Management of Biological Invasions (2014) Volume 5, Issue 1: 63–72
doi: http://dx.doi.org/10.3391/mbi.2014.5.1.06

Research Article

A rapid assessment method for an invasive mollusc in an Irish lake

Dan Minchin[1,2]* and Bernadette White[3]

[1]*Marine Organism Investigations, Marina Village, Ballina, Killaloe, Co Clare, Ireland*
[2]*Coastal Research and Planning Institute, Klaipeda University, H Manto 84, LT92294, Lithuania*
[3]*RPS Group, Lyrr Building, IDA Business and Technology Park, Mervue, Galway, Ireland*

E-mail: moiireland@yahoo.ie (DM), bernadette.white@rpsgroup.com (BW)

**Corresponding author*

Received: 4 December 2013 / Accepted: 10 March 2014 / Published online: 15 March 2014

Handling editor: Justin McDonald

Abstract

A rapid assessment method to evaluate the relative impact of zebra mussel, *Dreissena polymorpha*, was undertaken in a 11.5 km^2 temperate lake within an Irish drumlin landscape. The lake was divided into three assessment units: the north lake, the south lake and a river section situated downstream of the two lake assessment units. Survey work was conducted as a single survey in September 2011. Following an evaluation of the mussel abundance and distribution range within each assessment unit, the Biological Pollution Level (BPL) was calculated. Additional environmental information was obtained from historical monitoring conducted by the Irish Environmental Protection Agency. The zebra mussel was rated as having a high abundance and distribution range in one lake assessment unit, was absent in the second lake assessment unit, and had a low abundance and distribution range for the river assessment unit. Ninety-three stations were surveyed in two and a half days illustrating a practical approach to monitoring which can meet legislative requirements.

Key words: rapid assessment, biopollution, abundance and distribution range, alien, pH, *Dreissena*

Introduction

Rapid assessment surveys (RAS) for non-indigenous species (NIS) have been undertaken in ports, covering a wide range of habitats (Hewitt et al. 2004), and in marinas by examining the floating units of boardwalks (Pedersen et al. 2005; Arenas et al. 2006). These involved an examination of a wide range of biota by several specialists. Surveys that target selected impacting NIS are more efficient and can provide useful information using less field staff. Such surveys have used marinas due to their ease of access at all tidal stages allowing for cost-effective monitoring (Ashton et al. 2006; Minchin 2007). A limitation however is that these surveys concentrate on sessile biota and their associates, but neglect infaunal species. The targeting of a single species, and examination of the habitats they are likely to occupy, is a more selective approach (Minchin 2012). This can reduce the duration of a survey for a species of particular concern making it practical for more frequent monitoring, over several years (Minchin et al. 2005; Minchin and Zaiko 2014).

The zebra mussel *Dreissena polymorpha* (Pallas) originates from the Ponto-Caspian region and can dominate many of the inland water bodies they invade (Pollux et al. 2010). The zebra mussel is an ecosystem engineer (Karatayev et al. 2002) that impacts upon river (Higgins and Vander Zanden 2010) and lake ecosystems (Stanczkowska and Lewandowski 1993; Minchin and Zaiko 2014). As an ecosystem engineer, the species directly or indirectly controls the availability of resources to other organisms. They can create new habitats from their extensive growths and shell accumulations, which in turn alters sediment texture and provides refuges for example, snails and gammarids (Stewart et al. 1998). Their filtration ability results in increased water clarity due to the removal of particles greater than 0.4 µm with consequent declines in phytoplankton chlorophyll levels (Lucy et al. 2005)

