St-Ro4	147	N53.99786 W008.24857	15.5	N	-	Mud (submerged gastropods and dead *Dreissena*)	2
On site	3	1421	St-Ro4	148	N53.99760 W008.24842	15.6	Y	Y	*Fontinalis* + *Dreissena* druse	2
30 m from	4	1421	St-Ro4	149	N53.99762 W008.24803	15.8	Y	Y	Mud (submerged gastropods and single live *Dreissena*)	2
20 m from	1	1432	St-Ro5	150	N53.99820 W008.24880	13.7	N	-	Mud + *Cladophora*	1
10 m from	2	1432	St-Ro5	151	N53.99821 W008.24915	13.7	-	-	Didn't trigger	-
	3	1432	St-Ro5	152	N53.99811 W008.24890	15.8	Y	Y	Druse only	2
20 m from	4	1432	St-Ro5	153	N53.99809 W008.24881	13.3	Y	Y	Stone, pebble and druse.	3
SE Bullock	1	23450	Area 4	155	N54.00040 W008.22860	3.6	N	-	Mud mainly, silt and sand + *Fontinalis*	1
	2	23450	Area 4	156	N54.00038 W008.22840	1.7	Y	Y	Rock, Druse + *Cladophora*	4
	3	23450	Area 4	157	N54.00038 W008.22840	2.0	Y	Y	Rock and druse	4
	4	23450	Area 4	158	N54.00038 W008.22836	1.9	Y	Y	Rock and druse	4
SE Bullock	1	23226	Area 41	159	N54.00035 W008.22854	2.8	Y	Y	Rock, Druse + *Cladophora*	4
	2	23226	Area 41	160	N54.00042 W008.22843	3.2	Y	Y	Rock and druse	4
	3	23226	Area 41	161	N54.00046 W008.22836	3.0	Y	Y	Loose *Dreissena* (rock)	4

Grab Samples, Lough Key Date: 17/08/01

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	*Dreissena* Yes/No	New Settlement	Sediment Category	Category Number
W. Sally Isl	1	323	Area 3	162	N53.99752 W008.23849	3.6	Y	Y	Stone, gravel and druse	3
	2	323	Area 3	163	N53.99754 W008.23845	3.5	Y	Y	Stone, gravel and druse	3
	3	323	Area 3			3.5	Y	Y	Druse	3
	1	1388	Area 2	164	N53.99433 W008.23903	5.6	Y	Y	Gravel and druse	3
	2	1388	Area 2	165	N53.99435 W008.23898	5.6	Y	Y	Mud, gravel and druse	3
	3	1388	Area 2	166	N53.99440 W008.23882	5.4	Y	Y	Gravel and single *Dreissena*	3
	1	1393	Area 21	167	N53.99488 W008.23794	5.4	Y	Y	Mud, gravel, dead gastropds, pebble and druse	3
	2	1393	Area 21	168	N53.99489 W008.23781	4.9	Y	Y	Gravel and single *Dreissena*	3
	1	23828	Area 7	169	N53.98757 W008.26810	2.3	Y	Y	Old plant debris, *Sparganium*, druse	3
	2	23828	Area 7	170	N53.98766 W008.26804	2.4	Y	Y	Old plant debris, *Sparganium*, druse	3
	3	23828	Area 7	171	N53.98772 W008.26817	2.3	Y	Y	*Anodonta* x 2, mud and druse	3
	4	23828	Area 7	172	N5398771 W008.26821	2.2	N	-	Condensed plant debris	3
	1	1376	ST-Roc6	173	N53.99815 W008.24475	9.2	Y	Y	Druse only (rock)	3
	2	1376	ST-Roc6	174	N53.99825 W008.24477	10.1	Y	Y	Single *Dreissena*'s (rock)	3
	3	1376	ST-Roc6	175	N53.99840 W008.24481	10.2	Y	Y	Druse only (rock)	3
	1	327	327	176	N5400172 W008.24714	3.6	Y	Y	Single Dreissena's (rock)	3
	2	327	327	177	N54.00177 W008.24720	3.4	Y	Y	Druse only (rock)	3
	3	327	327	178	N54.00183 W008.24729	2.9	Y	Y	Druse and singles (rock)	3
	1	334	334	179	N54.00511 W008.24873	3.1	Y	Y	Gravel and druse	3
	2	334	334	180	N54.00514 W008.24880	3.4	Y	Y	*Anodonta*, gravel and druse	3
	3	334	334	181	N54.00520 W008.24864	3.9	Y	Y	Druse only (rock)	4
	4	334	334	182	N54.00529 W008.24877	5.6	Y	Y	Druse only (rock)	4
	1		Area 6	183	N54.01200 W008.26908	2.4	Y	Y	*Cladophora* mats and *Dreissena* druses	3
	2		Area 6	184	N54.01200 W008.26914	2.4	Y	Y	*Dreissena* attached to caddis, stones and gravel,	3
	3		Area 6	185	N54.01203 W008.26919	2.6	Y	Y	*Cladophora*, gravel, druse	3

Grab Samples, Lough Key				Date: 18/08/01						
Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	*Dreissena* Yes/No	New Settlement	Sediment Category	Category Number
Between St-Ro2 and St-Ro3	1	None	None	186	N53.99694 W008.24787	13.4	N	-	Mud and dead *Dreissena*	1
	2			-	Missed input	12.8	Y	Not checked	Stone and live single *Dreissena*'s	3
				187	N53.99707 W008.24789	13.4	Y	Y	Stone and live single *Dreissena*'s - grab stuck on rock	3
Between St-Ro3 and St-Ro4	1	None	None	188	N53.99749 w008.24813	17.1	N	-	Mud only	1
	2			189	N53.99743 W008.24823	17.5	Y	Not checked	Rock and druse	3
Between St-Ro4 and St-Ro5	1	None	None	190	N53.99799 W008.24858	14.6	Y	Not checked	Mud, plant debris, gastropods, few single live *Dreissena* and dead *Dreissena*	2
	2			191	N53.99800 W008.24835	15.7	N	-	Mud only	1
	3			192	N53.99807 W008.24852	13.4	Y	Not checked	Rock and druse	3
West Bullock Isl.	1	None	None	193	N54.00178 W008.24001	3.7	Y	Not checked	Stone and single *Dreissena*'s	3
	2			194	N54.00187 W008.24009	3.7	Y	Not checked	Stones and *Dreissena*'s on them	3
	3			195	N54.00179 W008.24016	3.0	Y	Not checked	Rock and single *Dreissena*'s	4
	4			196	N54.00169 W008.24025	3.4	Y	Not checked	Mud, rock and druse	3
	5			197	N54.00153 W008.23960	2.6	Y	Not checked	Stones and *Dreissena*'s on them	3
	6			198	N54.00165 W008.23964	3.0	Y	Not checked	Rock and druse	4
	7			199	N54.00174 W008.23968	3.4	N	-	Nothing	-
	8			200	N54.00178 W008.23976	3.5	N	-	Rock - empty	4
	9			201	N54.00203 W008.24011	5.0	N	-	Mud	1
	10			202	N54.00092 W008.23993	3.6	Y	Not checked	Rock and druse	4
	11			203	N54.00090 W008.24013	3.9	N	-	Mud (very shelly)	2
	12			204	N54.00093 W008.24050	5.3	N	-	Mud (very shelly)	2
	13			205	N54.00217 W008.24681	3.7	Y	Not checked	*Cladophora* and *Dreissena*	2
	14			206	N54.00218 W008.24694	4.2	Y	Not checked	Single *Dreissena*'s	2
	15			207	N54.00217 W008.24706	3.9	Y	Not checked	*Cladophora* and *Dreissena*	2
	16			208	N54.00190 W008.24789	3.1	Y	Not checked	Gravel and *Dreissena* (33mm shellof *Dreissena* here)	3
	17			209	N54.00189 W008.24792	3.6	Y	Not checked	Mud, gravel and *Dreissena*	2
	18			210	N54.00195 W008.24810	4.3	Y	Not checked	Mud, gravel, gastropods and *Dreissena*	3
	19			211	N54.00206 W008.24833	6.0	N	-	Mud (maerly)	1
	20			212	N54.00222 W008.24864	9.0	N	-	Mud (Silky)	1
	21			213	N54.00183 W008.24797	3.3	Y	Not checked	Rock and druse	4
	22			214	N54.00173 W008.24803	2.7	N	-	Rock	4
	23			215	N54.00156 W008.24802	3.3	Y	Not checked	Rock and druse	4
	24			216	N54.00151 W008.24823	3.5	Y	Not checked	Rock and druse	4
	25			217	N54.00144 w008.24837	3.7	Y	Not checked	Rock and druse	4
	26			218	N54.00130 W008.24854	3.9	N	-	Rock - nothing	4
	27			219	N54.00123 W008.24860	4.1	N	-	Rock - nothing	4
	28			220	N54.00119 W008.24865	4.2	N	-	Rock - nothing	4
	29			221	N54.00112 W008.24872	4.9	N	-	Rock - nothing	4
	30			222	N54.00098 W008.24884	5.2	N	-	Pebbles and maerl	2

Grab Samples, Lough Key				Date: 18/08/01						
Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	*Dreissena* Yes/No	New Settlement	Sediment Category	Category Number
West Bullock Isl.	31	None	None	223	N54.00069 W008.24910	5.1	N	-	Maerl and gastropods	2
	32			224	N54.00062 W008.24912	5.1	N	-	Maerl, pebbles, and *Dreissena* shell	3
	33			225	N54.00050 W008.24921	5.1	N	-	Rock , empty	4
	34			226	N54.00039 W008.24927	5.3	N	-	Rock , empty	4
	35			227	N54.00025 W008.24936	5.4	N	-	Rock , empty	4
	36			228	N54.00024 W008.24936	5.4	N	-	Rock , empty	4
	37			229	N54.00020 W008.24941	5.4	N	-	Mud and gastropods	2
St-Roc6	38	None	None	230	N54.00166 W008.24836	3.0	Y	Not checked	Druse	3
	39			231	N53. 99826 W008.24444	10.2	Y	Not checked	Some single *Dreissena*'s	3
	40			232	N53.99828 W008.24467	9.3	N	-	Rock , empty	4
	41			233	N53.99832 W008.24486	11.1	N	-	Mud and gastropods	1
	42			234	N53.99823 W008.24454	9.1	Y	Not checked	Some single *Dreissena*'s	3
	43			235	N53.99833 W008.24479	10.2	N	-	Rock , empty	4
	44			236	N53.99811 W008.24450	9.2	Y	Not checked	Druse	3
	45			237	N53.99820 W008.24453	9.1	Y	Not checked	Cobble, stone and *Dreissena*'s on them	3
Area 2	46			238	N53.99412 W008.23917	5.6	Y	Not checked	Stone with *Dreissena*'s	3
	47			239	N53.99410 W008.23924	6.1	Y	Not checked	Druse	3
	48			240	N53.99409 W008.23924	5.8	-	-	Didn't trigger	3
	49			241	N53.99409 W008.23929	6.1	-	-	Druse	3
				242	N53.99620 W008.24668				No sample taken here	
John 2	50			243	N53.99625 W008.24675	12.3		-		
	51			244	N53.99618 W008.24716	11.7		-		
John 1	52			245	N53.00451 W008.25713	11.5	Y	Not checked	Rock with druse	4
	53			246	N53.00458 W008.25731	11.3	Y	Not checked	Rock with druse	4

Grab Samples, Lough Key — **Date: 14/08/01**

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	Dreissena Yes/No	New Settlement	Sediment Category	Category Number
NW Bullock	1	Area 1	None	66	N54.00528 W008.23640	5.6	N	-	Mud (shelly), gastropods	2
	2	Area 1	None	66	N54.00528 W008.23640	5.2	Y	Not checked	Mud (shelly), *Anodonta* with *Dreissena*, druse (13 grams)	3
	3	Area 1	None	67	N54.00519 W008.23646	6.6	Y	Not checked	Mud (shelly), 1 *Anodonta* with *Dreissena*, 2 *Anodonta* without am, druse (5	3
Long Isl Bay	1	Area 2	None	68	N54.01658 W008.27129	5.5	N	-	Mud (Silky), no *Dreissena*	1
	2	Area 2	None	68	N54.01582 W008.27529	5.5	N	-	Mud (Silky), no *Dreissena*	1
	3	Area 2	None	68	N54.01582 W008.27529	5.5	N	-	Mud (Silky), no *Dreissena*	1
Long Isl Bay	1	Area 2	None	69	N54.01582 W008.27529	2.5	N	-	Mud (Shelly), no *Dreissena* : > 10 grams of gastropod shell	2
	2	Area 2	None	69	N54.01582 W008.27529	2.5	N	-	Mud (Shelly and maerly), no *Dreissena* : >10 grams of gastropod shell	2
	3	Area 2	None	69	N54.01582 W008.27529	2.5	N	-	Mud (Shelly), *Anodonta* - no *Dreissena*	2
N. Hog Island	1	Unkonwn	None	70	N54.00511 W008.25889	13.4	N	-	Mud (Silky), no *Dreissena*	1
	2	Unkonwn	None	70	N54.00511 W008.25889	13.2	N	-	Mud (Silky), no *Dreissena*	1
	3	Unkonwn	None	70	N54.00511 W008.25889	13.2	N	-	Mud (Silky), no *Dreissena*	1
N. Hog Island	1	Unkonwn	None	71	N54.00258 W008.25371	18.1	N	-	Mud (Silky), no *Dreissena*	1
	2	Unkonwn	None	71	N54.00258 W008.25371	18.1	N	-	Mud (Silky), no *Dreissena*	1
	3	Unkonwn	None	71	N54.00258 W008.25371	17.9	N	-	Mud (Silky), no *Dreissena*	1
N. Hog Island	1	Unkonwn	None		N54.00717 W008.26059	18.1	N	-	Mud (Silky), no *Dreissena*	1
	2	Unkonwn	None		N54.00717 W008.26059	18.1	N	-	Mud (Silky), no *Dreissena*	1
	3	Unkonwn	None		N54.00717 W008.26059	17.9	N	-	Mud (Silky), no *Dreissena*	1
East Hog Isl	1	Unkn 8	None		N53.9971 W008.2535	10.5	N		Mud (Silky), no *Dreissena*	1
	2		None		N53.9971 W008.2535	10.5	N		Mud (Silky), no *Dreissena*	1
Hog Isl. deep buoy	1	Unknown	None	72& 73	N53.99830 W008.25055	24.0	N	-	Mud (Silky), no *Dreissena*	1
N.W. Hermit Isl.	1	3522	None		N54.00616 W008.25027	15.5	N	-	Mud (Silky), no *Dreissena*	1
	2	3522	None		N54.00717 W008.26059	15.6	N	-	Mud (Silky), no *Dreissena*	1
	3	3522	None		N54.00717 W008.26059	15.3	N	-	Mud (Silky), no *Dreissena*	1
S.E. Hermit Isl.	1	Unkn 9	None		N53.9988 W008.24305	12.3	N		Mud (Silky and fine shells), very fine plant detritus, no *Dreissena*	1
	2		None		N53.9988 W008.24305	12.4	N		Mud (Silky and fine shells), decaying leaves; no *Dreissena*	1
East of Boyle River	1	Area 3	None	74	N53.99161 W008.26354	4.2	N	-	Mud with some sand, *Anodonta* (small and large) under mud	1
	2	Area 3	None	74	N53.99161 W008.26354	4.2	N	-	Mud and plant detritus, old gastropods	1
	3	Area 3	None	74	N53.99161 W008.26354	4.4	N	-	Mud and plant detritus, old gastropods, peat ball	1
West Green Isl.	1		None	75	N53.99206 W008.23497	2.3	Y	Not checked	Rock with *Dreissena* druse	4
	2		None	75	N53.99206 W008.23497	2.3	Y	Not checked	Rock with *Dreissena* druse	4

Grab Samples, Lough Key Date: 13/08/01

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	Dreissena Yes/No	New Settlement	Sediment Category	Category Number
Drummons Bay	1	Gravelly-sand	None	62	N53.98752 W008.24232	2.3	N	-	Soft Mud and *Anodonta*, Subsurface -gastropods, *Pisidium* & organic fibres	3
	2				N53.98686 W008.24066	1.4	Y (6g)	Not checked	Primarily mud with stone with *Dreissena*. *P. lucens* and *Fontinalis*	3
	3				N53.98752 W008.24232	1.4	Y (20g)	Not checked	Primarily mud with stone, *L. trisulca*, Subsurface - gastropods	3
	4				N53.98752 W008.24232	1.4	Y (4g)	Not checked	Primarily mud with stone, trichoptera, *L. trisulca*, *P. lucens*, Subsurface - *Pisidium*, chironomids and gastropods	3
Rockingham	1	Gravelly-sand	None	63	N53.98715 W008.23605	3.4	Y (18g)	Not checked	Rock and stone with *Dreissena*	4
	2				N53.98715 W008.23605	3.4	Y (19g)	Not checked	Rock, stone and *Anodonta* with *Dreissena*	4
	3				N53.98715 W008.23605	3.4	Y (6g)	Not checked	Stone with *Dreissena*	3
Rockingham follie	1	Gravelly-sand	None	64	N53.98659 W008.23149	4.1	N	-	Mud only	1
	2				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and old *Anodonta*	1
	3				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and *Pisidium*	1
	4				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and plant detritus	1
W. Orchard Island	1	Gr-San	None	None	N53.99384 W008.23876	3.2	Y (11g)	Not checked	Gravel only and *Dreissena*	3
	2				N53.99384 W008.23876	3.6	Y (25g)	Not checked	Stone and hit rock/stone	4
	3				N53.99384 W008.23876	3.2	Y (19g)	Not checked	Cobble and stone	4
N. Boyle River	1	Gravelly-sand	Ridboy	None	N53.90095 W008.26770	2.5	N	-	*Anondonta* stuck in the grab only	3
	2				N53.90095 W008.26770	2.7	Y	Not checked	Mud, stone with *Dreissena* druse and old *Phragmites australis*	3
	3				N53.90095 W008.26770	2.6	Y	Not checked	*Anodonta* with *Dreissena* druse, branch with *Dreissena* druse, lot of old plant detritus and *Sparganium*	3
S. Hermit Isl. (Ridge	1	None	None	90	N53.99652 W008.24724	13.7	N	-	Silky mud, one dead *Dreissena* shell, a twig	1
	2			91	N53.99605 W008.24729	10.0	Y	Not checked	Rock with *Dreissena* druse	4
	3			92	N53.99602 W008.24733	10.9	N	-	Mud, some small pebbles; Subsurface - old decaying *Anodonta*	2
	4			93	N53.99570 W008.24675	8.6	Y	Not checked	Stone with a few *Dreissena*	3
	5			94	N53.99570 W008.24679	9.8	Y	Not checked	Stone with a few *Dreissena*	3
	6			95	N53.99570 W008.24693	10.3	Y	Not checked	Stone/rock and mud	4
S. Hermit Isl.	1	GSSHER	None	None	N54.00139 W008.24899	4.5	Y	Not checked	Druses only	3
	2	Gravelly-sand			N54.00170 W008.24851	3.6	Y	Not checked	One *Dreissena* and *Asellus*	3
	3				N54.00170 W008.24851	4.2	Y	Not checked	Druses only - hit rock	4
	4				N54.00118 W008.24874	4.8	Y	Not checked	Druses only	3
	5				N54.00118 W008.24874	5.1	Y	Not checked	Gravel, pebbles and sand, dead *Dreissena* and gastropods	3
	6				N54.00097 W008.24902	5.0	Y	Not checked	Gravel, pebbles and sand, druse and gastropods; clay under top layer	3
N. Hog Isl. (Ridge)	1	Gravelly - sand	None	99	N54.00332 W008.25872	4.7	Y	Y	Mud and *Anodonta* with *Dreissena* and recent settlement	3
	2			100	N54.00342 W008.25853	7.0	N	-	May have triggered early	3
	3			101	N54.00329 W008.25838	5.9	Y	Not checked	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3
	4			102	N54.00339 W008.25816	12.2	N	-	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3
	5			103	N54.00335 W008.25808	10.4	N	-	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3

