Cyfoeth Naturiol Cymru
Natural Resources Wales

Llyn Tegid Hydroacoustic Survey 2014

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Centre for Ecology & Hydrology, Lancaster

Report No 41

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Report series:	NRW Evidence
Report number:	41
Publication date:	January 2015
Contract number:	EAS0822
Contractor:	Centre for Ecology & Hydrology, Lancaster
Contract Manager:	R. Thomas
Title:	Llyn Tegid Hydroacoustic Survey 2014
Author(s):	**I. J. Winfield, J. M. Fletcher, J. B. James**
Technical Editor:	
Peer Reviewer(s)	R. Thomas
Approved By:	R. Thomas
Series editor(s):	
Restrictions:	None

Distribution List (core)

NRW HQ Library	1
NRW Operations North & Mid Library	1
Dolgellau National Library of Wales	1
Welsh Assembly Government Library	1
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Recommended citation for this volume:

Winfield, I. J., Fletcher, J. M., James, J. B. 2015. Llyn Tegid Hydroacoustic Survey 2014. NRW Evidence Report No: 41, 44pp, NRW, Bangor

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2. Executive Summary

1. The conservation importance of the gwyniad (*Coregonus lavaretus*, conspecific with schelly in England and powan in Scotland and collectively known as whitefish) population of Llyn Tegid in Wales is recognised on a national level. Nevertheless, for a number of years it has been considered to be threatened by deteriorating environmental conditions, especially those associated with eutrophication. Following a first and unsuccessful attempt to establish a refuge population in early 2003, a full population assessment was made in the summer of that year using a generic protocol for the assessment of whitefish (i.e. *Coregonus lavaretus* and vendace (*Coregonus albula*)) populations developed by Scottish Natural Heritage and subsequently adopted by the Joint Nature Conservation Committee, with the addition of the determination of oxygen and temperature profiles and Secchi depth. Similar assessments, but without the gill-netting component of the protocol, were made in the summers of 2004, 2005, 2006, 2007, 2008, 2009 and 2012. The formal status of the population was classified as unfavourable (maintained), due to a consistent failure to record the required percentage of young fish, in all years except 2009 when it was classified as favourable. Within this period, successful second, third and fourth translocation attempts were carried out in early 2005, 2006 and 2007.

2. The objectives of the present project were to collect and analyse hydroacoustic survey and associated environmental data during the summer of 2014, to interpret them with respect to similar data from earlier years, and to consider their implications for the current status of the gwyniad and its habitat in Llyn Tegid.

3. A hydroacoustic survey on 26 August 2014 recorded a geometric mean total abundance of gwyniad of 326.4 fish ha^{-1}, with lower and upper 95% confidence limits of 120.7 and 882.7 fish ha^{-1}, respectively, while the mean percentage contribution by small individuals to the population was 36%, with lower and upper 95% confidence limits of 30% and 43%, respectively. Under the whitefish assessment protocol, gwyniad abundance passed its performance indicator in 2014 as it did in 2003, 2004, 2005, 2006, 2007, 2008, 2009 and 2012, while its population demographic structure failed due to a failure to record the required percentage (90%) of young fish, as it did in all earlier years with the exception of 2009. This gwyniad population density estimate converted to an absolute population estimate of 135,119 individuals (95% confidence limits of 49,958 and 365,451 individuals, respectively).

4. Oxygen and temperature profiles recorded on 26 August 2014 ranged from 9.3 mg L^{-1} and 15.6 °C at the surface to 3.1 mg L^{-1} and 9.2 °C at the bottom of the water column (approximate depth 39 m), respectively. The oxygen profile showed a discontinuous decrease in concentration with depth including almost no fall in the upper 10 m, while the temperature profile showed a strong thermocline at approximately 15 m. Secchi depth was 3.7 m.

5. On the basis of the above assessments, the overall condition of the gwyniad population in 2014 is considered to be unfavourable (maintained). A catastrophic loss of the entire population due to oxygen depletion, water level variation or any impact from an introduced ruffe (*Gymnocephalus cernuus*) population remains unlikely in the short to medium term, although environmental conditions continue to give cause for concern and continued monitoring of water quality conditions throughout the water column is desirable.