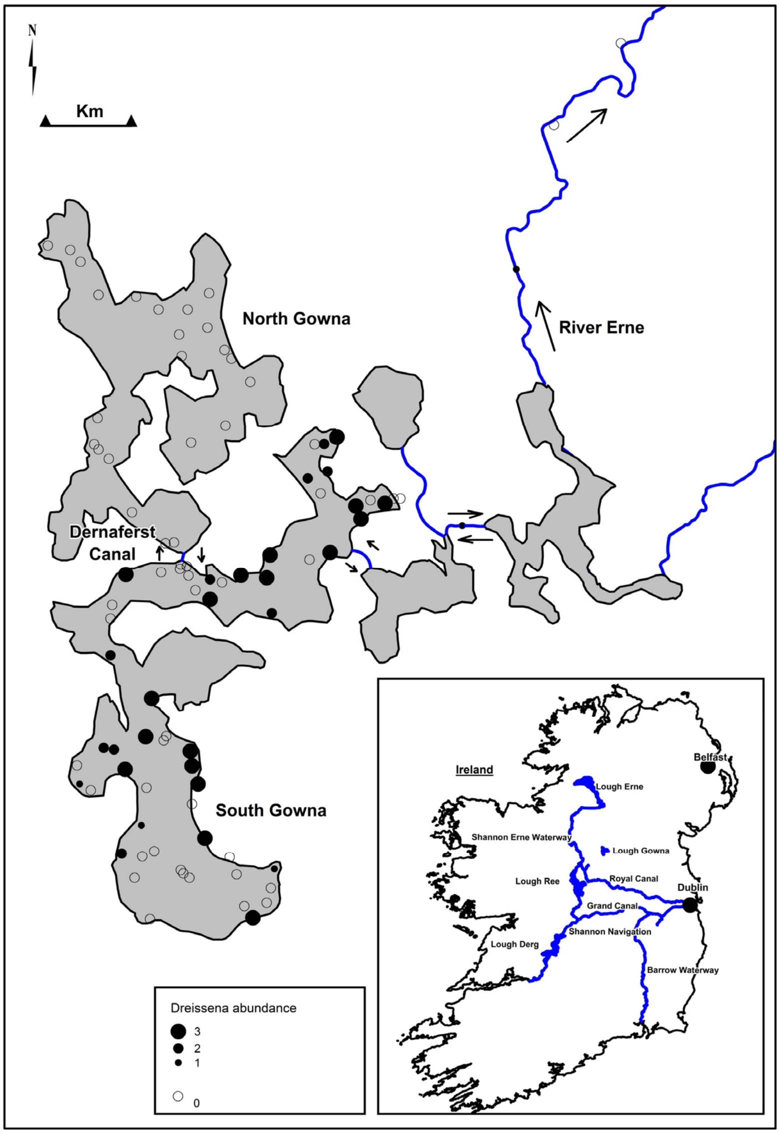

Figure 1. The inland waterways of Ireland and position of Lough Gowna. Lough Gowna and Erne River showing distribution of stations and assessment units North Gowna (NG), South Gowna (SG) and the Erne River (ER). Arrows indicate water flow directions. Mussel abundance 0 absent, 1 low, 2 moderate and 3 abundant.

and small zooplankton (Reeders et al. 1993), which are either consumed or bound in mucus parcels and discharged to accumulate within the benthos. These wastes enrich sediments and provide energy for benthic deposit feeders (Karatayev et al. 2007). The resulting increased water clarity enables rooting macrophytes to extend to deeper water (Sullivan et al. 2010). The accumulations on exposed living unionid shell often leads to extirpation of local populations (Ricciardi et al. 1998; Schloesser et al. 1996; Strayer and Malcom 2007). These features result in significant changes to ecosystem functioning (Stanczkowska and Lewandowski 1993) by altering biodiversity (Minchin et al. 2002), as well as having economic impacts on ecosystem services (Karatayev 2007) and water quality status (Atalah et al. 2010).

The zebra mussel was recorded in Ireland for the first time in 1997 (McCarthy et al. 1998). It is suggested that it originally arrived in 1993-1994 into the lower River Shannon catchment most probably via imports of used leisure craft from Britain (Pollux et al. 2003) (Figure 1). Conditions in Ireland are suitable for the expansion of zebra mussel and it continues to spread (Millane et al. 2008). The spread of high impacting aquatic NIS is of concern in relation to biodiversity and water quality management.

Table 1. ADR classes of abundance and distribution according to Olenin (2007).

	DISTRIBUTION SCALE			
ABUNDANCE	One locality	Several localities	Many localities	All localities
Low	A	A	B	C
Medium	B	B	C	D
High	B	C	D	E

In order to evaluate the status of a NIS, a simple meaningful and practical approach is required to monitor change in the environment. In this account we examine a lake colonised by zebra mussel using the Abundance and Distribution Range (ADR), estimate an impact level using the Biopollution Level (BPL) method of Olenin et al. (2007) and evaluate it usefulness for adoption to satisfy broader national monitoring requirements for Directives such as the Water Framework Directive (WFD) (2000/60/EC), Marine Strategy Framework Directive (MSFD) (2008/56/EC) or to fulfil protection of natural biodiversity as required under the Habitats Directive (92/43/EEC), or the Convention on Biological Diversity (2006).

Methods

Lough Gowna lies within a drumlin belt in the northern midlands of Ireland (53º50'N, 07º33'W) and has a surface area of 11.5km^2. The lake consists of two lakes, separated by a short ~150m canal (Dernaferst canal) between North Gowna (NG) and South Gowna (SG), with water flowing freely in both directions between the lake sections as influenced by lake water levels (Figure 1). The Erne River (ER) flows to and from the lake depending on rainfall events, causing variable lake levels. Both lake assessment units and an assessment unit constituting a section of the ER downstream of Lough Gowna were included in the study site i.e. three assessment units. Twenty-eight sites in NG, fifty-seven in SG, and eight sites on the ER were surveyed. Sites examined included shallow and deep water areas, stream deltas, macrophytes and littoral regions including areas of human interference, such as slipways, quays and angling stands. The lake is economically important for the angling of cyprinid species and municipal water is abstracted from NG.

Sampling was based on direct observations, use of a Van-Veen grab together with a basket dredge to make collections at depths to over 5m. In shallows, hand collections and tongs were used to remove fouled stones. Retrieved mussels were measured for shell length. A secchi disc was used to measure water transparency. Historical data, for chlorophyll-*a* (the extraction methodology of chlorophyll-*a* and other related pigments was in hot methanol and the absorbance of the solution was read at 665 and 750nm on a UV Spectrophotometer), alkalinity (end point titration (to pH 4.5) with sulphuric acid) and water transparency (measured using a secchi disc), were provided by the Irish Environmental Protection Agency (EPA).

The biopollution assessment method (Olenin et al. 2007) has been used to evaluate the relative impact of a single species over a wide area (Olenina et al. 2010) or of many impacting species (Zaiko et al. 2011). The biopollution method first requires an assessment of the ADR for each assessment unit. The assessment is based on the abundance and frequency of zebra mussel at all stations examined.

Abundance is classed as *'low'* when it makes up only a small part of a community; *'moderate'* when it is frequent but less than half of the abundance of the native community, and *'high'* should it exceed half of the overall abundance and dominates.