Grab Samples, Lough Key **Date: 13/08/01**

Site	Grab No.	Ivor Ref.	WP. Ref.	WP No.	Grid Ref:	Depth (m)	Dreissena Yes/No	New Settlement	Sediment Category	Category Number
Drummons Bay	1	Gravelly-sand	None	62	N53.98752 W008.24232	2.3	N	-	Soft Mud and *Anodonta*, Subsurface -gastropods, *Pisidium* & organic fibres	3
	2				N53.98686 W008.24066	1.4	Y (6g)	Not checked	Primarily mud with stone with *Dreissena*. *P. lucens* and *Fontinalis*	3
	3				N53.98752 W008.24232	1.4	Y (20g)	Not checked	Primarily mud with stone, *L. trisulca*, Subsurface - gastropods	3
	4				N53.98752 W008.24232	1.4	Y (4g)	Not checked	Primarily mud with stone, trichoptera, *L. trisulca*, *P. lucens*, Subsurface - *Pisidium*, chironomids and gastropods	3
Rockingham	1	Gravelly-sand	None	63	N53.98715 W008.23605	3.4	Y (18g)	Not checked	Rock and stone with *Dreissena*	4
	2				N53.98715 W008.23605	3.4	Y (19g)	Not checked	Rock, stone and *Anodonta* with *Dreissena*	4
	3				N53.98715 W008.23605	3.4	Y (6g)	Not checked	Stone with *Dreissena*	3
Rockingham follie	1	Gravelly-sand	None	64	N53.98659 W008.23149	4.1	N	-	Mud only	1
	2				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and old *Anodonta*	1
	3				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and *Pisidium*	1
	4				N53.98659 W008.23149	4.1	N	-	Mud only; Submerged gastropods and plant detritus	1
W. Orchard Island	1	Gr-San	None	None	N53.99384 W008.23876	3.2	Y (11g)	Not checked	Gravel only and *Dreissena*	3
	2				N53.99384 W008.23876	3.6	Y (25g)	Not checked	Stone and hit rock/stone	4
	3				N53.99384 W008.23876	3.2	Y (19g)	Not checked	Cobble and stone	4
N. Boyle River	1	Gravelly-sand	Ridboy	None	N53.90095 W008.26770	2.5	N	-	*Anondonta* stuck in the grab only	3
	2				N53.90095 W008.26770	2.7	Y	Not checked	Mud, stone with *Dreissena* druse and old *Phragmites australis*	3
	3				N53.90095 W008.26770	2.6	Y	Not checked	*Anodonta* with *Dreissena* druse, branch with *Dreissena* druse, lot of old plant detritus and *Sparganium*	3
S. Hermit Isl. (Ridge	1	None	None	90	N53.99652 W008.24724	13.7	N	-	Silky mud, one dead *Dreissena* shell, a twig	1
	2			91	N53.99605 W008.24729	10.0	Y	Not checked	Rock with *Dreissena* druse	4
	3			92	N53.99602 W008.24733	10.9	N	-	Mud, some small pebbles; Subsurface - old decaying *Anodonta*	2
	4			93	N53.99570 W008.24675	8.6	Y	Not checked	Stone with a few *Dreissena*	3
	5			94	N53.99570 W008.24679	9.8	Y	Not checked	Stone with a few *Dreissena*	3
	6			95	N53.99570 W008.24693	10.3	Y	Not checked	Stone/rock and mud	4
S. Hermit Isl.	1	GSSHER	None	None	N54.00139 W008.24899	4.5	Y	Not checked	Druses only	3
	2	Gravelly-sand			N54.00170 W008.24851	3.6	Y	Not checked	One *Dreissena* and *Asellus*	3
	3				N54.00170 W008.24851	4.2	Y	Not checked	Druses only - hit rock	4
	4				N54.00118 W008.24874	4.8	Y	Not checked	Druses only	3
	5				N54.00118 W008.24874	5.1	Y	Not checked	Gravel, pebbles and sand, dead *Dreissena* and gastropods	3
	6				N54.00097 W008.24902	5.0	Y	Not checked	Gravel, pebbles and sand, druse and gastropods; clay under top layer	3
N. Hog Isl. (Ridge)	1	Gravelly - sand	None	99	N54.00332 W008.25872	4.7	Y	Y	Mud and *Anodonta* with *Dreissena* and recent settlement	3
	2			100	N54.00342 W008.25853	7.0	N	-	May have triggered early	3
	3			101	N54.00329 W008.25838	5.9	Y	Not checked	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3
	4			102	N54.00339 W008.25816	12.2	N	-	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3
	5			103	N54.00335 W008.25808	10.4	N	-	Mud with a lot of gastropods, some of which have *Dreissena* druses attached	3

Appendix 3: Halia Oceanographic Video : Substrate Analysis

Tape No. 1

				Substrate (%)								Plants									
Date	WP	Boat/Shore	Video time	Rock	Stone	Mud	Anodonta	Plant debris	Pebbles	% Cover	Anodonta (m^2)	*S. lacustris*	*P. australis*	*N. lutea*	*E. canadensis*	*S. emersum*	*L. trisulca*	*Potamogeton sp.*	*Cladophora*	*Charophyte*	*Fontinalis*
06/07/01	40	Boat to shore	-26.19/0.00	5	10	75	10			100	5	+		+	+	+	+				
06/07/01	39	Shore	-3.29.49	5	25	65	5			100				+			+		+		
06/07/01	39	Boat	-3.21.10		5	90	5			100	5			+		+			+		
06/07/01	37	Boat	-3.08.08	5	5	85	5			100	4				+	+		+	+		
06/07/01	37	Shore	-3.01.42			95	5			100	5	+		+		+	+	+	+		
06/07/01	32	Boat	-3.00 /+28.28			100				100	0			+		+	+				
06/07/01	32	Shore	-2.56/+32.60	5	35	60	<5			90	2			+	+	+	+				
06/08/01	34	Boat	-2.47/+41.38	5	10	85	<5			100	2			+	+	+					
06/08/01	34	Shore	-2.39/+49.33	5	50	40	5			100	5	+		+	+	+					
06/08/01	30	Boat	-2.33/+55.46			100					0						+				
06/08/01	30	Shore	-2.28/+1.00.57			100				100	1	+				+					
06/08/01	29	Boat and shore	-2/0.23/1.04.45		5	90		5		20	0	+		+	+	+	+	+		+	
06/08/01	1	Boat	-2.13/+1.15.52			95			5	100	1					+				+	
06/08/01	1	Shore	-2.06/+1.22.32		25	75	<5			100	3	+				+		+		+	
06/08/01	3	Boat and shore	-2.01/+1.28.56			95	<5		5	100	<1					+					
06/08/01	6	Boat	-1.55/+1.34.49			100				100	<1			+		+					
06/08/01	8a	Shore	-1.50/+1.40.20		35	60	<5	<5		85	3	+				+			+		
06/08/01	8	Boat	-1.39/+1.50.57			100	<5			100	1				+	+					
06/09/01	10	Boat	-1.32/+1.58.44	<5	<5	90	<5			100	3					+			+		
06/09/01	10a	Shore	-1.23/+2.07.11		5	95	5	<5		100	2	+				+			+		
06/09/01	13	Boat	-1.17/+2.13.28		<5	95	<5			100	3			+		+					
06/09/01	13a	Shore Island	-1.10/+2.20.36	5	50	40	5			100	?	+				+		+	+		
06/09/01	16	Boat (W. of isl)	-1.01/+2.29.25			100	<1			100	<1			+		+	+		+		+
06/09/01	16a	Shore Island (W. of isl)	-0.53/+2.38.40		<1	100	<1	<5		100	<1	+		+	+	+			+		
06/09/01	19a	150m W. of WP 19 (Shore)	-0.45/2.46.22		<1	100		<5		100	<1			+		+	+		+	+	+
06/09/01	19	150m E. of WP 19 (Boat)	-0.36/+2.55.47	Cladophora mats - substrate not visible															++		
06/09/01	21	Shore	-0.31/+3.00.04		<1	100	<1			100	1				+	+			+	+	
06/09/01	25	Shore	-0.25/+3.06.31		<5	100	<1			100	1					+					
06/09/01	27	Shore	-0.19/+3.12.47		5	95	<5			100	3			+		+			+		

Appendix 3: Halia Oceanographic Video : Substrate Analysis

Tape No. 2

				Substrate (%)								Plants									
Date	WP	Boat/Shore	Video time	Rock	Stone	Mud	Anodonta	Plant debris	Pebbles	% Cover	Anodonta (m^2)	*S. lacustris*	*P. australis*	*N. lutea*	*E. canadensis*	*S. emersum*	*L. trisulca*	*Potamogeto sp.*	*Cladophora*	*Charophyte*	*Fontinalis*
13/06/01	57	Shore	0.00.31-0.05.55	50	50					70	0-1			+					+		
13/06/01	58	Shore	0.06.00	10		90				50	2	+		+	+	+	+			+	
13/06/01	59	Shore	0.11.00	70	30					55	0			+				+	+		
13/06/01	60	Shore	0.16.07	70	30					50	0								+		
13/06/01	61	Shore	0.19.58			100				100	1								+		
13/06/01	61	Shore	0.24.37	50	50					50	0								+		
13/06/01	62	Boat	0.26.03			100				100	1				+		+		++		
13/06/01	62A	Shore (270m e of 62)	0.31.26	5	30	65				50	2	+		+	+						
13/06/01	63	Boat	0.35.52			100				100	1						+		++		
13/06/01	64	Boat	0.41.30	60	30	10				50	0				+				+		
13/06/01	65	Boat	0.45.02	70	30					40	0										
13/06/01	65A	Shore	0.50.31	70	30					40	0								++		
13/06/01	66	Boat	0.52.10			100				100	1								+		
13/06/01	66A	Shore (60m west of 66)	0.58.01	70	30					40	0			+	+	+		+			
13/06/01	67	Shore	1.03.01	50	40				10	85	0								+		
13/06/01	68	Shore	1.11.17	50	40				10	60	0								++		
13/06/01	69	Shore	1.18.04		10	90				100	1			+	+	+		+	+		
13/06/01	70	Shore	1.24.24	70	25				5	60	0								+		
13/06/01	71	East of rocky outcrop	1.29.26			100				0	0										
13/06/01	72	Shore	1.30.00	45	30	25	<5			50	1								+		
13/06/01	73	Reeds	1.36.30		5	95				100	3	+				+			+		
14/06/01	74	Shore	1.42.07		20	75	5			100	4	+			+				+		
14/06/01	75	Shore	1.47.50	5	5	90				90	3			+	+						
14/06/01	76	Shore	1.53.00	80	20					90	0								+		
14/06/01		Shore			10	90				100	3				+	+			+		
14/06/01	77	Shore	1.58.37			100				100	<1										
14/06/01	77A	Shore	2.02.00	75	20	3				80	0										
14/06/01	1	Shore	2.05.07		10	85	5			100	3	+		+	+	+			+		
14/06/01	2	Shore	2.11.00		15	80	5			90	2	+		+	+	+	+		+		
14/06/01	3	Shore	2.16.50		10	85	5			100	1	+				+					
14/06/01	4	Shore	2.22.00		10	90				90	1	+				+					
14/06/01	5	at WP	2.26.40		5	90	5			100	3	+		+	+	+		+	+		
14/06/01	6	Shore	2.37.25		20	75	5			100	3	+		+		+			+		
14/06/01	7	Shore	2.43.45	20	40	35	5			100	3	+			+	+					
14/06/01	8	WP	2.50.04																		
14/06/01	9	WP	2.50.30		5	90	5			100	2	+				+			+		
14/06/01	10	WP	2.55.50		<5	95	5			100	3					+					
14/06/01	10A	Shore	3.00.05		5	95				100	1	+				+			+		
14/06/01	11	WP	3.03.35		5	95				100	1								+		
14/06/01	11A	Shore	3.09.40		5	95				100	1			+					+		
14/06/01	12	Shore	3.15.00		10	85	5			100	5	+		+	+			+	+		
14/06/01	13	Shore	3.20.45	70	20	5	5			80	3					+					
14/06/01	14	Shore	3.27.54	80	20					80	0										
14/06/01	15	Shore	3.31.00	65	20	15				80	2										
14/06/01	16	Shore	3.36.00	60	10	30				100	3			+		+			+		
14/06/01	17	Shore	3.42.50		5	90	5			100	5			+		+					

Appendix 3: Halia Oceanographic Video : Substrate Analysis

Tape No. 3

				Substrate (%)								Plants										
Date	WP	Boat/Shore	Video time	Rock	Stone	Mud	Anodonta	Plant debris	Pebbles	% Cover	Anodonta (m2	*S. lacustris*	*P. australis*	*N. lutea*	*E. canadensis*	*S. emersum*	*L. trisulca*	*P. perfoliatus*	*Cladophora*	*Charophyte*	*Fontinalis*	*E. fluviatile*
17/06/01	18A	50 m west of 18	0.00.00		<5	95	<5			100	2	+		+	+	+						
17/06/01	19	Middle of Lake	0.10.05																			
17/06/01	20	Shore	0.10.13	25	25	50				90	3	+			+	+		+	+			
17/06/01	21	Island Shore	0.19.08								5					+		+	+			
17/06/01	22	Mainland Shore	0.26.30	50	20	25	5			10	6					+			+			
17/06/01	23	Island Shore	0.31.47	55	20	25				80	1	+			+	+			+			
17/06/01	24	Mainland Shore	0.38.22	10	10	65	5		10	75	3			+		+		+	+			
17/06/01	25A	N. side of Island	0.45.20	25	20	50			5	90	2	+						+	+			
17/06/01	26	Mainland Shore	0.49.01			80	15	<1	5	100	12			+	+	+						
17/06/01	27	West of Island	0.57.51	35	20	40	5	<1		100	5	+			+			+				
17/06/01	28	Mainland Shore	1.02.01			100				100	1			+	+	+				+		
17/06/01	29	Boat and shore	1.04.45 (Tape 1)		5	90		5		20	0	+		+	+	+	+	+		+		
17/06/01	30	Shore	1.00.57 (Tape 1)			100				100	1					+						
17/06/01	31	South of Island	1.11.23	0	<5	90	<5			100	2				+	+						
17/06/01	32A	70 m west of 32	1.15.06			100				100	1	+		+		+			+			
17/06/01	34	Shore	1.20.28	60	10	25	5	<1	<5	100	5			+		+			+			
17/06/01	35A	70 m east of Shore	1.26.06	70	10	20				70	3			+	+	+			+			
17/06/01	36	Shore	1.32.11	60	10	30			<5	80	3			+	+	+			++			
17/06/01	37	Marker Buoy	1.39.19			100				100	1											
17/06/01	38	Island	1.43.55			100				0	0						+					
17/06/01	39	Shore	1.48.37		10	85			5		1	+		+		+			+			
17/06/01	40	Shore	1.55.46	60	30	10				85	0	+		+					+			
17/06/01	41	50 m from 40	2.00.40																			
17/06/01	42	Boat	2.00.46			100				100								+				
17/06/01	43	Video not working																				
17/06/01	44	No WP given	2.22.24		15	80	5			100	4			+		+	+		+	+		
#######	45	Shore	2.27.44		5	95				100	1	+		+	+	+	+		+	+		
#######	46	Shore	2.34.52			100				100	1			+					+			
#######	47	Shore	2.40.15			100					0			+				+	+			
#######	48	Shore	2.42.09		10	85	5			100	3	+			+	+	+		+			
#######	49	Shore	2.49.24	5		100				5						+			++		+	
#######	50	Shore	2.53.17	30	20	50				90	1	+			+	+			+			
#######	51	Shore	2.57.34	20	30	50				100	1								+			
#######	52	60 m north 52-Island	3.01.06	35	25	35			5	70	1		+		+	+	+	+	+			+
#######	53	North of Island	3.10.10	35	25	30			10	85	1								+			
#######	54	North of Island	3.18.47	70	30	0				90	<1								++			
#######	55	70 m west of E. Island	3.22.19	70	10	10			10	90	<1				+				+			

Appendix 4 Larva/Veliger Densities/L 1998-2003

1998

Date	Site A	Site B	Site C	Site D
Jul wk 4	0.036	0.014	0.02	0.02
Aug wk 1	0.619	0.094	0.03	0.69
Aug wk 2	1.03	0.37	nd	**2.6**
Aug wk 3	1.65	0.43	0.49	1
Aug wk 4	1.88	0.7	1.3	0.74
Sep wk 1	1.77	0.14	0.56	0.38
Sep wk 2	0.86	0.1	0.52	0.22

1999

Date	Site A	Site B	Site C	Site D
Jul wk 2	6.3	2.9	8.1	nd
Jul wk 3	8.1	4.6	2.3	nd
Jul wk 4	4.2	1.5	**8.6**	4.5
Aug wk 1	8.4	4.2	4.4	2.8
Aug wk 2	5.6	3.3	11	0.2
Aug wk 3	2.4	4.6	7.1	1.1
Aug wk 4	2.5	2	3.7	0.6
Sep wk 1	0.6	0.2	1	0.3
Sep wk 2	0.6	0.01	0.4	0.2
Sep wk 3	0.07	0.1	0.28	0
Sep wk 4	0.3	0.1	0.05	0