6. Prioritised recommendations were made for further work including;: profiling of oxygen and temperature conditions (high priority), continuation of monitoring plan for the translocation to Llyn Arenig Fawr (high priority), further hydroacoustic surveys (high priority), fine-scale vertical analysis of existing hydroacoustic data (high priority), horizontal hydroacoustic survey (high priority), making gwyniad hydroacoustic data available to the wider research community (high priority), further survey gill netting (high priority), refinement of the analysis of historic lake level data if a detailed inshore bathymetry is now available (medium priority), use of hydroacoustics, underwater camera(s) and/or otter (*Lutra lutra*) feeding activities to locate current gwyniad spawning grounds (medium priority), mapping and characterising of gwyniad spawning grounds (low priority), further assessment of the population demographic criterion (low priority).

3. Introduction

3.1. Background

As much of the present project comprised the repetition of hydroacoustic assessments of the gwyniad (*Coregonus lavaretus*) population of Llyn Tegid conducted in 2003 (Winfield *et al.*, 2003a), 2004 (Winfield *et al.*, 2005a), 2005 (Winfield *et al.*, 2006a), 2006 (Winfield *et al.*, 2007a), 2007 (Winfield *et al.*, 2008a), 2008 (Winfield *et al.*, 2009a), 2009 (Winfield *et al.*, 2010a) and 2012 (Winfield *et al.*, 2013a), the following background is based on that presented in the report of the initial 2003 assessment.

The conservation importance of the gwyniad (conspecific with schelly in England and powan in Scotland) population of Llyn Tegid in Wales is recognised on a national level by its protection under Schedule 5 of the Wildlife and Countryside Act, 1981, and by its inclusion in a list of globally threatened/declining species in the U.K. Biodiversity Action Plan (Winfield *et al.*, 2013b). Nevertheless, this population, which is the only representation of the species in Wales, is considered to face a range of environmental threats of varying magnitude, including eutrophication, sedimentation on spawning grounds, lake-level fluctuations, species introductions and potentially climate change (Winfield, 2001; Thomas *et al.*, 2013). A short review of the ecology and biology of the gwyniad, including the mechanisms by which such threats may impact on its population status, may be found in Winfield & Fletcher (2001). Fuller accounts are given in Winfield *et al.* (1994a), Winfield *et al.* (1994b) and Thomas *et al.* (2013).

Assessments of environmental data by Winfield (2001) and Winfield & Fletcher (2001) led to the conclusion that several of the above environmental problems had become considerable at Llyn Tegid, a view which has been supported more recently by Burgess *et al.* (2006) who concluded that the lake is now in overall unfavourable condition as a result of a loss of extent of standing water, poor water quality in terms of nutrients and oxygen levels and excessive growth of cyanobacteria or green algae, an unnatural hydrological regime and significant environmental change in the form of eutrophication. Although management procedures could in theory be developed to combat these problems, there are at present no fully effective mechanisms to deal with diffuse pollution and sediment transport into the lake. Recent schemes to reduce diffuse pollution in the Afon Twrch and Afon Llafar tributaries in the form of a Catchment Sensitive Farming demonstration project administered by the Welsh Assembly have made a valuable contribution to solving these problems, but they are limited to a small catchment and so are unlikely to result in a full recovery of the lake. In addition, management of the environmental threat posed by the introduction of new species to a water body is even more difficult. In the context of the gwyniad the most important species introduction issue is that of the ruffe (*Gymnocephalus cernuus*), which Winfield *et al.* (1994a) and Winfield *et al.* (1996a) demonstrated had become extremely abundant in Llyn Tegid by the early 1990s. This development gives cause for concern because elsewhere in the U.K this species is known to consume large numbers of *Coregonus* eggs during the winter months. (Maitland *et al.*, 1983; Winfield *et al.*, 1996b; Winfield *et al.*, 1998; Winfield *et al.*, 2004). This fear has been substantiated by observations of gwyniad egg consumption by ruffe reported by staff of the then Environment Agency Wales (EAW) as documented in Winfield (2001).