The distribution of zebra mussel is classed as follows: *'local'*, where it occurs at one station; '*several localities'* where it is present in less than half of the stations; '*many localities'* where it is found in more than half of the available localities, and '*all localities'* where it occurs at all stations.

Combinations of abundance and distribution produce a scale that ranges from: *'A'* - few individuals at one locality to *'E'* - where a species occurs in high numbers in all localities (Table 1). The ADR must be determined before a BPL assessment can be made. The level of impact on the community (C), habitat (H), and ecosystem function (E) are evaluated separately and are each made up of five levels ranging from 0 to 4, accordingly: 0 = no impact; 1 = weak impact; 2 =

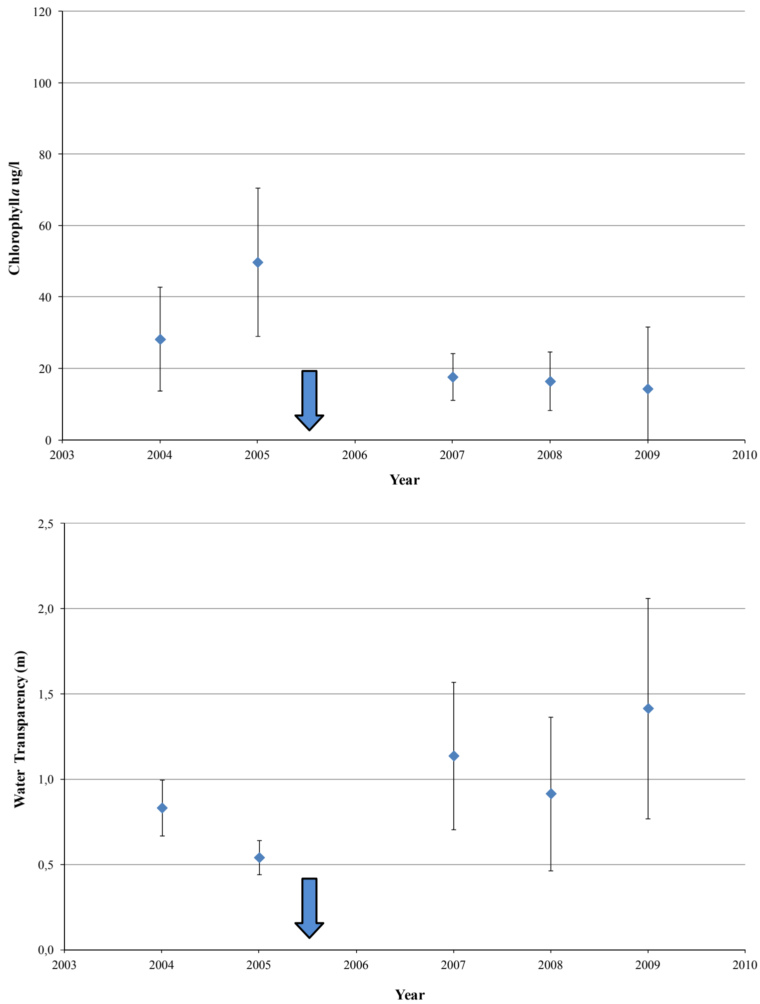

Figure 2. Above: Chlorophyll levels in South Gowna. Arrow indicates probable period of mussel arrival. Below: Variability of mean water transparency (m) in South Gowna. Arrow indicates probable period of mussel arrival. Standard deviations shown.

moderate impact; 3 = strong impact, and 4 = massive impact. The greatest level for either C, H, or E is used to evaluate the impact state within each assessment unit. Here we limit the BPL assessment to habitat impact based on the alteration, where noted, and reduction in the spatial extent of the original habitat. Determining the impacts on community structure (C) and ecosystem function (E) required additional historical information which could not be obtained for the study site. Levels of biopollution were determined using the online service Biological Invasion Impact/Biopollution Assessment System (BINPAS) available at http://corpi.ku.lt/databases/binpas/ and described by Narščius et al. (2012). The method has been sufficiently robust to quantify impacts in a standard and repeatable way where there is adequate information.

Results

Zebra mussels were abundant in SG, none were found in NG and in the ER mussels were found only within 4km downstream of the lake. Boulders, cobbles, stones and gravel were frequent in the littoral zone throughout both lake assessment units except where there were stream deltas. Water transparency in NG was 0.8m and in SG ranged from 2.7 to 2.9 (based on three measurements in each lake section). At the time of the survey the pH levels from NG and SG ranged from 8.0 to 8.2 (based on two measurements in NG and three measurements in SG).

In the mussel infested lake SG chlorophyll-*a* levels declined from 28.22 µg/l in 2004 to 14.33 µg/l in 2009 and water transparency increased from 0.83m in 2004 to 1.42m in 2009 (Figure 2).