2000

Date	Site A	Site B	Site C	Site D	Site E
Jun wk 4	11.5	3.6	nd	2.2	9.5
Jul wk 1	3.0	5.8	1.6	0.9	0.0
Jul wk 2	1.1	0.6	2.7	0.5	0.7
Jul wk 3	0.0	4.0	7.7	0.7	nd
Jul wk 4	7.0	16.7	10.8	2.4	7.4
Aug wk 1	3.0	**19.8**	2.8	2.0	6.1
Aug wk 2	1.7	1.7	1.9	1.8	2.3
Aug wk 3	2.1	1.7	1.7	0.7	2.6
Aug wk 4	0.1	0.5	0.7	0.1	0.6
Sep wk 1	0.3	0.4	0.5	0.3	0.5
Sep wk 2	0.1	0.3	0.2	nd	0.3
Sep wk 3	0.1	0.1	0.0	0.1	0.1

Appendix 4 Larva/Veliger Densities/L 1998-2003

2001

Date	Site A	Site B	Site C	Site D	Site E
Jun wk 2	0.0	0.1	0.0	0.0	0.0
Jun wk 3	0.1	0.1	0.3	0.3	0.1
Jun wk 4	0.9	0.1	1.3	0.4	0.3
Jul wk 1	8.2	7.9	6.7	0.0	3.7
Jul wk 2	2.8	0.6	3.4	0.2	0.7
Jul wk 3	5.0	0.2	0.6	0.3	0.7
Jul wk 4	2.7	**16.8**	3.0	0.8	2.7
Aug wk 1	3.4	5.7	4.3	2.5	4.9
Aug wk 2	5.8	3.7	4.1	0.3	2.5
Aug wk 3	0.7	2.0	2.3	0.2	3.8
Aug wk 4	0.2	0.0	0.0	0.0	0.1

2002

Date	Site A	Site B	Site C	Site D	Site E
Jun wk 2	0.1	0.1	0.0	0.1	nd
Jun wk 3	nd	0.2	0.2	0.1	nd
Jun wk 4	2.4	0.3	0.6	0.7	nd
Jul wk 1	5.2	0.8	4.2	0.2	6.9
Jul wk 2	**39.4**	2.9	3.0	0.2	4.7
Jul wk 3	12.4	24.9	12.7	3.1	11.4
Jul wk 4	6.2	8.8	8.7	1.7	9.5
Aug wk 1	2.7	8.7	15.3	2.3	nd
Aug wk 2	5.5	0.3	0.6	0.6	11.5
Aug wk 3	4.9	2.8	1.0	0.2	nd
Aug wk 4	9.7	2.7	5.8	0.9	2.0
Sep wk 1	0.5	1.1	1.9	0.1	1.2
Sep wk 2	0.4	0.5	0.3	0.0	0.0
Sep wk 3	0.2	0.1	0.1	0.1	0.0

2003

Date	Site A	Site B	Site C	Site D	Site E
Jun wk 2	0.6	0.5	0.3	0.2	0.7
Jun wk 3	1.5	1.6	1.1	1.5	1.7
Jun wk 4	4.4	1.3	2.8	0.2	6.0
Jul wk 1	3.6	4.1	0.5	0.3	11.7
Jul wk 2	6.6	2.1	8.8	0.3	2.7
Jul wk 3	4.4	1.2	3.8	1.5	6.9
Jul wk 4	3.6	7.8	0.6	0.9	10.1
Aug wk 1	13.9	18.3	**45.2**	1.5	11.3
Aug wk 2	2.9	0.9	0.4	0.1	13.0
Aug wk 3	0.4	1.6	0.7	0.3	1.9
Aug wk 4	1.3	5.7	7.5	0.1	0.9
Sep wk 1	1.9	0.4	2.4	nd	0.9
Sep wk 2	1.3	2.2	5.2	0.0	0.7
Sep wk 3	0.2	0.1	0.0	0.1	0.1
Oct wk 1	0.0	nd	0.1	0.0	nd

nd = no data (due to weather conditions)

Appendix 5 Site A Veliger Size Distribution 1998-2003

	July wk 2	July wk 3	July wk 4		August wk 1		August wk 2		August wk 3		August wk 4		Sept wk 1		Sept wk 2	
Veliger(um)	**1999**	**1999**	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**	**1998**	**1999**
70							2	nd								
80	1						5					2				
90				13	21	3	36					3		2		
100	30		4	123	100	69	114		40	10	41	24	14	15	4	2
110	36	22	2	21	76	112	95		66	15	51	31	34	32	11	8
120	56	32	5	9	38	94	54		96	22	56	9	53	12	28	4
130	60	17	6	4	9	31	36		91	19	55	5	63	14	20	1
140	23	20	1	2	7	19	29		102	4	40	4	45	9	13	1
150	17	17	2		8	9	15		94	4	60	5	41	7	10	
160	16	12	1		2	7	2		64	5	44	5	51	1	2	1
170	11	15	2		5	4	2		84	1	66	3	50	4	19	1
180	5	13		1	3	1			59	3	29	1	38	5	9	
190	1	15		1		1	1		51	4	42	3	43	1	21	
200	2	55		1	1	2			45	8	46		43		28	1
210	1	33			1				14	10	31	2	44	1	29	1
220	1	29	1	1	1	1			11	16	29	2	47	2	28	2
230	1	20			1		1		6	10	20	1	63	2	18	2
240	2	12		2		2			3	17	18	2	62		25	
250	1	12		1		1	3		4	52	31		59	1	7	2
260	1	11					1		2	25	5		13		6	
270		2								8	3	1	5		2	
280	1									6	1		7			
290																

Appendix 5 Site B Veliger Size Distribution 1998-2003

Veliger (um)	July week 1 2000	July week 1 2001	July week 1 2002	July week 1 2003	July week 2 2000	July week 2 2001	July week 2 2002	July week 2 2003	July week 3 2000	July week 3 2001	July week 3 2002	July week 3 2003
70								0				1
80								2				1
90	3	5		2	2	5	1	24	14	2		8
100	6	20	30	13	3	7	29	75	47	2	8	25
110	29	11	66	24	11	2	52	38	38	2	19	29
120	41	25	23	33	11	4	13	2	27	1	25	24
130	25	23	10	23	9	2	20	0	9	0	12	10
140	7	18	15	17	4	3	20	2	7	0	26	13
150	9	18	1	19	6	1	15	1	10		24	23
160	15	9	2	11	11	0	5	4	13		18	10
170	7	4		3	12	1	7	0	12		2	4
180	5	7		3	4		5	0	6		2	1
190	3	0		1	5		2	1	8		4	0
200	1	6		1			1	1	3		4	1
210		3							1		4	
220		4							0		1	
230		2							0		1	
240									1		1	
250												
260												
270												
280												
290												
300												

Veliger (um)	July week 4 1998	July week 4 1999	July week 4 2000	July week 4 2001	July week 4 2002	July week 4 2003	August week 1 1998	August week 1 1999	August week 1 2000	August week 1 2001	August week 1 2002	August week 1 2003
70			2			7		3	0			0
80			3	1		7	1	5	4	2		3
90		1	10	14		25	2	50	16	7		16
100	2	23	39	29	9	27	14	20	30	29	16	19
110		24	32	9	36	25	19	28	23	10	34	34
120	3	31	46	37	22	16		15	23	5	14	23
130		8	18	10	12	10	1	17	23	9	5	13
140		3	20	20	8	7	1	10	19	18	14	4
150		1	17	13	10	6	1	8	20	18	11	9
160		1	14	6	6	4	2	3	15	6	7	4
170			11	2	6	3		6	14	9	6	4
180			7	4	8	1		3	5	1	7	5
190			6	1	17	1		2	6	11	5	2
200		1	6	2	7	0			5	5	6	4
210			5	1	3	2		1	3	7	2	2
220		1	1		3	6			4	4	8	4
230			1		2	2			4	1	5	3
240		1	0			1			1	2	8	1
250		2	2						1	3	1	
260		1	1							1	2	
270												
280												
290												
300								1				

Appendix 5 Site B Veliger Size Distribution 1998-2003

Veliger(um)	August week 2					August week 3						August week 4						Sept week 1		Sept week 2	
	1998	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003	1998	1999	2000	2001	2002	2003	2002	2003	2002	2003
70	1	0			0			0			1		5	0		10	10		3		3
80	1	3			2		1	1			0		4	1		22	22		6		3
90	8	9	2		6	2		3	4		6		8	5	1	47	47		17		4
100	39	31	3	2	11	14	6	12	8	18	9	6	66	2	16	32	32	8	39		14
110	40	17	15	4	18	28	16	19	7	13	15	14	23	6	38	10	10	11	47	5	33
120	28	8	10	1	29	40	20	24	4	19	15	13	25	3	14	5	5	13	23	10	15
130	19	5	9	0	25	32	14	17	6	17	16	28	10	11	8	5	5	9	8	6	13
140	16	10	12	1	15	32	4	11	5	12	19	31	3	9	5	4	4	9	3	3	11
150	6	28	20	8	6	25	2	13	9	11	19	20	9	3	14	2	2	21	1	4	15
160	4	31	18	2	6	18	1	21	6	9	15	9	5	1	12	4	4	20	0	5	16
170	3	18	11	2	2	13	7	27	8	19	15	21	9		9	3	3	15	0	4	12
180		13	10	2	7	8		16	5	16	3	7	7		3	2	2	12	0	4	5
190		14	1	1	4	10	6	15	2	5	6	21	2		2	3	3	4	2	5	1
200	1	10	3	5	3	6	3	8	10	3	6	15	1		3	1	1	6		5	2
210		9		1	6	8	7	6	5	1	3	10	2		8			2		4	1
220		3		1	6	3	8	2	3	5	0	9	2		9			5		4	1
230		3		3	3	2	12	4	2	2	1	7			6			5		2	0
240				1	0		13	1		3	0	8	2		4			4		1	0
250				1	1	4	18				1	2	1					1			1
260							29					1	2					1			
270					16					1											
280					6																
290					7																
300																					

Appendix 5 (ctd) Site C Veliger Size Distribution 1998-2003

Veliger(um)	July week 1				July week 2					July week 3				
	2000	2001	2002	2003	1999	2000	2001	2002	2003	1999	2000	2001	2002	2003
70	1				1				1					
80	2	1			1		1		3			1		
90	6	11		1		2	5		8		6	7		4
100	36	15	20	11	30	23	23	19	48	3	28	9	8	21
110	36	12	61	24	36	34	13	37	35	6	36	3	45	46
120	20	20	26	28	67	31	10	9	3	9	51	2	27	20
130	16	15	16	28	64	25	4	11	3	3	26	1	10	6
140	9	19	23	20	29	28	3	30	4	5	16	2	13	7
150	6	22	17	18	27	19	9	19	6	13	13	0	20	14
160	6	12	2	10	24	10	7	19	13	8	9	0	11	14
170	4	7	2	2	18	4	6	8	10	5	6	0	5	9
180	1	6	1	4	14	2	11	5	8	3	9	1	2	3
190	3	0		2	4	2	1	10	5	4	5		2	0
200		4		2	3	3	12	3	2	12	8		2	1
210		3			5	1	6		1	8	1		1	1
220		3			4		9			10	3		3	0
230		2			9		2			4	1		1	3
240		1			2		1			3	1		0	1
250					4		3				1		1	
260										1				
270														
280					2									
290														
300														

Veliger (um)	July week 4						August week 1					
	1998	1999	2000	2001	20002	2003	1998	1999	2000	2001	2002	2003
70			6			2						2
80			3	1		0	3		5	7		0
90		13	14	7		10	17		9	18		4
100		92	36	27	5	19	45	55	12	7	15	27
110	1	84	25	8	36	31	50	46	17	8	40	25
120	1	36	21	24	26	12	24	38	14	3	10	20
130		13	14	15	16	15	3	22	4	7	6	13
140		7	16	22	14	13	1	7	16	12	12	9
150	1	11	12	11	9	8	5	4	17	7	7	10
160	1	2	15	3	11	10	5	1	27	4	1	6
170		4	7	2	10	3	4	3	17	16	2	7
180		3	10	1	7	6	3	3	10	3	3	4
190			4	0	9	1	3	1	12	11	5	3
200		1	7	3	4	3	1	2	18	9	12	13
210		1	6	0	2	2		1	9	9	4	2
220		1	2	0	2	6	1			4	9	0
230		2	2	0	1	7	1			5	11	3
240		1	0	0		2		1		4	12	2
250		1	2	1						2	1	
260												
270												
280		1						1				
290												
300												

Appendix 5 (ctd) Site C Veliger Size Distribution 1998-2003

	August week 2				August week 3						August week 4					September week 1				September week 2			
Veliger (um)	**2000**	**2001**	**2002**	**2003**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**1998**	**1999**	**2000**	**2002**	**2003**	**1998**	**1999**	**2002**	**2003**	**1998**	**1999**	**2002**	**2003**
70															18								2
80	4			1			1			1			1		38				1				3
90	5	2		6			3	7		7		1			60		1		7				6
100	8	11	1	19	11	1	5	3	17	19	52	153	2	16	22	3	18	3	19	3	6	2	20
110	7	8	8	19	37	14	7	6	8	46	76	41	1	36	3	12	21	7	46	7	7	3	18
120	7	13	6	30	29	18	8	5	21	36	44	14	4	15	1	25	10	14	36	12	8	1	11
130	7	15	3	35	23	11	6	10	16	9	40	9	6	5	1	21	26	16	9	9		1	8
140	12	17	5	14	36	5	9	15	6	3	28	11	3	12	3	14	12	22	3	9	3	6	20
150	20	21	5	6	25	4	18	11	5	2	30	20	3	11	1	18	19	13	2	11		3	14
160	24	15	9	2	18	2	16	14	5	5	20	10	5	7	1	9	7	16	5	3	3	2	14
170	24	15	8	2	14	5	25	8	6	6	29	10	10	12	0	11	5	22	6	8	4	1	15
180	19	4	4	6	10	7	22	3	5	2	18	7	8	7	1	5	9	5	2	12	2	2	7
190	13	5	1	3	6	3	14	8	11	4	31	7	4	11	0	5	5	8	4	11	4	3	5
200	17	4	4	3	6	15	9	1	10	1	34	5	1	2	0	14	6	11	1	10	3	3	6
210	3	3	6	3	3	15	4	1	5	3	24	1		2	1	15	5	6	3	12		2	1
220	1	3	2	0	3	40	1		1	3	22	2		5		15	4	2	3	11	3	1	
230		2	1	0	2	44			4	1	16	1		5		6	7	9	1	13		0	
240			5	0	1	63			2	2	25	1		4		2		2	2	4	1	1	
250			1	1	2	97			2		23	1		0		3		2		4		1	
260			1			73			1		8	2		1						2		1	
270						38					3	2								3			
280						11						1								3			
290																							
300						1																	

Appendix 6: Estimated Zebra Mussel Juvenile Settlement, Summers 1998 -2003

Week	Date	Site A	Site B	Site C	Site D	Site E	Sum Sites A-D
June week 4	2001	45	0	0	45	0	90
	2002	45	45	nd	45	nd	135
July week 1	2002	45	0	nd	45	45	90
	2003	0	180	0	0	0	180
July week 2	2000	0	0	0	0	0	0
	2001	710	980	11,500	90	0	13,280
	2002	45	2,340	1,670	45	45	4,100
	2003	90	0	0	0	0	90
July week 3	2000	45	450	270	0	0	765
	2001	1,330	1,100	25,000	440	265	27,870
	2002	45	45	90	3000	45	3,180
	2003	90	4,300	nd	0	2,670	4,390
July week 4	1998	0	0	0	0	nd	0
	1999	500	10,000	7,000	0	nd	17,500
	2000	2,520	2,340	2,610	225	999	8,694
	2001	1,000	4,000	4,500	3,500	2,500	15,500
	2002	90	0	1,670	140	140	1,900
	2003	4,330	3,000	2,000	0	2,330	9,330
August week 1	1998	0	0	0	0	nd	0
	1999	12,000	26,000	23,000	270	nd	61,270
	2000	28,000	86,500	5,000	200	18,500	138,200
	2001	0	1,000	3,500	6,000	2,500	10,500
	2002	2,670	1,670	1,340	340	1,000	6,020
	2003	8,670	4,330	9,000	2,330	7,670	32,000
August week 2	1998	130	360	0	0	nd	490
	1999	11,500	24,000	43,000	5,500	nd	84,000
	2000	10,000	27,500	24,500	45	10,000	62,045
	2001	6,000	14,000	39,000	11,500	1,500	70,500
	2002	90	4,000	2,335	0	45	6,425
	2003	7,330	15,670	22,670	670	22,670	46,340
August week 3	1998	360	1,290	2,930	400	nd	4,980
	2000	17,500	16,000	18,000	45	13,000	51,545
	2001	2,500	3,000	18,500	500	7,000	24,500
	2002	45	360	620	45	45	1,070
	2003	4,000	19,670	169,670	4,000	77,330	197,340
August week 4	1999	23,000	27,000	52,000	13000	nd	115,000
	2000	20,000	22,500	7,000	405	14,500	49,905
	2001	2,000	1,000	5,500	1,000	500	9,500
	2002	360	45	400	90	0	895
	2003	2,000	9,670	2,000	1,670	8,330	15,340
September week 1	1998	900	1,020	4,800	620	nd	7,340
	1999	220	360	670	220	nd	1,470
	2000	15,000	4,000	6,500	45	7,500	25,545
	2001	0	1,000	3,000	1,000	10,500	5,000
	2002	0	140	220	0	45	360
	2003	670	1,000	330	330	3,300	2,330
September week 2	1998	4,000	5,000	3,000	20,670	nd	32,670
	1999	800	360	670	220	nd	2,050
	2001	2,500	500	2,000	0	4,500	5,000
	2002	0	1,670	nd	45	175	1,715
	2003	1,330	2,000	7,000	1,000	4,000	11,330
September week 3	1998	890	3,370	0		nd	4,260
	1999	0	90	0	90	nd	180
	2000	5,500	8,000	900	135	3,000	14,535
	2001	0	500	0	0	1,000	500
	2002	0	140	220	0	45	360
	2003	nd	1,330	330	1,330	1330*	4,320
October week 1/2	1998	130	nd	750	0	nd	880
	1999	90	180	540	0	nd	810
	2000	3,500	6,000	2,000	45	8,000	11,545
	2001	0	90	0	0	0	90
	2002	1,000	0	1,000	0	0	2,000
	2003	nd	1,330	1330	0	1670*	4,330
Total Site settlement	1998-2003	205,615	372,425	541,535	81,355		