Given the above concerns, a detailed translocation project plan (Winfield & Fletcher, 2001) covering theoretical considerations, an assessment of Llyn Arenig Fawr (National Grid Reference SH 847 380) as the proposed receiver site, a translocation strategy and a post-release monitoring strategy was subsequently commissioned by the then Countryside Council for Wales (CCW), the then EAW and the Snowdonia National Park Authority (SNPA). A collaborative translocation programme was subsequently carried out by these organisations between 2003 and 2007 as documented in detail in Winfield *et al.* (2003b), Winfield *et al.* (2005b), Winfield *et al.* (2006b) and Winfield *et al.* (2007b). In July 2009, an initial assessment of the success of this translocation recorded a low abundance of fish in Llyn Arenig Fawr but encouragingly also captured a single adult gwyniad (Winfield *et al.*, 2010b). These activities are also reviewed by Thomas *et al.* (2013).

In addition to the above translocation efforts, a comprehensive assessment of the status of the gwyniad population of Llyn Tegid was undertaken in the summer of 2003 by Winfield *et al.* (2003a) using hydroacoustic and gill netting techniques conforming to the then newly developed standardised survey and monitoring protocol for the assessment of whitefish (i.e. *Coregonus lavaretus* and vendace (*Coregonus albula*)) populations described by Bean (2003). This protocol was subsequently adopted by the Joint Nature Conservation Committee (JNCC) for Common Standards Monitoring (CSM) throughout the U.K. (JNCC, 2005a). Note, however, that JNCC (2005a) erroneously stipulates an age class (or population demographic) structure criterion of 70%, although this figure is actually 90% (JNCC error confirmed by C. W. Bean, Scottish Natural Heritage, *pers. comm.*).

The assessment of the gwyniad population of Llyn Tegid in 2003 concluded that on the basis of Bean (2003) its overall condition was unfavourable (maintained) (Winfield *et al.*, 2003a). Within the hydroacoustic component of the assessment, it was notable that although a geometric mean gwyniad total abundance of 348.6 fish ha^{-1}, with lower and upper 95% confidence limits of 208.5 and 583.0 fish ha^{-1}, was relatively high for this species in a U.K. context, the mean percentage contribution by small (assumed to be 0+/1+ age class) individuals to the population was only 34%, with lower and upper 95% confidence limits of 12 and 57%. This latter parameter failed to meet the population demographic structure criterion of 90% specified by Bean (2003) for a population in favourable condition. Subsequent assessments in 2004 (Winfield *et al.*, 2005a), 2005 (Winfield *et al.*, 2006a), 2006 (Winfield *et al.*, 2007a), 2007 (Winfield *et al.*, 2008a) and 2008 (Winfield *et al.*, 2009a), with those of 2005 to 2007 including early, mid and late summer surveys, continued to show a failure to meet the population demographic structure criterion. Possible reasons for these failures, which were unexpected given the age structure of the gwyniad population in 2003 revealed by the survey gill netting, were discussed in a recent summary of gwyniad research by Winfield *et al.* (2008b). In a subsequent hydroacoustic assessment carried out for the gwyniad population of Llyn Tegid in 2009, the population demographic structure passed its performance indicator for the first time by meeting the required percentage (90%) of young fish (Winfield *et al.*, 2010a). However, the most recent assessment in 2012 again failed to meet the population demographic structure criterion (Winfield *et al.*, 2013a). Finally in the context of gwyniad population assessments, it may also be noted that the adoption of the protocol of Bean (2003) by JNCC for CSM guidance for freshwater fauna in the form of JNCC (2005a) has also facilitated the first pan-U.K. comparable assessments of this rare fish species (Winfield *et al.*, 2013b). This whitefish assessment guidance provided by JNCC (2005a) also incorporates some additional environmental criteria developed for the CSM assessment of standing waters by JNCC (2005b).). Note that specific responsibility for the assessment and conservation of gwyniad now falls under the remit of Natural Resources Wales (NRW).

3.2. Objectives

The objectives of the present project were to collect and analyse hydroacoustic survey and associated environmental data during the summer of 2014, to interpret them with respect to similar data from earlier years, and to consider their implications for the current status of the gwyniad and its habitat in Llyn Tegid.

4. Methods

4.1. Approach

Winfield *et al.* (2003a) and the reference therein to Bean (2003) clearly indicated the required methodology for the present hydroacoustic survey, although two proposed minor deviations from the protocol of Bean (2003) were previously presented to and accepted by the then CCW. These deviations are documented towards the end of this section.