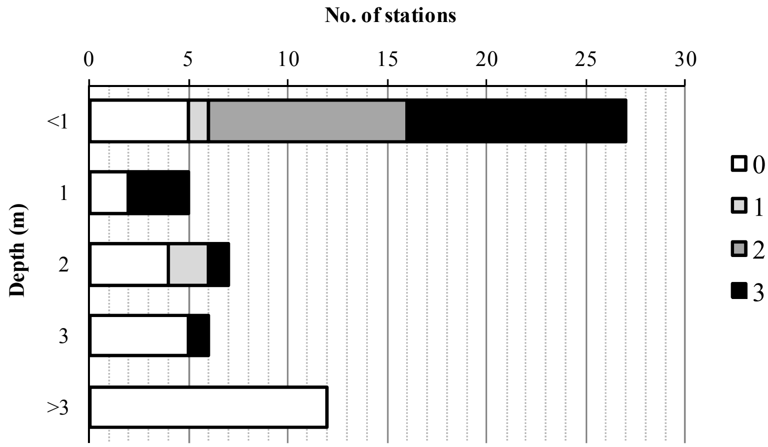

Figure 3. Depth distribution of *D. polymorpha* in the lower assessment unit of southern Lough Gowna according to depth. Series 0 = none found; Series 1 = low abundance; Series 2 = moderate abundance (<50% cover); Series 3 = abundant (>50% cover).

In NG the zebra mussel was absent, no shell material was found, despite the wide range of similar habitats to SG that were sampled, including littoral gravels to boulders and deeper water muds. Here, since the zebra mussel was absent, the ADR and BPL have no value.

In SG the zebra mussel attached to gravels and boulders about the lake perimeter at depths of -0.3m to -2.5m forming the key habitat zone where mussels were likely to exist. Individuals were most abundant within <-1m (Figure 3). Less frequently clusters of the mussel found attached to shell, were obtained at depths to -3m. None were found at greater depths characterised by mud substrate. The zebra mussel was clearly visible in the shallows and consisted of chalky white shells (Figure 4). The mussel valves were weak and some were perforated showing underlying tissues. Drifts of shells were cast on the shore and had accumulated in the shallows. In stream delta areas, few mussels were found. No living specimens were found in the canal between the two lake assessment units, although the canal delta fan area in SG had many strewn mussel shells.

The zebra mussel was abundant at more than half of the stations in SG therefore an ADR of 'D' was calculated (Table 1). Their occurrence provided a refuge for amphipods *Gammarus duebeni* Lilljeborg, 1852, the non-indigenous *G. tigrinus* Sexton, 1939 and *Chelicorophium curvispinum* (G.O. Sars, 1805) within interstitial spaces together with the gastropod *Potamopyrgus antipodarum* (J.E. Gray, 1853). The zebra mussel had overgrown

Figure 4. Some of the chalky shelled zebra mussels appeared to have four rings.

the shells of the few living *Anodonta anatina* (Linnaeus, 1758) recovered from a muddy region of SG, obtained together with many vacant unionid shells. The presence of the zebra mussel had a strong impact with resultant modification of the habitat and therefore is classified as having a BPL=3.

The majority of mussels in SG were adult specimens, suggesting a low recruitment having occurred during 2010 and 2011. The smallest individuals were found at the southernmost end of SG, and some of these were attached to aquatic macrophytes, near to a stream with a limestone catchment. Size distributions indicate a single peak for the shell length frequency distribution

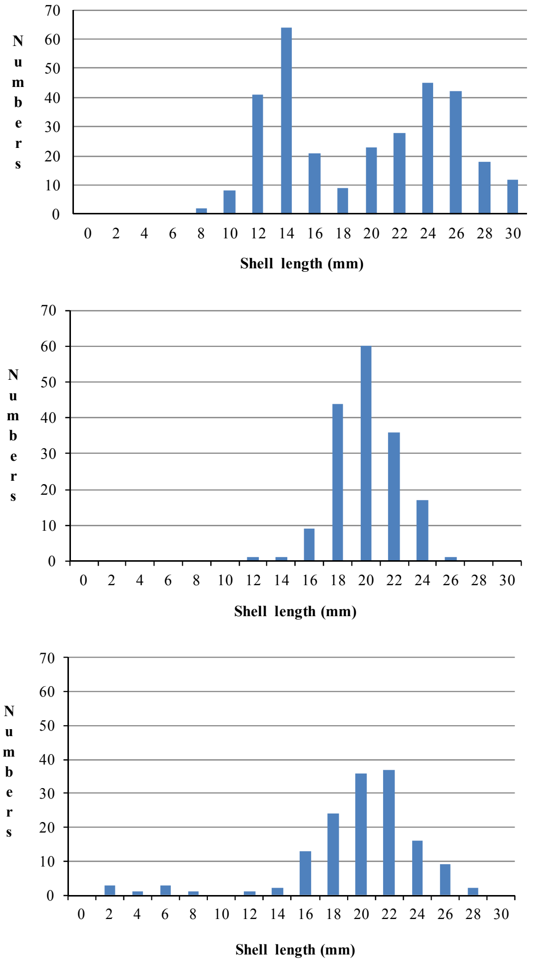

Figure 5. Shell length (mm) frequency distributions of mussels from South Lough Gowna. Near lake exit (above), 0.5km west of canal (middle) and most southern shore (bottom).

for mussels collected at the southern end and western side of SG and there were two modes near the lake outlet (Figure 5).

In the ER assessment unit, the zebra mussel was found in low numbers to a distance of 4km from the lake, at sites near a bridge. No individuals were found further than 4km downstream. The ADR for this region was judged to be ‘A’ and impacts on the community or habitats were considered as being weak and so could not have a value exceeding a BPL= 1.

In this study according to the BINPAS requirements the level of confidence in our survey was high for both lake assessment units due to direct observation and the large number of stations. There were difficulties sampling the ER section because access was impracticable in many places and as a result the assessment has a low confidence level associated with it.