Appendix 7: Snorkel Sites 2001

Site 1: Drummons Bay Date: 11/08/01

Depth: 1 metre

Substrate	% Substrate	%zm cover
Stone	0	
Mud	100	
Peat	0	
Anodonta	<1	
Other	0	

No stone present

Plants	1	2	3	4	5	6	7	8	9	10
Old *P. australis*	264	269	93	280	481	579	403	324	417	396
New *P. australis*	0	0	<1	<1	<1	<1	<1	<1	<1	<1
S. lacustris	0	<1	0	0	0	<1	<1	<1	<1	<1
N. lutea	0	<1	<1	0	0	0	0	0	0	0
P. natans	<1	<1	<1	<1	0	0	0	0	0	<1
P.lucens	0	0	0	0	<1	<1	<1	<1	<1	<1
Fontinalis	<1	2	0	0	0	0	0	0	0	0
Sparganium	0	0	0	0	0	<1	0	0	0	0

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
2-3	0	100	<5	30

Appendix 7: Snorkel Sites 2001

Site 2: Drumbridge Bay Date: 16/08/01

Depth: 1.2 metre

Stone

25 cm^2 quadrat on stones has a zm biomass of 254 grams

Substrate	% Substrate	%zm cover
Stone	75	75
Mud	25	0
Peat	0	0
Anodonta	<1	
Other	0	0

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	0	0	0	<1	0	0	0	0	0	0	20
New *P. australis*	0	0	0	0	0	0	0	0	0	0	50
S. lacustris	0	0	0	0	0	0	0	0	0	0	40
N. lutea	0	0	<1	<1	0	0	0	0	0	0	2
P. natans	0	0	0	<1	<1	<1	0	0	0	0	
P. sp.	0	0	<1	<1	0	0	0	0	0	0	
Sagittaria	0	0	<1	0	0	0	0	0	0	0	
Lemna trisulca	0	<1	0	0	0	0	0	0	0	0	
Fontinalis	0	0	0	0	0	0	0	0	0	0	
E. canadensis	0	0	0	0	0	0	0	0	0	0	
Sparganium	0	0	0	0	<1	<1	<1	0	0	0	

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	75	30

Appendix 7: Snorkel Sites 2001

Site 3: Church Island Date: 15/08/01

Depth: 0.5 - 3.0 metres

Substrate	% Substrate	%zm cover
Stone	40	90
Rock	20	90
Mud	40	0
Peat	0	0
Anodonta	<1	100
Other	0	0

Stone

25 cm^2 quadrat on stones has a zm biomass of 380 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	0	0	0	0	0	0	0	0	0	0	0
New *P. australis*	0	0	0	0	0	0	0	0	0	0	0
S. lacustris	<1	0	0	0	0	0	0	0	0	0	30
N. lutea	0	2	0	0	0	2	0	0	0	0	1
P. perfoliatus	0	0	0	0	0	0	0	0	0	0	-
Sparganium	0	0	0	0	0	0	0	0	0	0	-

Cladophora mats on the bottom

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
2	0	100	100	30

Appendix 7: Snorkel Sites 2001
Site 4: Stag Island Date: 15/08/01

Depth: 0.5 - 3.0 metres

Stone
25 x 20 cm^2 quadrat on stones has a zm biomass of 330 grams

Substrate	% Substrate	%zm cover
Stone	10	80
Boulder	0	0
Rock	0	0
Mud	90	0
Peat	0	0
Anodonta	5	100
Other	0	0

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	107	75	259	63	96	60	94	180	2	3	10
New *P. australis*	<1	0	0	<1	<1	0	<1	0	0	<1	25
S. lacustris	<1	<1	<1	<1	0	0	<1	<1	<1	<1	60
N. lutea	<1	0	0	0	0	0	0	0	0	0	3
P. perfoliatus	0	0	0	0	0	0	0	0	0	0	-
P. sp.	<1	0	0	0	0	0	0	0	0	0	-
E. canadensis	<1	<1	<1	<1	0	0	0	0	0	0	-
Chara sp.	0	<1	0	0	0	0	0	0	0	0	-
Sparganium	0	0	0	0	0	0	0	0	0	0	-

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	100	30

Appendix 7: Snorkel Sites 2001

Site 5: Hermit Island Date: 15/08/01

Depth: 0.5 - 3.0 metres

Stone

25 x 22 cm^2 quadrat on stones has a zm biomass of 265 grams

Maerl and new settlement on zm.

Substrate	% Substrate	%zm cover
Stone	20	80
Boulder	40	80
Rock	40	80
Mud	0	0
Peat	0	0
Anodonta	3	100
Other	0	0

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	0	0	0	0	0	0	0	0	0	0	0
New *P. australis*	0	0	0	0	0	0	0	0	0	0	0
S. lacustris	0	0	0	0	0	0	0	0	0	0	45
N. lutea	0	0	0	0	0	0	0	0	0	0	0
P. lucens	0	0	0	0	0	0	0	0	0	0	-
P. sp.	<1	0	0	0	0	0	0	0	0	0	-
Myriophyllum	<1	0	<1	0	0	0	0	0	0	0	2
Sparganium	0	0	0	0	0	0	0	0	0	0	1

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	100	30

Appendix 7: Snorkel Sites 2001

Site 6: Bullock Island Date: 10/08/01

Depth: 2 metres

Stone

25 cm^2 quadrat on stones has a zm biomass of 275 grams

Substrate	% Substrate	%zm cover
Stone	<5	90-95
Mud	95	0
Peat	0	0
Anodonta	5-10	90
Other	0	0

Plants	1	2	3	4	5	6	7	8	9	10
Old *P. australis*	0	0	0	0	0	0	0	0	0	0
New *P. australis*	0	0	0	0	0	0	0	0	0	0
S. lacustris	<1	<1	0	<1	<1	<1	<1	<1	<1	0
N. lutea	<1	<1	0	0	0	0	0	0	0	0
Fontinalis	<1	0	0	0	0	0	0	0	0	0
Sparganium	<1	<1	<1	<1	<1	<1	<1	0	0	0

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
7-9	0	100	90	30

Appendix 7 : Snorkel Sites 2001

Site 7: Green Island

Date: 13/08/01

Secchi Disc: 2.3 metres   Temp: 18.5 C

Depth: 1.5 metre

Substrate	% Substrate	%zm cover
Stone	50	40
Mud	50	0
Peat	0	0
Anodonta	<1	
Other	0	0

25 cm^2 quadrat on stones has a zm biomass of 280 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	41	102	111	116	70	82	24	97	50	113	2
New *P. australis*	3	2	1	10	12	0	0	4	12	0	25
S. lacustris	0	0	0	0	0	0	0	0	0	0	15-20
N. lutea	52 (Rhizoid)	1	1	1	1	0	0	0	0	0	
P.lucens	0	0	0	0	0	0	0	0	0	0	
E. canadensis	0	0	0	0	0	0	0	0	0	0	
Sparganium	1	2	2	2	2	0	1	0	1	0	

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
6	0	100	100	30

Appendix 7: Snorkel Sites 2003

Site 1: Drummons Bay **GPS: IG8417 0426** Date: 10/08/03

Depth: 1 metre Temp: 23.0 C

Substrate	% Substrate	%zm cover
Stone	0	0
Mud	100	0
Peat	0	0
Anodonta	<1	100
Other	0	0

No stones at this site

Plants	1	2	3	4	5	6	7	8	9	10
Old *P. australis*	10	3	6	4	3	16	3	0	<1	2
New *P. australis*	0	0	<1	0	0	0	0	0	0	0
S. lacustris	0	<1	0	0	0	0	0	0	0	<1

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
<1	0	100	100	30

Anodonta have dropped below the surface and only a small portion of some remain exposed above the surface

Appendix 7: Snorkel Sites 2003

Site 2: Drumbridge Bay at Crannog **GPS IG 8232 0412** Date: 08/08/03

Temp:24.7 C

Depth: 1.2 metre

Substrate	% Substrate	%zm cover
Stone	75	50
Mud	25	0
Peat	0	0
Anodonta	<1	80
Other	0	0

Stone

25 x 25cm2 quadrat has a zm biomass of 143 grams
25 x 25 cm^2 quadrat has a zm biomass of 306 grams
25 x 25cm^2 quadrat has a zm biomass of 167 grams

Mean zm biomass = 205 grams
Stones from 0.5 metre depth

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	0	0	0	0	0	0	0	0	0	0	20
New *P. australis*	0	0	0	0	0	0	0	0	0	0	50
S. lacustris	0	0	0	<1	0	0	0	0	0	0	80

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	80	30

Appendix 7: Snorkel Sites 2003

Site 3: Church Island Date: 11/08/03

Depth: 0.5 - 3.0 metres

Substrate	% Substrate	%zm cover
Stone	40	50
Rock	20	50
Mud	40	0
Peat	0	0
Anodonta	<1	100
Other	0	0

Stone

25x25 cm^2 quadrat on stones has a zm biomass of 166 grams
25x25 cm^2 quadrat on stones has a zm biomass of 210 grams
25x25 cm^2 quadrat on stones has a zm biomass of 231 grams

Mean zm biomass = 202g

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
S. lacustris	<1	0	0	0	0	0	0	0	0	0	30

No *P. australis* at this site

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cove	No.
4	0	100	100	30

Appendix 7: Snorkel Sites 2003

Site 3: Stag Island **GPS: IG82267 06961** **Date: 12/08/03**

Depth: 2.0 metres

Distance from Shore: 8 metres

Substrate	% Substrate	%zm cover
Stone	10	80
Boulder	0	0
Rock	0	0
Mud	90	0
Peat	0	0
Anodonta	5	100
Other	0	0

Stone

25 x 25 cm^2 quadrat has a zm biomass of 592 grams
25 x 25 cm^2 quadrat has a zm biomass of 331 grams
25 x 25 cm^2 quadrat has a zm biomass of 269 grams

Mean zm biomass = 397 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	<1	<1	0	7	0	1	8	1	1	3	10
New *P. australis*	0	0	0	0	0	0	0	0	0	0	25
S. lacustris	0	0	0	0	0	0	0	0	0	<1	60

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	100	30

Appendix 7: Snorkel Sites 2003

Site 5: Hermit Island **GPS IG 8368 0600** **Date: 09/08/03**

Depth: 0.5 - 3.0 metres Temp: 21.6

Substrate	% Substrate	%zm cover
Stone	20	70
Boulder	40	70
Rock	40	70
Mud	0	0
Peat	0	0
Anodonta	3	100
Other	0	0

Stone

25 x 25 cm^2 quadrat has a zm biomass of 207 grams
25 x 25 cm^2 quadrat has a zm biomass of 244 grams
25 x 25 cm^2 quadrat has a zm biomass of 277 grams

Mean zm biomass = 242 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
S. lacustris	0	<1	0	0	0	0	0	0	0	0	45

No *P. australis* at this site

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
4	0	100	100	30

Appendix 7: Snorkel Sites 2003

Site 6: Bullock Island **GPS: IG84945 05989** Date: 09/08/03

Depth: 1-2 metres Temp: 21.6 C

Substrate	% Substrate	%zm cover
Stone	<5	85
Mud	95	0
Peat	0	0
Anodonta	5-10	100
Other	0	0

Stone

25 x 25 cm^2 quadrat has a zm biomass of 201 grams
25 x 25cm^2 quadrat has a zm biomass of 148 grams
25 x 25 cm^2 quadrat has a zm biomass of 253 grams

Mean zm biomass = 201 grams

Plants	1	2	3	4	5	6	7	8	9	10
S. lacustris	0	0	0	0	0	0	0	0	0	0

No *P. australis* at this site, *E fluviatile* present in v. low numbers, also without zm colonization.

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
4-5	0	100	100	30

Appendix 7 : Snorkel Sites 2003
Site 7: Green Island Date: 8/08/03

Temp: 20.6 C

Depth: 1.5 metre

Substrate	% Substrate	%zm cover
Stone	5	50
Mud	25	0
Peat	0	0
Anodonta	<1	100
Rock	70	50

Stone

25 x 25cm^2 quadrat on stones has a zm biomass of 44 grams
25 x 25cm^2 quadrat on stones has a zm biomass of 45 grams
25 x 25cm^2 quadrat on stones has a zm biomass of 93 grams

Mean zm biomass = 61 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	2	6	1	4	4	4	4	4	<1	<1	20
New *P. australis*	3	2	1	10	12	0	0	4	12	0	20
S. lacustris	0	0	<1	0	0	0	0	0	0	0	60

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	100	30

Appendix 7: Snorkel Sites 2003

Site 8: Clarendon **GPS: IG86643 05747** **Date: 12/08/03**

Depth: 2.0 metres Temp: 21.4 C

Substrate	% Substrate	%zm cover
Stone	70	100
Rock	20	100
Mud	0	0
Peat	0	0
Anodonta	10	100
Other	0	0

Rock/Cobble/Stones

25 x 25cm^2 quadrat has a zm biomass of 790 grams
25 x 25cm^2 quadrat has a zm biomass of 666 grams
25 x 25cm^2 quadrat has a zm biomass of 706 grams

Mean zm biomass = 721 grams

Plants	1	2	3	4	5	6	7	8	9	10	Density (m^2)
Old *P. australis*	15	36	48	24	35	20	<1	<1	4	4	10
New *P. australis*	0	2	0	0	0	0	0	0	0	0	25
S. lacustris	0	0	<1	0	0	0	0	0	0	0	60

Anodonta				
Density (m^2)	% Alive	% Dead	% zm cover	No.
3	0	100	100	30

APPENDIX 8

Biomass of zebra mussels along the eight transects in Lough Key, August 2002

	N	S	E	W	NE	SW	SE	NW
0-1	98	194	62	57	124	4	67	52
	69	97	22	38	206	9	47	65
	131	52	30	51	42	13	112	83
1-2	91	129	165	57	12	10	84	40
	88	72	158	40	41	7	69	44
	190	146	9	47	74	0	88	19
2-3	65	64	75	82	35	6	106	0
	33	99	67	33	59	21	52	28
	45	66	117	66	71	11	93	25
3-4	44	58	49	90	15	0	42	14
	31	39	22	54	12	0	34	20
	43	40	59	30	10	5	39	0
4-5	44	37	0	0	3	0	14	0
	65	73	1	0	0	0	30	0
	80	53	19	0	0.5	0	35	0
5-6	23	3	0	0	1	0	5	0
	148	11	0	0	0	0	37	0
	33	21	0	1	0	0	0	0
6-7	0	0	0	0	0	0	0	0
	0	5	0	0	0	0	0	0
	0	0	0	0	0	0.5	0	0
7-8	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
11-12	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	2	0	0	0	0
12-13	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
19-20	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0

APPENDIX 8

Biomass of zebra mussels/m2 along the eight transects in Lough Key, August 2002

EPA	N	S	E	W	NE	SW	SE	NW
0-1	1568	3104	992	912	1984	64	1072	832
	1104	1552	352	608	3296	144	752	1040
	2096	832	480	816	672	208	1792	1328
1-2	1456	2064	2640	912	192	160	1344	640
	1408	1152	2528	640	656	112	1104	704
	3040	2336	144	752	1184	0	1408	304
2-3	1040	1024	1200	1312	560	96	1696	0
	528	1584	1072	528	944	336	832	448
	720	1056	1872	1056	1136	176	1488	400
3-4	704	928	784	1440	240	0	672	224
	496	624	352	864	192	0	544	320
	688	640	944	480	160	80	624	0
4-5	704	592	0	0	120	0	224	0
	1040	1168	40	0	0	0	480	0
	1280	848	760	0	20	0	560	0
5-6	368	120	0	0	40	0	80	0
	2368	440	0	0	0	0	592	0
	528	840	0	40	0	0	0	0
6-7	0	0	0	0	0	0	0	0
	0	200	0	0	0	0	0	0
	0	0	0	0	0	20	0	0
7-8	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
11-12	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	80	0	0	0	0
12-13	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
19-20	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0

APPENDIX 8

Total no. of zebra mussels along the eight transects in Lough Key, August 2002

	N	S	E	W	NE	SW	SE	NW
0-1	358	991	250	253	511	27	367	479
	337	312	82	167	671	41	341	570
	487	313	107	397	133	99	684	692
1-2	629	951	805	396	98	32	791	263
	527	636	455	230	524	34	722	190
	613	947	74	346	1286	0	660	108
2-3	707	529	691	490	263	28	986	0
	302	814	631	206	421	117	496	87
	398	641	748	482	487	65	873	122
3-4	282	386	293	374	113	0	382	35
	216	243	131	207	139	0	381	57
	272	257	374	116	92	1	380	0
4-5	163	185	0	0	16	0	153	0
	294	369	6	0	0	0	231	0
	342	245	73	0	0	0	296	0
5-6	108	16	0	0	0	0	33	0
	728	57	0	0	0	0	310	0
	170	92	0	2	0	0	0	0
6-7	0	0	0	0	0	0	0	0
	0	27	0	0	0	0	0	0
	0	0	0	0	0	1	0	0
7-8	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	18	0	0	0	0
11-12	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
19-20	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0

APPENDIX 8

Total no. of zebra mussels/m2 along the eight transects in Lough Key, August 2002

EPA	N	S	E	W	NE	SW	SE	NW
0-1	5728	15856	4000	4048	8176	432	5872	7664
	5392	4992	1312	2672	10736	656	5456	9120
	7792	5008	1712	6352	2128	1584	10944	11072
1-2	10064	15216	12880	6336	1568	512	12656	4208
	8432	10176	7280	3680	8384	544	11552	3040
	9808	15152	1184	5536	20576	0	10560	1728
2-3	11312	8464	11056	7840	4208	448	15776	0
	4832	13024	10096	3296	6736	1872	7936	1392
	6368	10256	11968	7712	7792	1040	13968	1952
3-4	4512	6176	4688	5984	1808	0	6112	560
	3456	3888	2096	3312	2224	0	6096	912
	4352	4112	5984	1856	1472	16	6080	0
4-5	2608	2960	0	0	640	0	2448	0
	4704	5904	240	0	0	0	3696	0
	5472	3920	2920	0	0	0	4736	0
5-6	1728	640	0	0	0	0	528	0
	11648	2280	0	0	0	0	4960	0
	2720	3680	0	80	0	0	0	0
6-7	0	0	0	0	0	0	0	0
	0	1080	0	0	0	0	0	0
	0	0	0	0	0	40	0	0
7-8	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	720	0	0	0	0
11-12	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
14-15	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
15-16	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
16-17	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
17-18	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
18-19	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
19-20	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0