The precise approach taken was influenced by our extensive experience in surveying and monitoring populations of gwyniad (e.g. Winfield *et al.* (1994a); Winfield *et al.* (1996a)), powan (e.g. Winfield *et al.* (2006c)), schelly (e.g. Winfield *et al.* (2003c)), vendace (e.g. Winfield *et al.* (2003d)) and Arctic charr (*Salvelinus alpinus*) (e.g. Winfield *et al.* (2003e), Winfield *et al.* (2006d)) in England, Scotland and Wales.

The basic approach taken for the hydroacoustic survey was as follows. Oxygen and temperature profiles and a Secchi depth reading were recorded during day-time, immediately followed by a hydroacoustic survey. A night-time hydroacoustic survey was then begun after sunset. Raw data files were then copied from the hard drive of the hydroacoustics system to a second laptop computer as a data security precaution and post-processed at a later date. This approach incorporated two minor deviations from the protocol of Bean (2003).

Firstly, rather than using the target strength to fish length relationship of Foote (1987), as indeed we have done in some of our early studies (e.g. Winfield *et al.* (1994a)), we used the relationship given by Love (1971) which allows wider comparisons because it includes an allowance for different sound frequencies. In practice, the fish lengths predicted by these two relationships for targets of a given strength differ only by very small amounts of no biological consequence. Secondly, rather than regard a vessel speed of 2.0 m s^{-1} as an absolute upper limit, we prefer to adopt this as a general target mean speed but vary actual speed depending on weather conditions.

4.2. Hydroacoustic survey

4.2.1. Field work

Day and night hydroacoustic surveys were undertaken on 26 August 2014, although the day survey could not be undertaken in full due to adverse weather conditions of strong winds.

Surveys were carried out using a BioSonics DT-X echo sounder with a 200 kHz split-beam vertical transducer of circular beam angle 6.5° operating under the controlling software Visual Acquisition Version 6.0.1.4318 (BioSonics Inc, Seattle, U.S.A., www.biosonicsinc.com). Throughout the surveys, data threshold was set at -130 dB, pulse rate at 5 pings s^{-1}, pulse width at 0.4 ms, and data recorded from a range of 0 m from the transducer. In addition to the real-time production of an echogram through a colour display on a laptop computer, data were also recorded to hard disk. The system was deployed from a 4.8 m inflatable dinghy powered by a 25 horse power petrol outboard engine moving at a speed of approximately 2.0 to 2.5 m s^{-1} (approximately 7.2 to 9.0 km h^{-1}), depending on wind conditions. Navigation was accomplished using a Garmin GPSMAP 60CSx GPS (Global Positioning System) (www.garmin.com) with accuracy to less than 10 m, while a JRC Model DGPS212 GPS (www.jrc.co.jp) with accuracy to less than 5 m inputted location data directly to the hydroacoustic system where they were incorporated into the recorded hydroacoustic data files. Prior to the surveys, the hydroacoustic system had been calibrated using a tungsten carbide sphere of target strength (TS) -39.5 dB at a sound velocity of 1470 m s^{-1}.

Surface water temperature was recorded before the day-time hydroacoustic survey was attempted following the route shown in Fig. 1, although due to strong winds only Transect 6 was surveyed between approximately 15.28 and 15.33 hours. Weather conditions had improved greatly by the evening and all 14 transects were surveyed after dark between approximately 21.11 and 22.50 hours during the night-time survey. Corresponding waypoints are given in Table 1 and shown in Fig. 1. Following Jurvelius (1991), coverage ratios (length of survey : square root of the research area) were calculated with respect to the lake's nominal total surface area (414 ha) and with respect to the area actually surveyed, where water depth exceeded approximately 5 m (274 ha) which is taken as the effective minimum water depth required for vertical hydroacoustics.