Discussion

The ADR provides a classification for a NIS at a certain point in time that is independent of previous surveys and so aids monitoring according to several legislative requirements, as in the case of monitoring under the WFD for freshwater, transitional or coastal water bodies, and could also be adopted for the MSFD for marine environments to satisfy requirements under Descriptor 2 Non-indigenous species. The ADR, although required as part of the BPL method, provides a scale which does not rely on historical information in order to make an assessment. In this study, we were able to contrast the state of two assessments units within a lake and a river assessment unit.

In this study we noted extensive encrustations on stones to boulders in SG and shells strewn over the shallow littoral region. Such habitat conditions were not noted in a previous visit in 2003 to the southern part of SG. These same incrustations support a community within the interstitial spaces that include gastropods and gammarids and it is likely that the presence of the zebra mussel will have also modified this benthic community including impacts upon unionids. Ecosystem changes are more difficult to evaluate, nevertheless there were declines in chlorophyll-*a* values and increases in water clarity consistent with the changes noted following the arrival of the mussel in water bodies elsewhere (Karatayev et al. 2002; Higgins and Vander Zanden 2010; Pothoven and Fahnenstiel 2014 and references therein). These increases in water clarity might have enabled the observed increase in aquatic rooting plants, such as the dense stands of the Canadian pondweed *Elodea canadensis* (Michx.) which had extended its range to deeper water in SG thereby providing additional settlement surfaces for pediveliger attachment (Sullivan et al. 2010). This pondweed was sparsely distributed in NG and was present only in shallower water.

Environmental conditions throughout Lough Gowna would appear to fall within the tolerance range of the mussel, according to the Hinks and Mackie (1997) model, with alkalinity levels ranging from 34–184 mg/l $CaCO_3$. Conditions are suitable for larvae once calcium levels exceed 22 mg/l (Cohen and Weinstein 2001). Temperatures within Irish lakes range from 3° to 21°C, with extremes of <1°C to 28°C (Lough Derg Science Group data), all within the acceptable range for survival of the zebra mussel (Spidle et al. 1995; Zaiko et al. 2009).

Measures of pH (8.0–8.2) at the time of the survey, from both lake sections, were within the tolerance range of the mussel. Records obtained from the EPA long term series indicated suitability during most of their annual assessments (7.4-8.4). Shells of mussels in SG had features that could be ascribed as being due to low levels of pH, as eroded and chalky-white weakened shells were common, with some perforated, and evidence of poor recruitment in 2010 and 2011 might be due to the greater susceptibility of larvae to low pH levels. Indeed, according to EPA data, an event would appear to have taken place on 7 December 2009 when pH levels within a few kilometres of either side of the canal had reduced to 6.8. Thus, it is possible there might have been periodic acidic flushes, outside of most of the monitoring dates that might explain the distribution and condition of mussels. The sustainability of the population might be compromised by such events in the future. The appearance of four rings on some shells found in this study and changes in Chlorophyll-*a* and increased water clarity would indicate an arrival before 2008 and after August 2003 when plankton samples from the southern part of SG were devoid of veligers (Minchin and Lucy 2003), a time when larvae would be expected to occur (Lucy 2006).

Recent studies undertaken by Claudi et al. (2012) show similar chalky characteristics for mussel shells, subjected to pH in the range of 7.3 to 7.1 in the laboratory. While Mikheev (1994) found settled mussels at a pH of 6.6, other authors agreed pH levels of 7.3 to 7.4 formed the minimum tolerance level based on a study of several lakes. According to Ramcharan et al. (1992), where pH levels were <7.3 in lakes, mussels did not survive and zebra mussels in two lakes he studied, with a pH of 7.3, died within thirty-five days. According to Hinks and Mackie (1997) pH levels >8.3 were best suited for juvenile and adult growth and Cohen and Weinstein (2001) considered lakes with a pH of 7.5 to 8.7 had a high colonisation potential. Mackie and Kilgour (1995) determined the lower threshold limit for the survival of veligers at 7.4 to 7.5.

Unfavourable conditions must persist in NG as it would have been expected that larvae, or their settled stages attached to plant debris would have been carried through the interconnecting canal following rainfall events with water flows from SG. Their spread may also have been expected with the frequent lake-boat traffic passing through the canal and with launches of overland craft coming from infested lakes elsewhere. There were adequate surfaces similar to the littoral zone in SG and macrophytes for mussels to attach to in NG; so substrate availability was not a limiting factor.

The BPL impact in SG is similar to lakes studies in other countries (Higgins et al. 2008) and in other parts of Ireland (Millane et al. 2008) where levels of 3 to 4 have been recorded for alkaline lakes (Minchin and Zaiko 2014). For example, Lough Allen, an oligotrophic lake on the River Shannon navigation in Ireland, has low calcium levels and a pH that lies outside of the normal physiological threshold of the mussel (Bowman 2000; Timpson and Lucy 1998). The acidity of the lake water is due to runoff from sandstones, grits and acid soils and so pH values in this lake have ranged from 6.2 to 7.5 (Bowman 2000). Water flowing downstream can become buffered by limestone, as has happened further downstream in the River Shannon. Such a pattern might explain the presence of mussels in SG and the ER due to the runoff from streams flowing over limestone. However, downstream survival of mussels can vary according to the size and depth of the river and levels of turbulence that result in higher mussel densities close to lake discharges (Lucy et al. 2008). Horvath and Crane (2010) found a lower survival of zebra mussel larvae when subjected to increased shear forces under laboratory conditions. The ER has shallow water sections where there is turbulence that could account for progressive mortality downstream and result in a decline of settled stages, a pattern that has been reported elsewhere (Hovarth et al. 1996; Hovath and Lamberti 1999; Lucy et al. 2008).