APPENDIX 9: *Anodonta anatina*, West of Church Island, November 1998

Living *Anodonta anatina*

Anodonta	Shell Length	Age	No. *Dreissena* on shell
1	8	6	6
2	9.2	7	33
3	8.8	6	135
4	7.7	4	9
5	7.1	4	31
6	7.9	4	2
7	9.5	5	123
8	5.3	2	2
9	8.3	4	8
10	7.7	4	6
11	8	4	17
12	9.2	5	14
13	9.8	4	58
14	8.6	5	56
15	8.6	7	18
16	9.7	4	159
17	8.2	4	314
18	6.9	3	164
19	8.2	3	202
20	9.2	3	274
21	9.4	4	270
22	6.9	4	167
23	9.9	5	173
24	9.3	4	185
25	8.6		78
26	8.4		28
27	7.9		45
28	8.6		66
29	9.4		60
30	7.1		10
31	7.5		87
32	9		35
33	9.4		136
34	7.7		50
35	9.7		83
36	7.5		75
37	8		55
38	9.1		4
39	8.7		42
40	8.3		126
41	8.7		120
42	9.7		62
43	8.6		72
44	8.7		135
45	9.4		53
46	8.6		89
47	8.2		22
48	8.2		45
49	8.8		117
50	7.2		23
51	9.1		52
52	8		28
53	8.1		88
54	7.5		100
55	9		211
56	8.6		24
57	8.9		10
58	8.6		58
59	9.3		56
60	8.2		159
61	8.5		45
62	7.5		51
63	8.2		40
64	7.1		33
65	7.4		105
66	7.9		89
67	8		10
68	8.4		82
69	7.4		110
70	8.9		51
71	5.1		25
72	9		90
73	7.8		44

Dead *Anodonta anatina*

Anodonta	Shell Length	Age	No. *Dreissena* on shell
1	9.9	7	37
2	9.2	6	72
3	9.9	8	16
4	7.3	5	39
5	8.7	5	77
6	10.3	5	107
7	9.8	7	11
8	10.6	9	87
9	9.4	5	218
10	11	8	362
11	8.3	6	35
12	9.5	8	102
13	6.8	5	64
14	7.8	5	36
15	9.8	7	100
16	10	6	170
17	9.5	6	28
18	9.4	7	98
19	10	6	154
20	9.8	6	52
21	9.5	6	73
27	8	10	358
28	7.4	8	316
29	7.8	7	379
30	9	7	608
31	9.9	7	212
32	9.6	8	105

APPENDIX 9: *Anodonta anatina,* Site 8, Clarendon Lock, July 1999

Shell Length (mm)	Whole/ Half Shell (w/h)	Dead/ Alive (d/a)	Weight (g)	Location *Dreissena* on Shell	No. *Dreissena* on Shell	Weight - *Dreissena* on shell (g)	Weight Ratios - *Dreissena* / *Anodonta*	Weight debris on shell (g)	1+ and 2+ zebra mussels biofouling *Anodonta* Number x mm length
39	w	a	2.92	P (O)	81	3.22	1.10	3.08	-
52	w	a	6.4	P (O)	138	7.65	1.20	9.15	-
53	w	a	8.98	P+ (O)	165	8.64	0.96	5.05	-
57	w	a	12.73	P (O)	153	6.36	0.50	10.21	-
58	w	a	13.40	P (O)	267	16.23	1.24	22.64	-
59	w	a	12.42	P+ (O)	316	13.14	1.06	6.41	-
62	w	a	13.18	P (O)	87	6.12	0.46	7.02	-
64	w	a	17.66	P+ (O)	320	17.90	1.01	10.72	1x22;1x34;1x36
64	w	a	21.12	P (O)	140	5.01	0.24	9.26	-
65	w	a	20.65	P+ (O)	191	10.18	0.49	9.12	-
66	w	a	14.87	P++ (O)	309	13.25	0.89	11.58	-
69	w	a	24.03	P (O)	436	12.43	0.52	22.89	-
73	w	a	20.06	P+ (O)	279	15.21	0.76	12.13	-
74	w	a	27.14	P (O)	260	11.23	0.41	12.59	-
76	w	a	32.31	P (O)	325	14.02	0.43	20.60	1x22;1x24
78	w	a	23.57	P+ (O)	217	16.44	0.70		-
26	w	a	0.96	H+++ (O)	-	3.34	3.48		-
47	w	a	3.67	H+++ (O)	-	5.13	1.40		-
50	w	a	6.97	P (O)	-	3.38	0.48		-
53	w	a	10.27	P (I&O)	-	15.98	1.56		-
54	w	a	9.98	P (O)	-	9.45	0.95		1x21
55	w	a	7.65	P (O)	-	7.94	1.04		-
56	w	a	8.28	P (O)	-	7.74	0.93		-
61	w	a	13.50	P (O)	-	15.90	1.18		1x22;1x28
61	w	a	8.71	P+ (O)	-	9.24	1.06		1x23
62	w	a	16.60	P (O)	-	7.26	0.44		-
63	w	a	14.85	P (O)	-	27.42	1.85		-
65	w	a	16.30	P (O)	-	14.69	0.90		1x21
65	w	a	15.20	P (I&O)	-	12.38	0.81		-
67	w	a	17.99	P (I&O)	-	16.68	0.93		-
67	w	a	13.07	P (O)	-	15.53	1.19		1x24;1x25
69	w	a	19.13	P+ (O)	-	19.63	1.03		-
74	w	a	21.48	P (O)	-	11.87	0.55		1x23
80	w	a	25.23	P (O)	-	25.06	0.99		1x23,1x24
29	w	d	1.16	P H+++ (0)	77	5.44	4.69		-
61	w	d	10.10	P++ (O)	488	23.99	2.39		-
71	w	d	13.50	H+++ (I&O)	667	25.40	1.88		-
74	w	d	9.86	P++ (I&O)	140	4.26	0.43		-
79	w	d	15.95	P (I&O)	-	32.91	2.06		1x21;1x23;1x24
82	w	d	23.17	P (O)	-	10.96	0.47		-
84	w	d	26.94	H++ (I&O)	-	17.73	0.66		1x22
91	w	d	24.82	P (I&O)	-	28.03	1.13		-
71	w	a	17.09	P++ (I&O)	923	29.10	1.70		2x21,1x22,1x24
78	w	a	19.29	P (I&O)	508	13.12	0.68		1x25
83	w	a	21.93	P++ (I&O)	528	9.92	0.45		1x22
85	w	a	32.65	P++ (I&O)	161	12.49	0.38		-
74	w	d	13.8	P+ (I&O)	406	6.55	0.47		-
90	w	d	29.34	P+++ H++ (I&O)	1,066	21.00	0.71		1x14,1x19,1x22,1x23,1x25
95	w	d	28.23	P H+++ (I&O)	407	21.99	0.78		1x20
101	w	d	32.54	P++ (I&O)	963	32.08	0.98		1x23,1x24

Note: Posterior ~ P; Inside/Outside ~ I/O; Half Shell Only ~ H
+ ~ 33% cover
++ ~ 66% cover
+++ ~ 100% cover

Collectors: Frances Lucy and Monica Sullivan
Data analysis and Table: Anne Skelly, BSc student
Project supervisor: Frances Lucy

APPENDIX 9: *Anodonta anatina*, Site 8, Clarendon Lock, November 1999

Shell Length (mm)	Whole/ Half Shell (w/h)	Dead/ Alive (d/a)	Weight (g)	Location *Dreissena* on Shell	No. *Dreissena* on Shell	Weight - *Dreissena* on shell (g)	Weight Ratios - *Dreissena / Anodonta*	Weight debris on shell (g)	1+ and 2+ zebra mussels biofouling *Anodonta* Number x mm length
73	w	a	33.95	P (O)	399	14.95	0.44	10.47	-
76	w	a	16.79	P+ (I&O)	255	11.76	0.70	3.89	-
95	w	a	62.56	P+ (O)	309	22.05	0.35	24.69	1X21
100	w	a	82.21	P+ (O)	754	30.42	0.37	6.69	1X21,1x25
101	w	a	59.55	P (O)	364	23.14	0.39	30.86	1x25
109	w	a	65.68	P++ (0)	568	30.78	0.47	13.96	1X23,1x27
58	w	d	5.53	P (I&O)	334	10.95	1.98	0.66	-
73	w	d	11.92	P (I&O)	539	19.03	1.60	3.94	-
79	w	d	15.62	P+ (I&O)	396	15.92	1.02	-	-
81	w	d	48.23	H (I&O)	1,001	39.72	0.82	2.82	1x18,1x20,2x23
83	w	d	25.35	P (I&O)	719	26.86	1.06	11.91	1x19,2x20
85	w	d	17.83	P+ (I&O)	627	28.93	1.62	5.49	1x21,4x22,1x23
86	w	d	18.12	H+++ (I&O)	1,051	38.04	2.10	12.63	2x21,1x24
87	w	d	19.34	P++ (I&O)	*852	*40.93	*1.74	*15.03	*1X22,1X23, 1X24
88	w	d	27.6	P+++ (I&O)	*852	*40.93	*1.74	*15.03	*1X21,1x25,1x28
89	w	d	20.11	P (I&O)	768	37.81	1.88	8.32	2x26
89	w	d	42.32	P+++ (O)	594	27.67	0.65	28.25	1x20
92	w	d	21.07	P+ (I&O)	755	25.84	1.23	4.57	-
93	w	d	30.81	H (I+O)	1,099	59.05	1.92	27.55	1x22,1x25,1x27
99	w	d	27.19	P++ (I&O)	697	31.69	1.17	8.50	1x22
104	w	d	49.36	P++ (I&O)	1,108	49.31	1.00	5.64	1x23,1x26
72	w	d	9.75	P H+++ (I&O)	-	8.84	0.91	-	1x23,1x25
79	w	d	16.82	P H+++ (I&O)	-	*28.37	*1.32	-	-
80	w	d	21.08	P (O)	-	8.5	0.40	-	1x25
82	w	d	21.45	P H+++ (I&O)	-	33.24	1.55	-	1x22,1x26,1x28
83	w	d	20.26	P H+++ (I&O)	-	15.57	0.64	-	1x19,1x22,1x25
84	w	d	17.69	P (I&O)	-	16.43	0.93	-	1x22,1x26
86	w	d	24.33	P H+++ (I&O)	-	19.13	0.79	-	-
87	w	d	25.98	H+++ (I&O)	-	36.38	1.40	-	1x20,1x21,3x23,1x24
88	w	d	28.8	P H+++ (I&O)	-	38.16	1.33	-	1x22,1x23,3x24,1x25
91	w	d	25.45	P+++ (I&O)	-	*28.37	*1.32	-	2x19,1x22,1x23,1x26
91	w	d	32.57	P+++ (I&O)	-	34.01	1.04	-	1x19,1x23,1x28
92	w	d	25.24	P, H+++ (I&O)	-	35.28	1.40	-	1x24,1x25
96	w	d	26.66	P++ H+++ (I&O)	-	44.97	1.69	-	1x17,1.22,2x23,1x29
98	w	d	34.49	P (I&O)	-	17.82	0.52	-	-
99	w	d	27.53	P H+++ (I&O)	-	42.82	1.56	-	1x20,1x25,1x27

Note: **Posterior ~ P** **+ ~ 33% cover**
Inside/Outside ~ I/O **++ ~ 66% cover**
Half Shell Only ~ H **+++ ~ 100% cover**

*** Two shells found together - results averaged between both**

Collectors: Frances Lucy and Monica Sullivan
Data analysis and Table: Anne Skelly, BSc student
Project supervisor: Frances Lucy

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2000

Site 1 16/08/2000

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	33	104	13	P
2	64	101	7	P
3	23	85	6	D
4	44	89	11	P
5	5	77	7	D
6	29	80	5	P
7	16	83	5	P
8	15	92	10	P
9	21	83	5	P
10	36	97	10	D
11	31	90	6	D
12	51	91	7	P
13	46	90	6	P
14	12	75	6	D
15	75	95	7	P
16	46	95	9	P
17	40	95	9	P
18	29	88	9	D
19	42	87	7	D
20	44	93	9	D
21	54	85	6	P
22	42	88	5	P
23	37	81	5	P
24	19	65	5	P
25	17	72	6	P
26	31	93	9	D
27	40	75	6	P
28	28	59	4	P
29	66	98	11	D
30	20	50	4	P
31	17	82	8	D

Site 2 17/08/2000

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	7	56	3	P

Note: this was a very small Anodonta, just dead, decaying tissue, pearly shell.

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2000

Site 3 **17/08/2000**

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	51	69	6	D
2	8	35	2	P
3	34	80	6	D
4	28	92	10	D
5	41	80	7	D
6	66	90	5	P
7	34	68	5	D
8	23	70	4	D
9	61	89	7	D
10	38	90	7	D
11	55	84	7	D
12	35	71	6	D
13	42	61	5	D
14	19	92	7	D
15	32	76	7	D
16	54	78	5	D
17	15	74	4	D
18	30	71	4	D
19	34	90	6	D
20	66	102	9	D
21	50	82	5	D
22	34	85	7	D
23	21	81	4	D
24	28	76	4	D
25	47	83	5	D
26	21	102	8	D
27	22	87	6	D
28	15	78	5	D
29	25	88	5	D
30	21	80	5	D

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2000

Site 4 **17/08/2000**

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	7	56	3	D
2	59	82	5	D
3	52	75	5	D
4	60	72	4	D
5	63	90	4	D
6	42	67	3	P
7	17	69	2	P
8	28	80	4	P
9	26	65	3	P
10	37	60	3	P
11	69	79	3	P
12	36	72	4	P
13	62	75	4	P
14	48	62	4	P
15	53	72	3	P
16	29	52	2	P
17	74	79	4	D
18	43	84	5	P
19	125	87	6	P
20	79	90	6	P
21	66	86	5	D
22	63	80	5	P
23	74	90	5	P
24	78	105	6	D
25	65	95	6	D
26	43	83	4	D
27	54	85	4	D
28	123	95	4	D
29	74	86	4	P
30	70	79	4	P

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2000

Site 6 **16/08/2000**

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	36	85	5	D
2	20	85	5	D
3	22	92	6	P
4	15	85	5	P
5	18	88	5	P
6	19	85	5	D
7	32	75	5	P
8	21	100	8	P
9	27	79	5	P
10	27	87	6	P
11	17	55	3	P
12	31	89	8	P
13	28	92	11	D
14	32	93	11	P
15	13	57	3	P
16	8	57	5	P
17	14	79	5	D
18	19	74	11	D
19	42	86	11	D
20	56	91	12	D
21	38	90	10	P
22	35	84	6	P
23	28	86	13	P
24	17	77	7	D
25	43	86	12	D
26	39	103	21	D
27	27	84	13	P
28	44	94	14	D
29	41	98	15	D
30	40	82	9	P

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2000

Site 5 **17/08/2000**

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	29	91	5	D
2	27	81	5	D
3	21	85	6	D
4	24	81	8	D
5	12	71	5	D
6	16	68	5	D
7	37	90	6	D
8	42	87	6	D
9	18	82	7	P
10	3	62	4	P
11	8	59	4	P
12	50	101	10	D
13	24	76	4	D
14	24	69	6	D
15	29	90	7	D
16	18	92	6	P
17	19	84	7	D
18	25	92	5	D
19	23	92	6	D
20	20	68	7	P
21	20	88	5	P
22	19	89	7	D
23	32	81	7	D
24	19	80	4	P
25	37	78	5	D
26	24	80	6	P
27	18	59	5	D
28	31	78	5	P
29	24	79	6	D
30	24	72	4	D

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2000

Site 7 **17/08/2000**

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	15	97	7	D
2	22	124	15	D
3	11	90	4	D
4	11	88	5	P
5	12	92	7	P
6	16	91	6	P
7	10	95	6	P
8	8	75	4	P
9	27	108	8	D
10	10	83	5	P
11	9	86	5	D
12	11	71	4	D
13	11	91	7	D
14	6	101	7	D
15	21	90	5	P
16	14	92	6	D
17	9	81	4	D
18	7	97	7	D
19	4	95	5	D
20	17	90	6	D
21	6	87	5	D
22	9	81	4	P
23	3	67	3	P
24	9	77	4	P
25	11	72	3	P
26	3	97	6	P
27	13	87	6	D
28	7	73	5	P
29	9	74	4	D
30	5	71	4	P

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2000

Site 8 17/08/2000

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	35	97	8	D
2	12	70	5	P
3	23	95	7	D
4	32	91	6	D
5	43	99	7	D
6	23	85	5	D
7	24	85	5	D
8	26	80	4	P
9	27	98	7	D
10	7	62	4	P
11	13	86	6	D
12	10	78	5	D
13	32	95	7	D
14	21	73	4	P
15	23	92	6	D
16	24	81	5	D
17	2	70	3	P
18	13	85	6	D
19	37	92	7	D
20	26	90	7	D
21	57	98	7	D
22	10	77	6	D
23	37	95	7	D
24	28	90	7	D
25	23	85	6	D
26	24	89	8	D
27	26	75	5	D
28	40	104	10	D
29	28	85	7	D
30	19	73	5	D
31	16	80	5	D
32	16	80	6	D
33	14	72	7	D
34	23	70	7	D
35	12	70	7	D

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2001

Site 1 Date: 11/08/01

Density: 2-3 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	10	88	12	Dull
2	24	110	8	Dull
3	21	82	9	Dull
4	25	95	8	Dull
5	16	97	10	Dull
6	22	106	7	Dull
7	0	88	5	Dull
8	25	95	7	Dull
9	10	90	5	Dull
10	21	71	4	Dull
11	<1	94	11	Dull
12	20	86	5	Dull
13	18	90	6	Dull
14	6	64	3	Dull
15	20	74	6	Dull
16	21	80	7	Dull
17	57	91	7	Dull
18	23	103	8	Dull
19	43	90	7	Pearly
20	27	87	7	Dull
21	53	84	8	Dull
22	16	88	5	Dull
23	22	108	11	Dull
24	20	107	10	Dull
25	40	88	6	Dull
26	50	88	8	Pearly
27	3	85	9	Dull
28	19	109	9	Dull
29	7	92	5	Dull
30	57	83	7	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2001

Site 2 | Date: 16/08/01

Density: 2 m^2 | Depth: 1.0 - 3.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	4	76	9	Dull
2	26	87	11	Dull
3	32	89	10	Dull
4	35	101	10	Dull
5	16	87	12	Dull
6	<1	60	10	Dull
7	30	91	9	Dull
8	14	78	11	Dull
9	<1	77	12	Dull
10	2	89	11	Dull
11	16	108	15	Dull
12	<1	87	13	Dull
13	<1	88	15	Dull
14	13	86	11	Dull
15	0	77	21	Dull
16	13	74	19	Dull
17	17	100	18	Dull
18	9	81	11	Dull
19	36	82	20	Dull
20	31	89	10	Dull
21	31	80	15	Dull
22	9	97	12	Dull
23	35	71	6	Dull
24	35	81	15	Dull
25	5	76	15	Dull
26	60	71	11	Dull
27	43	80	17	Dull
28	67	85	18	Dull
29	32	93	12	Dull
30	13	92	18	Dull