Conditions do not always seem suitable for recruitment in Lough Gowna, and survey results showed few settled individuals from the 2010 and 2011 year class. Large mussels have distinctive shell surface rings (Figure 4) which probably represent interruptions in growth in separate years. The small numbers of surviving unionids and large numbers of their fouled shells would indicate a comparatively recent arrival of the zebra mussel. The appearance of four rings on some shells found in this study together with the environmental data (Figure 2) would indicate an arrival before 2008 and after 2003, possibly during 2005 or 2006. In Lough Derg on the River Shannon system, some unionids survived up to ~5 years following introduction of the mussel, but none are known to have survived longer than 5 years (Minchin et al. 2005). Such a decline of unionids is consistent with the density of attaching zebra mussels found in Lough Gowna (Lucy et al. 2014).

Invasive species normally occur in abundance, and simple assessments of ADR as used in this study, can enable the determination of relative changes over time. Such studies can take place over a short sampling period, and where there is sufficient historical information, a BPL value can be obtained. In this case, the absence of zebra mussels from the north lake assessment unit, from which surface water is abstracted, presently does not require direct intervention at the municipal plant, but further monitoring of NG is advised.

Conclusions

The rapid assessment method using the ADR of the zebra mussel in two lake and a river assessment units was swiftly achieved. There was an absence of the mussel in NG whereas it was abundant and widely distributed at most stations in SG. A spatial and vertical distribution of mussel abundance was obtained in SG. In the river section, there was low mussel abundance and none were found beyond 4km downstream from the lake. The variable recruitment and poor condition of adult mussel shells in SG, which had weak and thin shells, with many having exposed tissues from eroded shell perforations, live on a precarious balance between suitable water quality conditions and those that might result in the population demise. Despite the precarious nature of the existence of this population, it is present in sufficient abundance to have altered the littoral zone by encrusting boulders and stones thereby altering habitat.

Acknowledgements

We are grateful for the helpful comments provided by three anonymous reviewers. We thank the Longford Local Authorities and Cavan County Council, working in partnership with the Heritage Council, and the project steering group for support to enable this work to have been undertaken. We thank the Office of Environmental Assessment of the Environmental Protection Agency for access to monitoring data obtained for Lough Gowna.

References

Arenas F, Bishop JDD, Carlton JT, Dyrynda PJ, Farnham WF, Gonzalez DJ, Jacobs MW, Lambert C, Lambert G, Nielsen SE, Pederson Porter JS, Ward S, Wood CA (2006) Alien species and other notable records from a rapid assessment survey of marinas on the south coast of England. *Journal of the Marine Biological Association of the United Kingdom* 86: 1329–1337, http://dx.doi.org/10.1017/S0025315406014354

Ashton G, Boos K, Shucksmith R, Cook E (2006) Rapid assessment of the distribution of marine non-native species in marinas in Scotland. *Aquatic Invasions* 1: 209–213, http://dx.doi.org/10.3391/ai.2006.1.4.3

Atalah J, Kelly-Quinn M, Irvine K, Crowe TP (2010) Impacts of invasion by *Dreissena polymorpha* (Pallas, 1771) on the performance of macroinvertebrate assessment tools for eutrophication pressure in lakes. *Hydrobiologia* 654: 237–251, http://dx.doi.org/10.1007/s10750-010-0391-8

Bowman J (2000) River Shannon, lake water quality monitoring 1998 to 1999. Environmental Protection Agency, Johnstown Castle Estate, Co Wexford, Ireland, 78 pp

Convention on Biological Diversity (2006) Secretariat of the Convention on Biological Diversity: *Global Biodiversity Outlook* 2. Montreal, 81 pp

Claudi R, Graves A, Taraborelli AC, Prescott RJ, Mastitsky SE (2012) Impact of pH on survival and settlement of dreissenid mussels. *Aquatic Invasions* 7: 21–28, http://dx.doi.org/10.3391/ai.2012.7.1.003

Cohen AN, Weinstein A (2001) Zebra mussel's calcium threshold and implications for its potential distribution in North America. San Francisco Estuary Institute, Richmond, California, 47 pp

EC (2000) Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for community action in the field of water policy. of the European Parliament and of the Council 23 October 2000

EC (2008) Directive 2008/56/EC on establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) of of the European Parliament and of the Council 17 June 2008

Hewitt C, Campbell ML, Thresher RE, Martin RB, Boyd S, Cohen BF, Currie DR, Gomon MF, Keogh MJ, Lewis JA, Lockett MM, Mays N, McArthur MA, O'Hara TD, Poore GCB, Ross DJ, Storey MJ, Watson JE Wilson RS (2004) Introduced and Cryptogenic Species in Port Phillip Bay, Victoria. Australia. *Marine Biology* 144: 183–202, http://dx.doi.org/10.1007/s00227-003-1173-x

Higgins TA, Grennan JM, McCarthy TK (2008) Effects of recent zebra mussel invasion on water chemistry and phytoplankton production in a small Irish lake. *Aquatic Invasions* 3: 14–20, http://dx.doi.org/10.3391/ai.2008.3.1.4

Higgins SN, Vander Zanden MJ (2010) What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. *Ecological Monographs* 80: 179–196, http://dx.doi.org/10.1890/09-1249.1

Hinks SS, Mackie GL (1997) Effects of pH, calcium, alkalinity, hardness and chlorophyll on the survival, growth and reproductive success of the zebra mussel (*Dreissena polymorpha*) in Ontario lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 2049–2057, http://dx.doi.org/10.1139/f97-114

Horvath TG, Lamberti GA (1999) Mortality of zebra mussel, *Dreissena polymorpha*, veligers during downstream transport. *Journal of Freshwater Biology* 42: 69–76, http://dx.doi.org/10.1046/j.1365-2427.1999.00462.x

Hovarth TG, Lamberti GA, Lodge DM, Perry WP (1996) Zebra mussel dispersal in lake-stream systems: source-sink dynamics? *Journal of the North American Benthologists Society* 11: 341–349

Horvath TG, Crane L (2010) Hydrodynamic forces affect larval zebra mussel (*Dreissena polymorpha*) mortality in a laboratory setting. *Aquatic Invasions* 5: 379–385, http://dx.doi.org/10.3391/ai.2010.5.4.07

Karatayev AY, Burlakova LE, Padilla D (2002) Impacts of zebra mussels on aquatic communities and their role as ecosystem engineers. In: Leppäkoski E, Gollasch S, Olenin S (eds), Invasive Aquatic Species of Europe: Distribution, Impacts and Spread. Kluwer Press, Dordrecht, pp 433–466, http://dx.doi.org/10.1007/978-94-015-9956-6_43

Karatayev AY, Padilla DK, Minchin D, Boltovskoy D, Burlakova LE (2007) Changes in global economies and trade: the potential spread of exotic freshwater bivalves. *Biological Invasions* 9: 161–180, http://dx.doi.org/10.1007/s10530-006-9013-9

Lucy FE (2006) Early life stages of *Dreissena polymorpha* (zebra mussel): the importance of long-term datasets in invasion ecology. *Aquatic Invasions* 1: 171–182, http://dx.doi.org/10.3391/ai.2006.1.3.12

Lucy FE, Burlakova LE, Karatayev AY, Mastitsky SE, Zanatta DT (2014) Zebra mussel impacts on unionids: a synthesis of trends in North America and Europe. In: Nalepa T, Schloesser D (eds), Quagga and zebra mussels. Taylor and Francis Group llc, Baton Rouge, pp 623–646

Lucy FE, Minchin D, Boelens R (2008) From lakes to rivers: downstream larval distribution of *Dreissena polymorpha* in Irish river basins. *Aquatic Invasions* 3: 297–304, http://dx.doi.org/10.3391/ai.2008.3.3.4

Lucy F, Sullivan M, Minchin D (2005) Nutrient levels and the zebra mussel population in Lough Key (2000-MS-5-M1). Synthesis Report. Environmental Protection Agency, Wexford, 160 pp

Mackie GL, Kilgour BW (1995) Efficacy of the role of alum in removal of zebra mussel veliger larvae from raw water supplies. *Water Research* 29: 731–744, http://dx.doi.org/10.1016/0043-1354(94)00154-Y

McCarthy TK, Fitzgerald J, O'Connor W (1998) The occurrence of the zebra mussel *Dreissena polymorpha* (Pallas, 1771), an introduced biofouling freshwater bivalve in Ireland. *Irish Naturalists' Journal* 25: 413–415

Mikheev VP (1994) Selectivity of zebra mussel feeding. In: Starobogatov JI (ed), Freshwater zebra mussel *Dreissena polymorpha* (Pall.) (Bivalvia, Dreissenidae): systematics, ecology, practical meaning. Nauka, Moscow, pp 126–129

Millane M, Kelly-Quinn M, Champ T (2008) Impact of the zebra mussel invasion on the ecological integrity of Lough Sheelan, Ireland: distribution, population characteristics and water quality. *Aquatic Invasions* 3: 271–281, http://dx.doi.org/10.3391/ai.2008.3.3.2

Minchin D (2007) Rapid coastal survey for targeted alien species associated with floating pontoons in Ireland. *Aquatic Invasions* 2: 63–70, http://dx.doi.org/10.3391/ai.2007.2.1.8

Minchin D (2012) Rapid assessment of the bryozoan, *Zoobotryon verticillatum* (Delle Chiaje, 1822) in marinas, Canary Islands. *Marine Pollution Bulletin* 64(10): 2146–2150, http://dx.doi.org/10.1016/j.marpolbul.2012.07.041

Minchin D, Lucy LE (2003) Monitoring of zebra mussels in the Shannon-Boyle navigation and their expansion to midland lakes, July-August 2003. Unpublished Report to the Marine Institute, Ireland, 30 September 2003, 42 pp

Minchin D, Lucy F, Sullivan M (2002) Zebra mussel: Impacts and Spread. In: Leppäkoski E, Gollasch S, Olenin S (eds), Invasive Aquatic Species of Europe: Distribution, Impacts and Spread. Kluwer Press, Dordrecht, pp 135–146, http://dx.doi.org/10.1007/978-94-015-9956-6_15

Minchin D, Lucy F, Sullivan M (2005) Ireland: a new frontier for the zebra mussel *Dreissena polymorpha. Oceanological and Hydrobiological Studies* 34: 19–30

Minchin D, Zaiko A (2014) Variability of zebra mussel (*Dreissena polymorpha*) impacts in the Shannon River system, Ireland. In: Nalepa T, Schloesser D (eds), Quagga and zebra mussels. Taylor and Francis Group llc, Baton Rouge, pp 587–597