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2001

Site 3 Date: 15/08/01

Density: 2 m^2 Depth: 1.0 - 3.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	17	51	2	Dull
2	41	89	23	Dull
3	20	92	20	Dull
4	35	86	15	Dull
5	58	92	12	Dull
6	45	101	16	Dull
7	22	82	10	Dull
8	55	95	15	Dull
9	43	90	7	Dull
10	41	89	16	Dull
11	35	100	17	Dull
12	50	92	23	Dull
13	25	84	22	Dull
14	26	88	30	Dull
15	27	99	20	Dull
16	28	63	5	Dull
17	29	96	9	Dull
18	20	94	15	Dull
19	45	82	9	Dull
20	48	96	9	Dull
21	27	58	4	Dull
22	49	87	7	Dull
23	26	64	6	Dull
24	17	89	23	Dull
25	27	40	3	Dull
26	13	34	2	Dull
27	20	79	15	Dull
28	31	94	18	Dull
29	13	93	28	Dull
30	39	75	6	Dull

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2001

Site 4 Date: 15/08/01

Density: 3 m^2 Depth: 2.0 - 3.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	24	49	3	Dull
2	59	74	6	Dull
3	72	78	5	Dull
4	32	70	7	Dull
5	44	67	3	Pearly
6	41	68	3	Dull
7	33	48	2	Pearly
8	57	83	4	Dull
9	30	48	3	Pearly
10	33	72	7	Dull
11	80	85	7	Dull
12	65	86	8	Dull
13	58	84	7	Pearly
14	67	87	8	Pearly
15	63	88	12	Dull
16	56	79	6	Dull
17	72	79	7	Dull
18	61	103	12	Dull
19	21	70	3	Dull
20	51	101	9	Dull
21	72	82	5	Dull
22	22	43	3	Dull
23	92	90	6	Dull
24	20	64	3	Dull
25	58	81	9	Dull
26	70	82	6	Dull
27	64	87	5	Dull
28	103	88	5	Dull
29	79	86	5	Pearly
30	54	56	2	Dull

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2001

Site 5 Date: 15/08/01

Density: 3 m^2 Depth: 2.5 - 3.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	13	66	4	Dull
2	13	77	8	Dull
3	28	92	9	Dull
4	44	78	7	Dull
5	41	78	13	Dull
6	32	84	12	Dull
7	34	86	8	Dull
8	28	80	10	Dull
9	12	55	5	Dull
10	33	95	7	Dull
11	33	100	11	Dull
12	22	73	5	Dull
13	22	58	3	Dull
14	41	85	7	Dull
15	34	102	15	Dull
16	42	84	5	Dull
17	27	79	4	Dull
18	25	68	5	Dull
19	19	57	3	Dull
20	20	68	6	Dull
21	33	77	9	Dull
22	26	92	24	Dull
23	36	95	8	Dull
24	35	87	7	Dull
25	21	85	18	Dull
26	49	100	9	Dull
27	15	64	7	Dull
28	18	87	5	Dull
29	23	82	9	Dull
30	24	85	13	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2001

Site 6 Date: 10/08/01

Density: 7-9 m^2 Depth: 2-2.5 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	12	88	9	Dull
2	26	85	8	Dull
3	43	90	11	Dull
4	31	99	11	Dull
5	38	92	9	Dull
6	26	92	15	Dull
7	30	95	15	Dull
8	31	90	12	Dull
9	49	90	12	Dull
10	24	100	16	Dull
11	26	92	14	Dull
12	27	85	7	Dull
13	23	91	11	Dull
14	28	91	12	Dull
15	29	85	12	Dull
16	28	88	9	Dull
17	28	85	12	Dull
18	54	82	8	Dull
19	54	95	14	Dull
20	43	93	18	Dull
21	56	93	15	Dull
22	30	95	13	Dull
23	35	90	12	Dull
24	23	90	14	Dull
25	31	98	7	Dull
26	30	100	13	Dull
27	24	80	8	Dull
28	29	87	10	Dull
29	23	92	10	Dull
30	29	100	8	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2001

Site 7 Date: 13/08/01

Density: 6 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	24	88	11	Dull
2	17	90	15	Dull
3	23	98	nd	Dull
4	21	82	nd	Dull
5	18	80	nd	Dull
6	29	95	nd	Dull
7	27	105	nd	Dull
8	29	90	nd	Dull
9	11	85	nd	Dull
10	45	94	nd	Dull
11	27	92	nd	Dull
12	22	81	nd	Dull
13	20	77	nd	Dull
14	11	84	nd	Dull
15	15	102	nd	Dull
16	15	100	nd	Dull
17	18	100	nd	Dull
18	33	91	nd	Dull
19	31	82	nd	Dull
20	24	83	nd	Dull
21	40	94	nd	Dull
22	21	92	nd	Dull
23	15	85	nd	Dull
24	23	87	nd	Dull
25	35	82	nd	Dull
26	24	91	nd	Dull
27	12	72	nd	Dull
28	21	88	nd	Pearly
29	30	90	nd	Dull
30	14	57	nd	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2001

Site 8 Date: 09/08/01

Density: 10 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	41	117	12	Dull
2	41	87	8	Dull
3	41	55	12	Dull
4	37	89	17	Dull
5	55	90	8	Dull
6	35	91	15	Dull
7	52	87	14	Dull
8	34	88	13	Dull
9	52	78	7	Dull
10	30	77	7	Dull
11	32	85	8	Pearly
12	37	100	18	Dull
13	27	83	8	Dull
14	26	74	6	Dull
15	19	90	8	Dull
16	49	97	13	Dull
17	53	95	11	Dull
18	36	93	9	Pearly
19	39	90	10	Dull
20	35	100	9	Dull
21	42	78	8	Dull
22	37	84	6	Dull
23	54	99	20	Dull
24	54	81	7	Dull
25	34	92	8	Dull
26	55	88	11	Dull
27	35	86	6	Pearly
28	22	67	6	Dull
29	45	94	9	Pearly
30	28	78	5	Dull

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2003

Site 1 Date: 10/08/03

Density: <1 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	19	87	8	Dull
2	24	96	nd	Dull
3	12	102	7	Dull
4	26	93	7	Dull & Pearly
5	19	96	nd	Pearly
6	6	104	nd	Dull
7	<1	106	8	Pearly
8	13	98	7	Dull
9	23	94	7	Dull & Pearly
10	18	55	3	Pearly
11	6	85	6	Dull & Pearly
12	8	88	nd	Dull
13	22	99	6	Dull & Pearly
14	6	84	6	Dull
15	25	88	7	Dull
16	28	109	9	Dull
17	27	88	7	Dull & Pearly
18	22	78	5	Dull
19	3	83	6	Pearly
20	21	86	6	Dull
21	9	87	nd	Dull
22	20	88	7	Dull & Pearly
23	0	78	6	Dull
24	9	95	8	Dull
25	46	91	6	Dull
26	24	89	8	Dull
27	18	89	nd	Dull
28	14	91	nd	Dull
29	16	82	nd	Dull
30	14	90	7	Dull & Pearly

nd = not determined due to shell condition

APPENDIX 9: *Anodonta anatina*, Snorkel Survey 2003

Site 2 Date: 10/08/03

Density: 3 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	35	105	10	Pearly and Dull
2	32	90	8	Dull
3	16	89	6	Pearly and Dull
4	14	82	7	Dull
5	17	80	nd	Dull
6	21	87	6	Dull
7	11	84	nd	Dull
8	3	73	nd	Dull
9	3	58	5	Dull
10	7	81	nd	Dull
11	20	110	13	Dull
12	11	84	6	Dull
13	14	79	nd	Dull
14	15	95	7	Dull
15	1	74	nd	Dull
16	30	83	nd	Dull
17	8	87	nd	Dull
18	10	82	nd	Dull
19	17	88	nd	Pearly
20	12	94	8	Dull
21	14	92	8	Dull
22	3	86	7	Dull
23	14	91	8	Dull
24	5	86	nd	Dull
25	15	93	nd	Dull
26	13	87	nd	Pearly
27	8	78	nd	Dull
28	1	64	nd	Dull
29	23	96	nd	Dull
30	9	76	nd	Dull

nd = not determined due to shell condition

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 3 Date: 10/08/03

Density: 4 m^2 Depth: 1.0 - 2.5 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	21	80	6	Dull
2	9	81	6	Dull
3	12	91	6	Dull
4	13	93	6	Dull
5	13	74	4	Dull
6	15	92	8	Dull
7	16	91	7	Dull
8	7	85	nd	Dull
9	11	95	7	Dull
10	13	89	9	Dull
11	5	75	5	Dull
12	6	96	8	Dull
13	3	62	7	Dull
14	3	75	7	Dull
15	13	103	13	Dull
16	18	100	8	Dull andPearly
17	12	90	7	Dull and Pearly
18	3	88	9	Dull
19	<1	58	3	Pearly
20	7	88	8	Dull
21	9	79	7	Dull and Pearly
22	3	88	9	Dull
23	12	84	7	Dull and Pearly
24	7	82	7	Dull
25	<1	65	5	Dull and Pearly
26	<1	83	9	Dull
27	2	86	7	Dull
28	2	62	6	Pearly
29	7	80	7	Dull and Pearly
30	8	83	8	Dull

nd = not determined due to shell condition

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 4 Date: 12/08/03

Density: 3 m^2 Depth: 2.0 - 3.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	17	72	6	Dull and Pearly
2	38	80	5	Dull and Pearly
3	28	77	4	Dull and Pearly
4	26	76	6	Pearly
5	3	76	nd	Dull
6	12	80	7	Dull
7	12	91	nd	Dull
8	21	77	6	Dull and Pearly
9	31	76	5	Dull and Pearly
10	17	69	6	Dull and Pearly
11	31	85	8	Dull
12	15	71	4	Dull
13	21	75	5	Dull
14	20	80	7	Dull
15	21	69	4	Dull and Pearly
16	16	68	5	Dull
17	14	92	nd	Dull
18	27	82	6	Dull
19	24	90	7	Dull
20	11	72	nd	Dull
21	16	43	3	Pearly
22	9	84	nd	Dull
23	16	59	nd	Dull and Pearly
24	9	73	nd	Dull
25	13	86	nd	Dull
26	25	91	7	Dull
27	18	76	6	Dull
28	11	62	4	Dull and Pearly
29	16	74	6	Dull and Pearly
30	8	61	5	Dull and Pearly

nd = not determined due to shell condition

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 5 Date: 09/08/03

Density: 3 m^2 Depth: 4.0 - 5.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	31	84	6	Pearly
2	19	84	7	Pearly
3	19	89	10	Dull
4	8	90	7	Pearly
5	5	85	10	Dull
6	13	96	9	Dull
7	8	73	7	Dull
8	10	62	5	Pearly
9	17	75	8	Pearly
10	13	82	9	Pearly
11	14	80	10	Dull and Pearly
12	11	62	4	Dull
13	21	87	9	Dull
14	13	58	3	Pearly
15	12	90	9	Dull
16	13	73	7	Dull
17	15	65	4	Pearly
18	18	72	7	Pearly
19	23	74	5	Dull
20	27	96	11	Dull
21	9	97	19	Dull
22	6	73	7	Pearly
23	21	71	7	Pearly
24	30	98	12	Dull
25	17	68	5	Dull and Pearly
26	16	86	9	Dull
27	13	95	10	Dull
28	30	79	7	Pearly
29	15	86	8	Pearly
30	23	75	7	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 6 Date: 09/08/03

Density: 4 m^2 Depth: 1.5-1.75 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	4	91	11	Dull
2	13	90	7	Dull
3	3	85	5	Dull
4	10	94	15	Dull
5	15	86	12	Dull and Pearly
6	15	84	9	Dull
7	4	70	4	Dull
8	16	99	14	Dull
9	25	89	10	Dull and Pearly
10	9	83	6	Dull
11	5	92	10	Dull
12	3	59	3	Dull
13	2	87	14	Dull
14	18	98	14	Dull
15	17	90	9	Dull
16	15	100	10	Dull
17	15	93	9	Dull
18	3	82	8	Dull
19	22	91	7	Dull
20	26	110	13	Dull
21	12	101	7	Dull
22	12	85	8	Dull
23	20	58	3	Dull
24	13	103	11	Dull
25	11	46	3	Dull and Pearly
26	2	80	8	Dull
27	1	87	8	Dull
28	1	81	7	Dull
29	20	97	8	Dull
30	1	91	8	Dull

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 7 Date: 08/08/03

Density: 3 m^2 Depth: 1-2 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	6	100	11	Dull and Pearly
2	20	100	11	Dull and Pearly
3	16	102	10	Dull
4	6	98	nd	Dull
5	22	90	8	Dull and Pearly
6	12	92	9	Dull and Pearly
7	13	90	8	Dull and Pearly
8	13	90	nd	Dull
9	3	90	nd	Dull
10	3	80	nd	Dull
11	2	86	9	Dull and Pearly
12	4	93	10	Dull
13	10	83	10	Dull and Pearly
14	7	87	nd	Dull and Pearly
15	10	96	nd	Dull and Pearly
16	13	80	8	Dull and Pearly
17	7	100	nd	Dull
18	8	85	7	Dull and Pearly
19	3	82	8	Dull and Pearly
20	5	92	9	Dull and Pearly
21	5	85	7	Dull
22	8	90	7	Dull
23	15	100	nd	Dull and Pearly
24	5	96	nd	Dull
25	2	90	8	Dull and Pearly
26	1	85	nd	Dull
27	1	81	6	Dull
28	3	70	7	Dull and Pearly
29	20	95	8	Dull and Pearly
30	1	66	6	Pearly

nd = not determined due to shell condition

APPENDIX 9: *Anodonta anatina* , Snorkel Survey 2003

Site 8 Date: 12/08/03

Density: 3 m^2 Depth: 2.0 m

No.	Biomass *Dreissena* /g	*Anodonta* Shell length/mm	*Anodonta* Age/Years	Dull / Pearly
1	46	95	nd	Dull
2	99	106	nd	Dull
3	49	86	6	Dull
4	55	96	nd	Dull
5	62	91	nd	Dull
6	56	85	nd	Dull
7	56	106	nd	Dull
8	75	97	nd	Dull
9	57	82	nd	Dull
10	44	74	5	Dull
11	81	96	nd	Dull
12	106	96	nd	Dull
13	62	93	nd	Dull
14	62	97	nd	Dull
15	33	96	nd	Dull
16	38	75	nd	Dull
17	36	94	nd	Dull
18	38	101	nd	Dull
19	51	97	nd	Dull
20	40	96	nd	Dull
21	49	90	nd	Dull
22	40	96	nd	Dull
23	40	98	nd	Dull
24	46	90	nd	Dull
25	45	95	nd	Dull
26	40	94	nd	Dull
27	32	102	nd	Dull
28	25	83	nd	Dull
29	39	79	nd	Dull
30	38	86	nd	Dull

nd = not determined due to shell condition

Appendix 10. Chlorophyll a and Transparency, Lough Key 1998-2003.

	Chlorophyll a ug/L						**Transparency/m**				
Date	**1**	**2**	**3**	**4**	**5**	**Algal Bloom**	**1**	**2**	**3**	**4**	**5**
28/1/01	0.49	0	0.78	ND	ND		1.3	1.2	1.6	ND	ND
19/02/02	2.62	ND	3.79	3.01	ND		1.5	1.3	ND	1.3	ND
22/03/02	4.08	3.21	3.5	4.76	ND		1.7	1.5	1.7	1.3	ND
17/03/03	3.21	6.03	3.5	3.21	ND		1.4	1.5	1.6	1.5	
01/04/01	3.12	4.84	3.63	3.53	ND		1.5	1.4	1.6	1	
07/04/02	1.17	1.95	1.36	1.26	ND		1.5	1.7	1.6	1.3	ND
13/4/01	3.83	12.1	3.22	2.02	ND		2	1.3	2	0.8	
11/04/03	3.89	7.49	4.87	6.32	ND		2.2	1.8	2.1	1.7	ND
25/04/02	2.33	2.72	3.31	4.18	ND		1.7	1.6	2	1.6	ND
01/05/01	0.97	0	0.39	0.29	ND		2	1.8	1.7	0.8	
09/05/02	3.5	6.42	4.96	5.64	ND		2.5	2.3	2.4	1.8	ND
15/5/01	5.05	3.89	4.28	3.02	ND		1.8	2	2	1.5	ND
16/05/03	3.99	3.79	5.35	3.26	ND		2.2	2.2	2.3	1.7	ND
29/05/01	3.5	3.3	0.58	4.28	0.58		2	2	2	1.7	2.1
30/05/02	2.72	4.77	3.11	2.33	ND		1.8	1.3	2.2	2	ND
31/05/03	3.7	8.17	5.06	5.06	ND		2.1	1.8	2.2	1.9	ND
10/06/01	0	0	1.36	4.86	1.75		1.8	1.6	2	1.7	1.5
12/06/02	1.65	2.14	1.95	2.53	ND		1.8	1.6	1.7	1.5	ND
18/06/02	ND	1.56	1.75	5.55	ND		ND	1.6	1.7	1.6	ND
15/06/03	7.88	3.89	11.18	10.99	6.22		2.2	2.1	2.2	1.8	2.1
23/6/01	4.08	4.48	1.95	3.89	4.67		2	1.9	1.9	2.1	1.2
28/06/02	5.1	3.89	4.87	3.5	ND		2.2	2	2.3	2	ND
30/6/00	14.79	9.93	7.88	14.89	13.63		2	1.9	1.9	0.4	1.9
30/6/01	5.05	5.45	5.84	3.5	3.5		1.8	1.7	2	0.9	2
30/06/03	5.75	7.49	7.88	7.88	10.22		2.8	2.5	3	1.8	2.7
07/07/00	4.48	6.03	4.28	14.8	3.11		2.4	2.5	2.3	0.5	2
06/07/01	4.48	3.31	3.89	4.96	2.53		2.5	1.8	3.1	2.4	0.8
06/07/02	3.31	3.6	7.3	5.94	5.35		1.9	1.8	1.9	1.8	1.8
07/07/03	6.03	9.73	9.05	4.77	4.09		2.1	2.1	2.8	1.8	2.4
14/7/00	5.26	2.43	3.6	3.02	17.71		2.4	2	2.5	0.9	1.9
15/7/01	3.69	6.42	5.05	3.31	3.7		2.3	1.7	2.3	2.7	1.5
13/07/02	9.24	3.89	5.45	5.74	3.11		ND	ND	ND	ND	1.5
14/07/03	5.35	3.41	3.89	6.52	8.17		2.6	2.3	2.8	1.75	2.6
19/07/98	9.8	7.7	14.2	18.8	ND		1.4	1.3	1.4	1.5	
21/07/99	4	6.25	5.64	ND	ND		2.6	2.2	2.2	ND	
21/7/00	7.69	10.9	10.22	5.14	ND	+	1.5	1.4	1.9	0.6	ND
21/7/01	5.45	1.95	3.31	3.7	2.92		2.3	1.8	2.6	1.3	2.5
21/07/02	7.2	7.49	9.63	5.83	7.49		1.8	1.7	1.9	1.1.	1.7
22/07/03	12.84	6.42	22.38	11.38	6.52	+	2.3	2.4	2.1	1.6	2.6
30/07/98	7.9	8.03	6.88	11.78	ND		1.5	1.5	1.5	0.6	
30/07/99	4.84	13.1	6.45	38.7	ND						
28/7/00	14.92	2.72	12.8	2.62	7.36		1.8	2	2	0.7	2.2
28/7/01	12.84	24.7	12.4	26.85	11.29	+	2.7	2.9	2.7	1.7	2.8
28/07/02	4.96	5.35	3.41	4.09	5.74		2	1.6	1.7	1.3	1.8
29/07/03	6.91	5.64	11.19	6.32	10.9		2.3	2.4	2.3	1.75	2.3