Narščius A, Olenin S, Zaiko A, Minchin D (2012) Biological invasion impact assessment system: from idea to implementation. *Ecological Informatics* 7: 46–51, http://dx.doi.org/10.1016/j.ecoinf.2011.11.003

Olenin S, Minchin D, Daunys D (2007) Assessment of biopollution in aquatic ecosystems. *Marine Pollution Bulletin* 55: 379–394, http://dx.doi.org/10.1016/j.marpolbul.2007.01.010

Olenina I, Wasmund N, Hajdu S, Jurgensone I, Gromisz S, Kownacka J, Toming K, Vaičiūtė T, Olenin S (2010) Assessing impacts of invasive phytoplankton. The Baltic Sea case. *Marine Pollution Bulletin* 60: 1691–1700, http://dx.doi.org/10.1016/j.marpolbul.2010.06.046

Pedersen J, Bullock R, Carlton JT, Dijkstra J, Dobroski N, Dyrynda P, Fisher R, Harris L, Hobbs N, Lambert G, Lazo-Wasem E, Mathieson A, Miglietta M–P, Smith J, Smith III J, Tyrrell M (2005) Marine Invaders in the Northeast: Rapid assessment survey of non-native and native marine species of floating dock communities, August 2003. MIT Sea Grant College Program No 05–3, 46 pp

Pollux B, Minchin D, Van der Velde G, Van Alen T, Van der Staay S, Hackstein J (2003) Zebra mussels in Ireland (*Dreissena polymorpha*), AFLP-fingerprinting and boat traffic both indicate an origin from Britain. *Journal of Freshwater Biology* 48: 1127–1139, http://dx.doi.org/10.1046/j.1365-2427.2003.01063.x

Pothoven SA, Fahnenstiel GL (2014) Lake Michigan after dreissenid mussel invasion: water quality and food web changes during the late winter/spring isothermal period. In: Nalepa T, Schloesser D (eds), Quagga and zebra mussels: biology, impacts and Control. Taylor and Francis, London, pp 545–553

Ramcharan CW, Padilla DK, Dodson SI (1992) Model to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha. Canadian Journal of Fisheries and Aquatic Sciences* 49: 2611–2620, http://dx.doi.org/10.1139/f92-289

Reeders HH, bij de Vaate A, Noordhuis R (1993) Potential of the zebra mussel (*Dreissena polymorpha*) for water quality management. In: Nalepa TF, Schloesser DW (eds), Zebra mussels: biology, impacts and control, Lewis Publishers, Boca Raton, pp 439–451

Ricciardi A, Neves RJ, Rasmussen JB (1998) Impending extinctions of North American freshwater mussels (Unionida) following the zebra mussel (*Dreissena polymorpha*) invasion. *Journal of Animal Ecology* 67: 613–619, http://dx.doi.org/10.1046/j.1365-2656.1998.00220.x

Schloesser DW, Nalepa TF, Mackie GL (1996) Zebra mussel infestation of unionid bivalves (Unionidae) in North America. *American Zoologist* 36: 300–310

Spidle AP, Mills EL, May B (1995) Limits to tolerance of temperature and salinity in the quagga mussel (*Dreissena bugensis*) and the zebra mussel (*Dreissena polymorpha*). *Canadian Journal of Fisheries and Aquatic Sciences* 52: 2108–2119, http://dx.doi.org/10.1139/f95-804

Stewart TW, Miner JG, Lowe RL (1998) Quantifying mechanisms for zebra mussel effects on benthic macroinvertebrates: organic matter production and shell-generated habitat. *Journal of the North American Benthological Society* 17: 81–94, http://dx.doi.org/10.2307/1468053

Stanczkowska A, Lewandowski K (1993) Thirty years of studies of *Dreissena polymorpha* ecology in Mazurian lakes of northeast Poland. In: Nalepa TF, Schloesser DW (eds), Zebra mussels: biology, impacts and control. CRC Press, Boca Raton, Florida, USA, pp 3–33

Sullivan M, Lucy F, Minchin D (2010) The association between zebra mussels and aquatic plants in the Shannon River system in Ireland. Chapter 21. In: van der Velde G, Rajagopal S, bij de Vaate A (eds), The Zebra Mussel in Europe. Backhuys Publishers, Leiden/Margraf Publishers, Weikersheim, pp 233–240

Strayer DL, Malcom M (2007) Effects of zebra mussels (*Dreissena polymorpha*) on native bivalves: the beginning of the end or the end of the beginning? *Journal of the North American Benthological Society* 26: 111–122, http://dx.doi.org/10.1899/0887-3593(2007)26[111:EOZMDP]2.0.CO;2

Timpson P, Lucy F (1998) Zebra mussel monitoring programme, Lough Allen. School of Science, Institute of Technology, Sligo, Ireland, 41 pp

Zaiko A, Daunys D, Olenin S (2009) Habitat engineering by the zebra mussel *Dreissena polymorpha* (Pallas) in a boreal coastal lagoon: impact on biodiversity. *Helgoland Marine Research* 63: 85–94, http://dx.doi.org/10.1007/s10152-008-0135-6

Zaiko A, Lehtiniemi M, Narščius A, Olenin S (2011) Assessment of bioinvasion impacts on a regional scale: a comparative approach. *Biological Invasions* 13: 1739–176, http://dx.doi.org/10.1007/s10530-010-9928-z