ND means no data, either due to seasonal sampling or adverse weather

Appendix 10 (Ctd.) Chlorophyll a and Transparency, Lough Key 1998-2003

	Chlorophyll a ug/L						Transparency/m				
Date	1	2	3	4	5	Algal Bloom	1	2	3	4	5
06/08/98	12.09	10.2	15.32	21.4	ND		1.3	1.3	1.5	0.5	ND
06/08/99	7.79	8.66	11.29	8.67	ND		2.5	2.1	2.3	0.7	ND
04/08/00	3.22	1.91	2.62	5.14	3.83		2.2	2	2.2	0.6	2.2
03/08/01	8.47	13.03	18.97	9.93	9.83	+	2.9	2.8	2.9	1	3.1
04/08/02	5.94	6.03	5.45	5.45	3.11		1.8	1.8	1.5	1.4	1.8
05/08/03	4.87	10.41	5.35	5.84	12.16		2.4	1.8	2.2	1.5	2.2
13/08/98	18.35	15.8	20.9	28.9	ND		1.5	1.5	1.6	0.9	ND
11/08/00	17.23	3.12	2.32	5.44	3.63		2.4	2	2.4	0.6	2.4
11/08/01	2.72	3.5	7.2	3.7	5.55		2.7	2.8	2.7	0.8	2.1
13/08/02	4.67	3.11	5.55	4.87	6.13		2.1	1.9	2	1.5	2.2
13/08/03	9.83	9.05	10.41	7.01	10.41		2.3	2.4	2.4	1.65	2.3
20/08/98	15.4	11.3	15.3	24.4	ND		1.5	1.6	1.5	0.5	ND
20/08/99	13.71	11.49	20.96	10.4	ND		2.3	2.5	2.3	0.7	ND
18/8/00	7.46	8.97	15.16	8.77	13.1		2.5	2.3	2.5	0.4	2.5
18/8/01	5.06	6.62	3.11	5.16	5.94		2.7	2.8	2.6	0.8	2.8
18/08/02	4.96	ND	2.14	5.35	5.35		2.1	2.1	2.4	1.5	2.2
19/08/03	3.21	3.7	4.09	3.6	3.99		2.7	2.5	2.6	1.72	2.6
26/8/00	9.78	11.49	5.54	8.36	7.76	+	1.9	1.9	2.3	0.9	2.2
24/8/01	2.92	2.14	5.74	2.72	3.31		2.7	2.7	2.8	1.8	2.8
23/08/02	6.03	9.73	6.81	4.18	2.72		2.3	2.3	2.3	1.7	2.3
26/08/03	3.21	5.25	3.99	4.77	7.59		2.6	2.6	2.5	1.7	2.7
31/08/02	3.89	2.63	3.6	3.89	4.48		2.4	2.3	2.4	1.5	2.2
02/09/98	79.1	23.6	29.4	21.7	ND		1.7	1.8	1.8	1.3	ND
03/09/99	6.88	7.09	6.2	6.88	ND		3	2.9	3.1	1.8	ND
02/09/00	2.62	6.55	4.94	ND	ND		2.5	2.5	2.4	0.6	2.3
02/09/01	3.02	7.88	3.5	3.79	3.31	+	3.4	2.9	3	1.7	3
02/09/03	9.34	13.52	12.16	7.78	9.83	+	3	2.5	2.4	1.68	2.7
09/09/98	20.02	22.94	20.22	11.88	ND		1.5	1.4	1.5	0.6	ND
07/09/00	ND	ND	ND	ND	ND		3.1	2.9	ND	ND	ND
08/09/01	3.79	ND	2.62	3.21	2.72		2.8	2.4	3.1	0.8	2.8
12/09/02	2.13	3.11	2.04	2.72	2.91		2.7	2.4	2.4	1.7	2.6
09/09/03	7.59	8.76	13.04	8.37	8.56	+	2.8	2.4	2.7	1.6	2.9
20/09/98	7.92	8.97	11.26	7.09	ND		1.5	1.9	2	1.3	ND
15/09/99	3.23	3.75	3.44	2.71	ND		2.3	2	2.3	1.5	ND
16/9/00	ND	ND	ND	ND	1.75		3.1	2.2	2.8	0.6	2.5
20/9/01	3.02	4.57	6.23	8.27	4.38		3	3	3	1.8	2.6
19/09/02	3.7	5.84	7.49	3.5	6.13	+	2.9	1.8	2	1.8	2.7
21/09/03	9.34	9.54	8.56	6.91	5.45		3	2.8	3	1.7	2.5
27/09/98	12.72	14.6	13.76	6.26	ND		1.6	1.6	1.6	1.3	ND
24/09/99	2.29	5.22	4.07	2.5	ND		2.3	2.2	2.2	1.8	ND
01/10/00	2.14	3.02	4.28	1.56	1.56		2.6	2.4	2.7	0.6	2.4
30/9/01	3.11	4.38	4.28	8.27	7		2.7	2.3	3	1.5	2.5
01/10/02	3.89	3.41	2.82	4.38	2.24		2.7	2.5	2.6	1	2.6
11/10/01	ND	ND	7.2	8.15	ND		ND	ND	2.9	1	ND
11/10/03	5.35	6.03	5.06	4.96	ND		3.2	2.9	3.1	1.8	2.8
22/10/00	1.75	2.14	1.36	1.85	1.85		2	1.7	2	0.7	1.7
21/10/01	3.79	3.79	5.25	3.69	3.5		2.6	2.3	2.6	1.9	2.6
28/10/02	4.28	6.91	5.35	4.87	ND		2	1.1	1.8	ND	ND
30/11/02	4.5	6.03	3.99	6.62	ND		1.2	1.2	1.1	1	ND
10/12/00	0.68	0.2	0.01	0.389	ND		1	0.9	1	0.5	ND
09/12/01	1.95	2.72	2.43	0.973	ND		1.4	1.4	1.4	1.2	ND

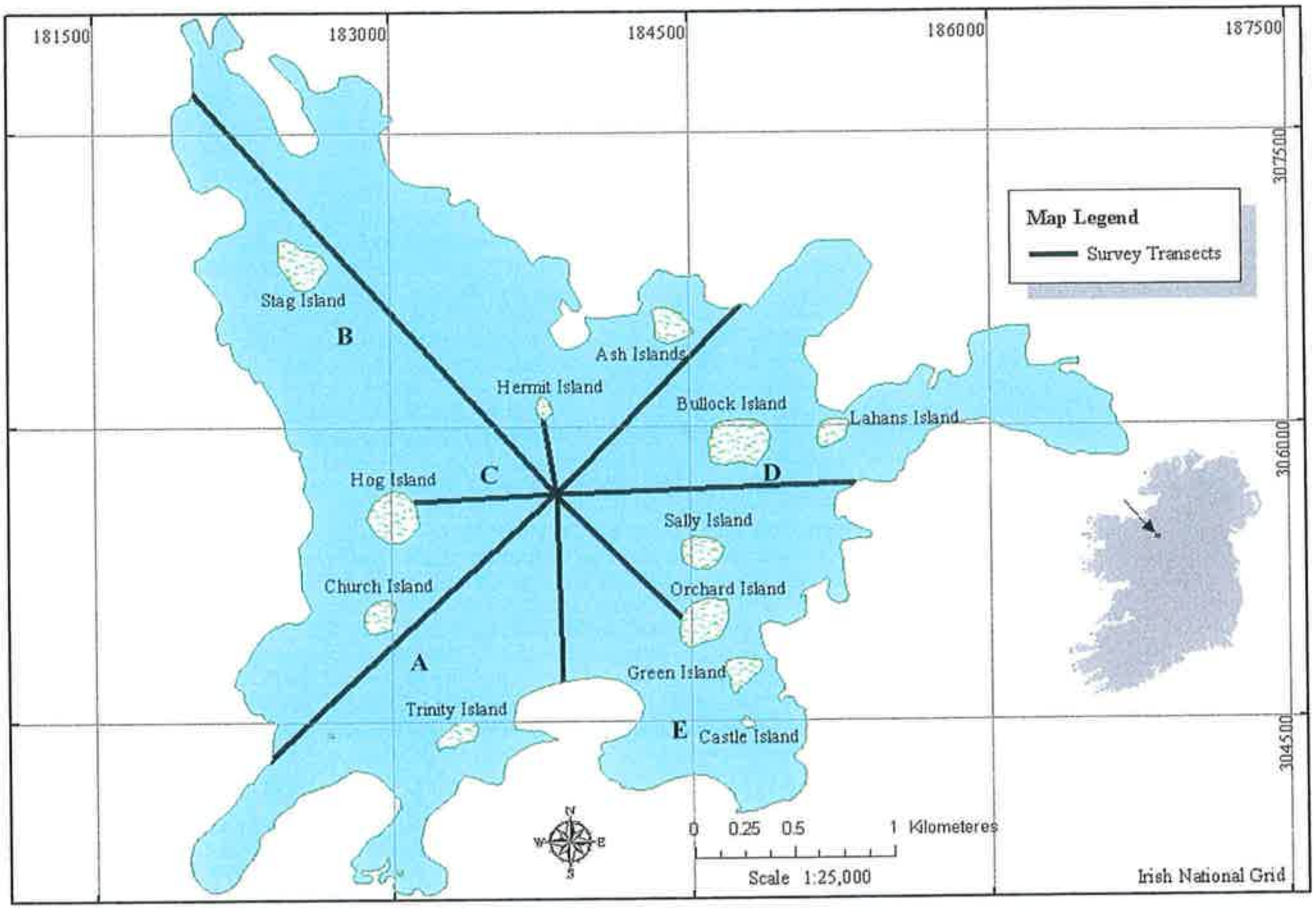


Fig 1 EPA Sampling Sites

Appendix 11 External Water Quality A. EPA Total phosphorus data, Lough Key 1995-1997

1995			1996			1997		
Date Sampled	**Station**	**TP ug/l P**	**Date Sampled**	**Station**	**TP ug/l P**	**Date Sampled**	**Station**	**TP µg/l P**
26-Apr-95	A/S	36	1-May-96	A/S	40	23-Apr-97	A/S	52
26-Apr-95	B/S	28	1-May-96	A/6m	52	23-Apr-97	A/6m	61
26-Apr-95	C/S	26	1-May-96	B/S	48	23-Apr-97	B/S	118
26-Apr-95	D/S	26	1-May-96	B/6m	92	23-Apr-97	B/6m	33
26-Apr-95	E/S	24	1-May-96	C/S	142	23-Apr-97	C/S	48
26-Apr-95	E/8m	28	1-May-96	C/6m	66	23-Apr-97	C/6m	41
26-Apr-95	A/6m	24	1-May-96	C/12m	52	23-Apr-97	C/12m	76
26-Apr-95	B/6m	30	1-May-96	C/18m	44	23-Apr-97	C/18m	49
26-Apr-95	C/6m	34	1-May-96	D/S	44	23-Apr-97	D/S	80
26-Apr-95	D/6m	26	1-May-96	D/5m	60	23-Apr-97	D/6m	46
26-Apr-95	C/18m	26	1-May-96	E/S	52	23-Apr-97	E/S	33
26-Apr-95	C/12m	24				23-Apr-97	E/6m	107
19-Jul-95	A/S	34	24-Jul-96	A/S	46	16-Jul-97	A/S	32
19-Jul-95	B/S	58	24-Jul-96	B/S	48	16-Jul-97	A/6m	36
19-Jul-95	C/S	120	24-Jul-96	C/S	130	16-Jul-97	B/S	33
19-Jul-95	D/S	42	24-Jul-96	D/S	48	16-Jul-97	B/6m	40
19-Jul-95	E/S	34	24-Jul-96	E/S	34	16-Jul-97	C/S	28
19-Jul-95	E/8m	36	24-Jul-96	B/8m	64	16-Jul-97	C/6m	35
19-Jul-95	B/6m	90	24-Jul-96	E/8m	36	16-Jul-97	C/12m	34
19-Jul-95	C/6m	36	24-Jul-96	C/6m	58	16-Jul-97	C/18m	44
19-Jul-95	D/6m	136	24-Jul-96	D/5m	42	16-Jul-97	D/S	31
19-Jul-95	C/12m	104	24-Jul-96	C/18m	216	16-Jul-97	D/6m	32
19-Jul-95	C/18m	52	24-Jul-96	C/12m	36	16-Jul-97	E/S	34
						16-Jul-97	E/6m	38
			26-Sep-96	A/S	350	18-Sep-97	A/S	82
			26-Sep-96	C/S	124	18-Sep-97	A/6m	70
			26-Sep-96	D/S	182	18-Sep-97	B/S	42
			26-Sep-96	E/S	194	18-Sep-97	B/6m	25
			26-Sep-96	E/8m	90	18-Sep-97	C/S	51
			26-Sep-96	A/6m	222	18-Sep-97	C/6m	48
			26-Sep-96	C/6m	62	18-Sep-97	C/12m	48
			26-Sep-96	D/6m	116	18-Sep-97	C/18m	68
			26-Sep-96	C/18m	268	18-Sep-97	D/S	63
			26-Sep-96	C/12m	160			
25-Oct-95	A/S	44	31-Oct-96	A/S	66	16-Oct-97	A/S	67
25-Oct-95	B/S	64	31-Oct-96	C/S	58	16-Oct-97	A/6m	62
25-Oct-95	C/S	58	31-Oct-96	D/S	64	16-Oct-97	B/S	77
25-Oct-95	D/S	72	31-Oct-96	E/S	70	16-Oct-97	B/6m	53
25-Oct-95	E/S	38	31-Oct-96	D/6m	64	16-Oct-97	C/S	71
			31-Oct-96	E/6m	244	16-Oct-97	C/12m	57
			31-Oct-96	C/18m	108	16-Oct-97	C/18m	72
						16-Oct-97	D/S	64
						16-Oct-97	D/6m	52
						16-Oct-97	E/S	66
mean = 48			**mean = 100**			**mean = 54**		

Appendix 11 External Water Quality A (ctd.). EPA water quality data for Lough Key, 2000

Date Sampled	Site	Temp °C	DO % Sat	Colour Hazen	Secchi m	Chlorophyll mg/m³	TP µg/l P	PO4 µg/l P
29/3/00	B/S	9.6	93	90	1.9	4.8	34	20
29/3/00	B/6	9.4	93	80			32	20
29/3/00	C/S	9.6	94	80	2	4.8	29	20
29/3/00	C/22m	9.3	93	90			31	23
29/3/00	D/S	9.7	92	80	2.5	2.8	28	21
29/3/00	D/6m	9.9	86	80			31	21
29/3/00	E/S	9.6	95	90	2.1		25	20
5/7/00	A/S	18.9	94	50	3	5.6	14	7
5/7/00	B/S	19.1	95	50	3.4	7.7	13	8
5/7/00	B/6m	17.2	84	50			18	12
5/7/00	C/S	18.8	93	50	3.8	4.4	18	10
5/7/00	C/22m	18.5	94	50			15	11
5/7/00	D/S	18.6	94	50	3.4	2.8	15	9
5/7/00	E/S	18.8	100	50	3.2		16	8
7/9/00	A/S	17.4	88	40	2.9	6.4	20	11
7/9/00	A/6m	17.3	92				21	12
7/9/00	B/S	17.4	89	50	2.4	6.9	23	11
7/9/00	B/6m	17.6	86				19	12
7/9/00	C/S	17.4	88	40	2.7	7.3	27	12
7/9/00	C/6m	17.4	88				19	12
7/9/00	D/S	17.3	91	40	3.1	3.2	17	12
7/9/00	D/6m	17.3	94				18	11
7/9/00	E/S	17.5	88	40		6	18	11
7/9/00	E/6m	17.6	88				29	12
4/10/00	A/S	14.2	87	55		3.2	25	21
4/10/00	B/S	14.2	86	60	2.9	2.8	27	22
4/10/00	B/6m	14.6	92	60			30	21
4/10/00	C/S	14.3	88	60	2.7	2.8	28	21
4/10/00	C/18m	14.1	89	60		xx	29	20
4/10/00	D/S	14.1	88	60	3.1	2.8	25	21
4/10/00	D/6m	13.9	89	50		xx	30	21
4/10/00	E/S	14.1	92	60	2.5	4.4	30	21
4/10/00	E/6m	14	91	60		xx	56	20

Appendix 11 External Water Quality A (ctd.). EPA water quality data for Lough Key, 2001

Date Sampled	Station	Temp °C	DO % Sat	Colour Hazen	Secchi m	Chlorophyll mg/m³	TP µg/l P	PO4 µg/l P	Silica mg Si/l
05/04/2001	A	7.5	11.1	nd	1.8	2	**1304**	47	1.664
05/04/2001	B	7.3	11.2	nd	1.9	1.6	29	32	2.222
05/04/2001	B/6m	7.4	10.9	nd			47	31	1.869
05/04/2001	C	7.3	11.1	nd	1.9	1.6	32	38	1.979
05/04/2001	C/18m	7.3	10.9	nd			29	21	1.895
05/04/2001	D	7.3	11.4	nd	2.3	0.8	141	20	2.24
05/04/2001	D/6m	7.4	10.7	nd			**2245.9**	7	2.2
05/04/2001	E	7.5	10.9	nd	2	1.6	21	18	2.09
05/04/2001	E/6m	7.7	10.8	nd			31	23	1.978
04/07/2001	A/S	18.3	93	nd	3	5.6	117	9.578	0.848
04/07/2001	A/6m	18.2	96	nd			106	7.248	0.866
04/07/2001	B/S	18.7	92	nd	3.2	6	90	8.098	0.937
04/07/2001	B/6m	17.8	86	nd			43	13.333	0.989
04/07/2001	C/S	18.2	95	nd	2.8	4.4	53	8.905	0.834
04/07/2001	C/12m	17.9	96	nd			42	10.347	0.922
04/07/2001	C/18m	18.4	70	nd			61	24.763	1.391
04/07/2001	D/S	18.4	93	nd	3.3	6	34	8.336	0.841
04/07/2001	D/6m	17.6	86	nd			37	15.988	0.973
04/07/2001	E/S	18.4	98	nd	3.3	5.2	32	9.245	0.901
04/07/2001	E/6m	18.4	94	nd			82	12.575	0.956
06/09/2001	A/6m	17.2	90	70	3.5	3.6	37	17	1.641
06/09/2001	B/5m	17.2	92	80	3.3	4	31	15	1.541
06/09/2001	C/S	17.2	90	70	3.9	4	29	12	1.556
06/09/2001	C/18m	17.2	92	70		4.4	133	18	1.527
06/09/2001	D/S	16.9	90	80	3.6	6.4	49	18	1.591
06/09/2001	D/5m	17	99	80		2.8	39	15	1.556
06/09/2001	E/S	17.4	91	60	3.5	5.6	53	17	1.567
03/10/2001	A/S	14.2	94	70	2.8	2	no sample	18	no sample
03/10/2001	A/6m	14	93	90			no sample	19	no sample
03/10/2001	B/S	14.5	95	60	2.9	2.4	no sample	12	no sample
03/10/2001	B/6m	14.5	95	60			no sample	18	no sample
03/10/2001	C/S	14.3	95	60	2.7	2	no sample	19	no sample
03/10/2001	C/18m	14.3	90	70			no sample	19	no sample
03/10/2001	D/S	14.2	93	60	3.3	1.6	no sample	18	no sample
03/10/2001	D/6	14.3	91	70			no sample	15	no sample
03/10/2001	E/S	14.3	93	60	3.1	4.4	no sample	13	no sample

Appendix 11 External Water Quality A (ctd.). EPA water quality data for Lough Key, 2002-2003

Date Sampled	Station	Temp °C	DO % Sat	Colour Hazen	Secchi m	Chlorophyl mg/m³	TP µg/l P	PO4 µg/l P	Silica mg Si/l
20/03/2002	A	6.5	90	90	1.9	2.4	25	11	0.83
20/03/2002	B	6.6	93	90	2	2.4	22	11	0.96
20/03/2002	C	6.5	91	90	2	2.8	20	<10	1.28
20/03/2002	C/18m	6.6	93	80			21	<10	1.1
20/03/2002	D	6.6	91	90	2.2	2.4	28	<10	1.32
20/03/2002	E	6.6	91	80	1.9	2.8	33	15	1.19
04/07/2002	A	15.7	92	100	2.1	1.2	41	17	1.13
04/07/2002	B	15.5	92	100	2.3	1.2	26	16	1.15
04/07/2002	B/6m	15.4	91	100			31	15	1.29
04/07/2002	C	15.5	90	100	2.2	1.6	33	17	1.39
04/07/2002	C/20m	15.5	91	100			182	17	1.19
04/07/2002	D	15.5	93	100	2.6	1.2	33	17	1.1
04/07/2002	D/6m	15.3	93	100			32	18	1.08
04/07/2002	E	15.7	93	100	2.1	3.2	38	16	1.15
26/03/2003	A/S	9.4	98	90	1.9	3.2	27	24	0.905
26/03/2003	A/6m	9.1	97	90		xx	31	26	0.96
26/03/2003	B/S	9.6	100	90	2.4	4	25	23	1.066
26/03/2003	B/6m	9.1	98	90		xx	25	43	1.046
26/03/2003	C/S	9.2	99	90	2	3.2	28	23	0.94
26/03/2003	C/18m	7.8	93	90		xx	31	25	1.057
26/03/2003	D/S	9.1	98	90	2.2	3.6	25	24	1.027
26/03/2003	D/6m	8.4	95	90		xx	27	25	1.072
26/03/2003	E/S	9.2	100	90	2.1	2.4	25	24	1.028
24/07/2003	A/S	18.2	96	50	3.1	5.2	25	5	0.251
24/07/2003	B/S	18.4	97	50	2.8	7.3	26	<5	0.249
24/07/2003	B/6	18.3	98	50			44	<5	0.239
24/07/2003	C/S	18.4	95	50	3	8.1	26	6	0.223
24/07/2003	C/21 m	18.3	94	50			24	6	0.23
24/07/2003	D/S	18.5	96	50	3.5	8.1	26	<5	0.234
24/07/2003	D/5 m	18.3	98	50			25	<5	0.233
24/07/2003	E/S	18.5	94.7	50	3	10.9	28	<5	0.237
11/09/2003	A/S	16.7	91	50	2.9	4.03	18	<5	1.022
11/09/2003	B/S	16.7	94	50	3.2	4.43	24	<5	1.012
11/09/2003	B/6M	16.7	94	50			26	<5	1.001
11/09/2003	C/S	16.7	92	50	3.2	4.03	14	<5	1.006
11/09/2003	C/18M	16.6	93	50			16	<5	0.99
11/09/2003	D/S	16.8	93	50	3.2	5.6	61	<5	1.019
11/09/2003	D/6M	16.8	94	50			34	<5	1.028
11/09/2003	E/S	16.9	94	50	3	6.45	17	<5	1.018
11/09/2003	E/6M	17	95	50			37	<5	1.015
07/10/2003	A/S	13.3	94	50	3.5	4	26	10	1.1
07/10/2003	B/S	13.2	94	40	3.3	3.6	23	9	1.1
07/10/2003	B/6M	13.3	95	40			37	11	1.1
07/10/2003	C/S	13.2	96	50	2.5	3.6	25	11	1.1
07/10/2003	C/18M	13.2	96	40			20	10	1.1
07/10/2003	D/S	13	95.5	50		3.6	26	10	1.2
07/10/2003	E/S	13.1	93	40	3.3	39.1	24	10	1.1
07/10/2003	E/6M	13.1	94	40			23	9	1.1

Appendix 11 External Water quality B. Boyle River (Br. Boyle Abbey) upstream Boyle sewage treatment plant and Boyle River (Drum Bridge) downstream Boyle sewage treatment plant (unpublished Lough Ree/ Lough Derg project data, 2001-2003)

	Upstream			**Downstream**		
SampleDate	**Temp °C**	**PO4 mg/L**	**TP mg/l P**	**Temp °C**	**PO4 mg/L**	**TP mg/l P**
21/02/2001	6	0.017	0.04	6	0.017	0.042
25/04/2001	10.6	0.001	0.031	10.3	0.004	0.034
12/06/2001	15	0.003	0.02	14.4	0.005	0.024
19/07/2001	16.1	0.003	0.03	16.3	0.005	0.031
30/08/2001	no data	0.011	0.022	no data	0.013	0.032
27/09/2001	no data	0.008	0.031	no data	0.024	0.057
18/10/2001	no data	0.017	0.04	no data	0.022	0.045
15/11/2001	no data	0.019	0.035	no data	0.02	0.089
17/01/2002	6	0.02	0.044	6	0.02	0.045
28/02/2002	4.8	0.016	0.04	4.9	0.017	0.038
07/03/2002	6.8	0.013	0.034	6.8	0.014	0.034
11/04/2002	10.3	0.005	0.024	10.2	0.007	0.031
23/05/2002	13	0.008	0.03	13	0.01	0.041
20/06/2002	15.3	0.014	0.034	15.3	0.014	0.03
10/07/2002	16	0.014	0.043	15.8	0.015	0.039
15/08/2002	16.8	0.011	0.027	16.3	0.013	0.03
12/09/2002	15.8	0.004	0.039	15.2	0.017	0.045
09/10/2002	12.8	0.01	0.031	12.6	0.027	0.062
21/11/2002	7.2	0.026	0.057	7.3	0.026	0.058
18/12/2002	2.6	0.023	0.045	2.6	0.023	0.043
21/01/2003	5.2	0.023	0.045	5.2	0.025	0.050
18/02/2003	3.3	0.016	0.028	3.4	0.017	0.041
26/03/2003	9.2	0.011	0.031	9.3	0.014	0.030
15/05/2003	11.5	0.004	0.017	11.4	0.018	0.034
12/06/2003	14.5	0.009	0.023	14.5	0.009	0.033
10/07/2003	18.3	0.008	0.036	16.7	0.016	0.027
14/08/2003	18.8	0.001	0.017	18.0	0.013	0.028
24/09/2003	12.5	0.013	0.016	11.7	0.003	0.027
16/10/2003	10.6	0.001	0.029	10.1	0.002	0.018

(shaded) Indicates commencement of 2002 sampling and Phosphorus removal

Appendix 11 (ctd) External water quality B. Flow and total phosphorus data for Boyle sewage treatment plant, 2001-2003

2001 Flow and Total P data

Date	Flow/m^3	Total P mg/L	TP load g
9-Jan-01	3645	0.13	473.85
16-Jan-01	2408	0.23	553.84
23-Jan-01	3776	25.76	97269.76
13-Feb-01	2942	0.245	720.79
2-Mar-01	2475	0.28	693
22-Mar-01	2113	0.766	1618.558
4-Apr-01	2899	0.41	1188.59
23-May-01	1777	0.321	570.417
5-Jun-01	1883	3.555	6694.065
19-Jun-01	2349	1.116	2621.484
4-Jul-01	2215	1.246	2759.89
14-Aug-01	2561	0.533	1365.013
10-Sep-01	1802	1.353	2438.106
23-Oct-01	805	1.47	1183.35
20-Nov-01	1289	2.444	3150.316
11-Dec-01	1698	2.332	3959.736
Mean	**2289**		**7954**
Annual Total	27468		2903

2002 Flow and Total P data

Date	Flow/m^3	Total P mg/L	TP load g
17-Jan-02	2485	0.257	638.645
19-Feb-02	3383	0.203	686.749
13-Mar-02	3130	0.139	435.07
23-Apr-02	2435	2.071	5042.885
29-May-02	3950	0.563	2223.85
19-Jun-02	3140	0.433	1359.62
19-Jul-02	1819	1.32	2401.08
1-Aug-02	1818	1.78	3236.04
17-Sep-02	1177	1.75	2059.75
16-Oct-02	2099	2.54	5331.46
25-Nov-02	2119	0.09	190.71
11-Dec-02	2128	0.41	872.48
Mean	**2474**		**2040**
Annual Total	**903010**		**744600**

2003 Flow and Total P data

Date	Flow/m^3	Total P mg/L	TP load g
22-Jan-03	2628	0.52	1366.56
24-Feb-03	2528	1.27	3210.56
12-Mar-03	3855	0.21	809.55
29-Apr-03	2737	4.465	12220.705
28-May-03	2422	0.2	484.4
25-Jun-03	1759	1.452	2554.068
22-Jul-03	1711	0.52	889.72
18-Aug-03	1772	1.55	2746.6
3-Sep-03	1329	2.09	2777.61
15-Oct-03	1877	0.35	656.95
27-Nov-03	2782	nd	nd
9-Dec-03	2196	nd	nd
Mean	**2300**		**2772**
Annual Total	**839500**		**1011780**

	2001	**2002**	**2003**
TP Load/kg/day	7.95	2.04	2.77
Weighted P kg/L	3.47*	0.825	1.22
TP/kg/ year	2902	745	1011

Calculated by dividing sum of daily loads by sum of daily flows (EPA method)

*** mean calculated without high outlier value on 23/1/01 is 0.819 mg/L**

APPENDIX 12: Photographs of Lough Key and Environs

Fig 1 Snorkel Site 2 (Drumbridge Bay), Boyle River and Boyle Town

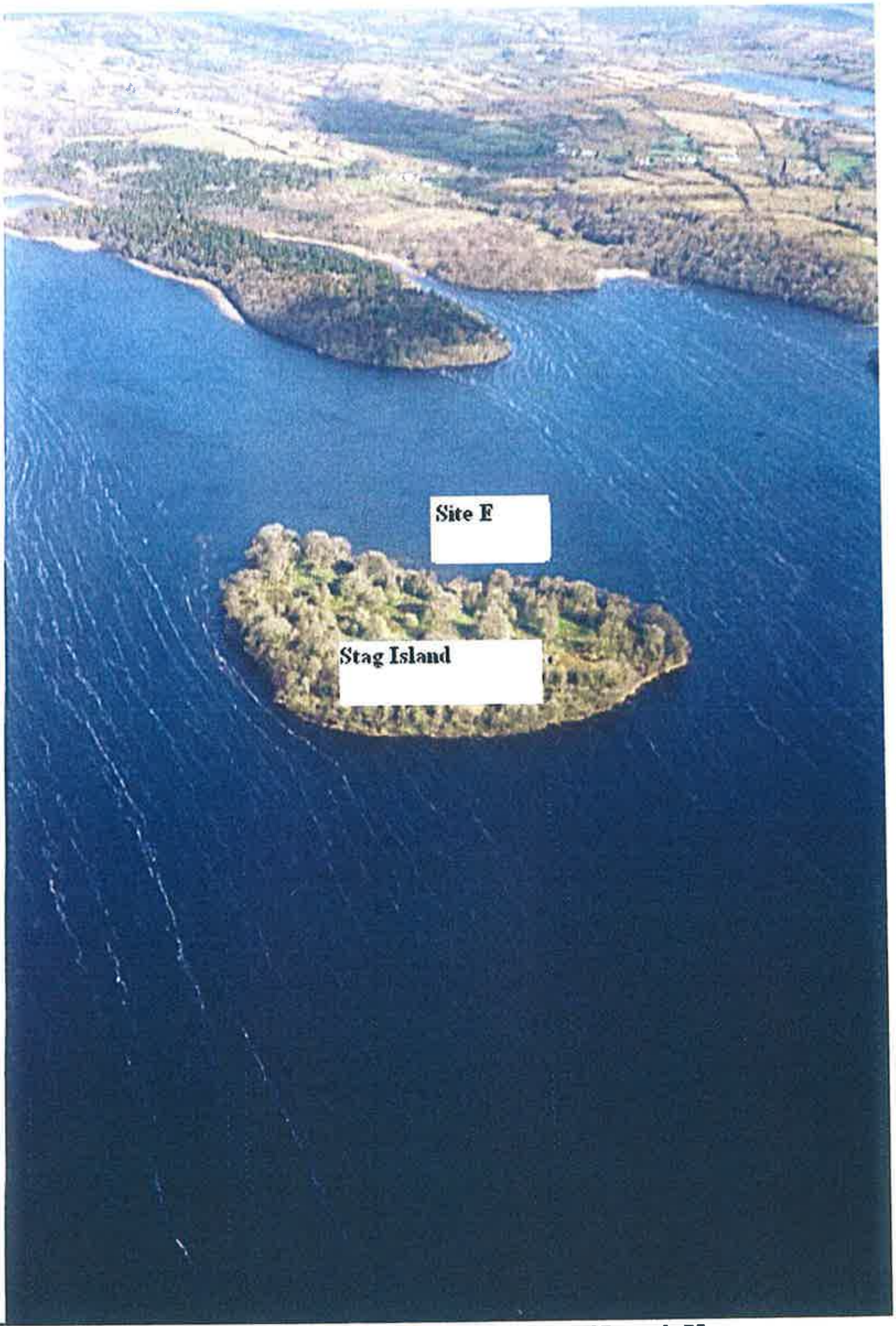


Fig 3 Monitoring Site E Stag Island, North end of Lough Key

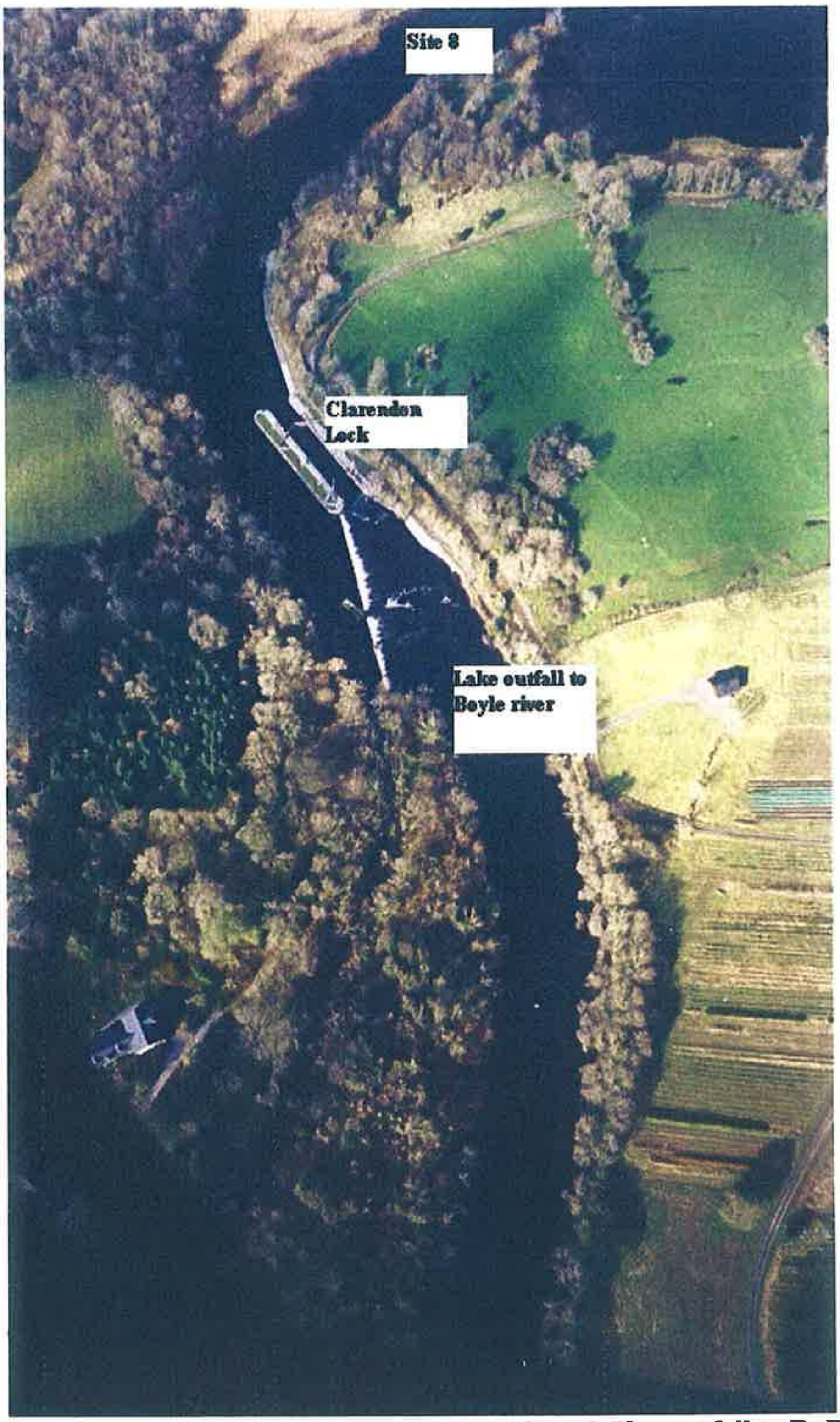


Fig 2 Snorkel Site 8, Clarendon Lock and Lough Key outfall to R. Boyle