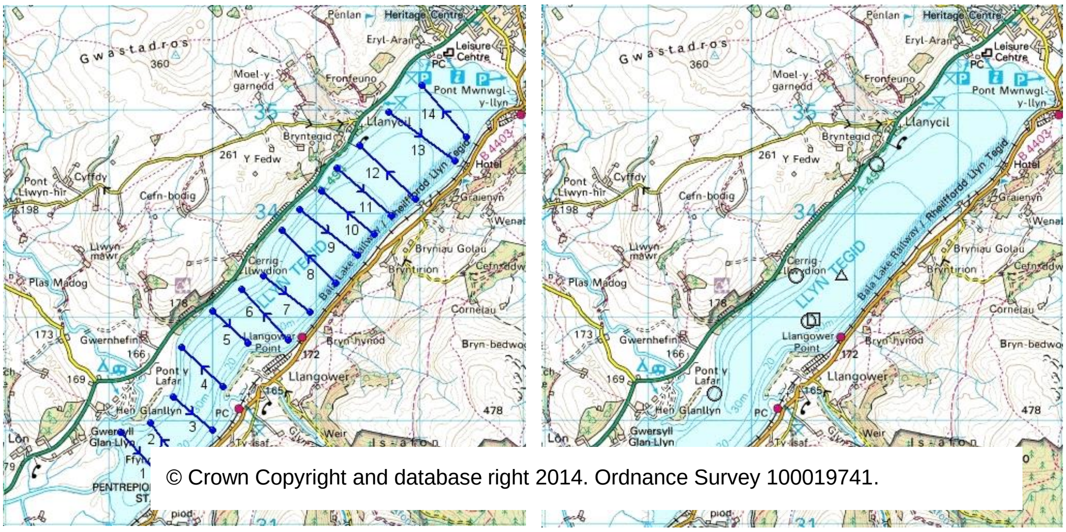


Figure 1 Locations of 14 hydroacoustic transects used at Llyn Tegid in 2014 (left map, with the direction of travel indicated by an arrowhead), one oxygen and temperature profiles and Secchi depth site used in 2014 (right map, indicated by a triangle), and five gill-netting sites used in 2003 (see Winfield *et al.* (2003a)) (right map, with bottom and surface nets indicated by circles and a square, respectively). Detailed location data are presented in Table 1. Scale is indicated by the 1 km grid. Based upon Ordnance Survey 1:25000 data.

Event	Latitude (North)	Longitude (West)
Transect 1 start	52, 52.380	3, 38.940
Transect 1 end	52, 52.160	3, 38.590
Transect 2 start	52, 52.260	3, 38.470
Transect 2 end	52, 52.430	3, 38.680
Transect 3 start	52, 52.570	3, 38.490
Transect 3 end	52, 52.400	3, 38.150
Transect 4 start	52, 52.630	3, 38.070
Transect 4 end	52, 52.830	3, 38.430
Transect 5 start	52, 53.020	3, 38.170
Transect 5 end	52, 52.860	3, 37.860
Transect 6 start	52, 52.880	3, 37.510
Transect 6 end	52, 53.140	3, 37.920
Transect 7 start	52, 53.210	3, 37.740
Transect 7 end	52, 53.030	3, 37.330
Transect 8 start	52, 53.180	3, 37.110
Transect 8 end	52, 53.450	3, 37.590
Transect 9 start	52, 53.560	3, 37.440
Transect 9 end	52, 53.330	3, 36.930
Transect 10 start	52, 53.440	3, 36.790
Transect 10 end	52, 53.660	3, 37.260
Transect 11 start	52, 53.780	3, 37.130
Transect 11 end	52, 53.540	3, 36.650
Transect 12 start	52, 53.630	3, 36.440
Transect 12 end	52, 53.900	3, 36.940
Transect 13 start	52, 54.080	3, 36.690
Transect 13 end	52, 53.830	3, 36.110
Transect 14 start	52, 53.960	3, 36.020
Transect 14 end	52, 54.220	3, 36.410
Profiles and Secchi depth	52, 53.098	3, 37.709

Table 1 GPS locations for 14 hydroacoustic transects and one oxygen and temperature profiles and Secchi depth site used at Llyn Tegid in 2014. Locations are given in degrees and decimal minutes.

As earlier analyses of hydroacoustic data collected at Llyn Tegid during day-time surveys by Winfield *et al.* (2003a) showed them to have little obvious value for the present gwyniad monitoring programme, such data were not analysed further here although they were collected and archived with little extra effort in case an appropriate use becomes apparent in the future.

4.2.2. Laboratory examination and analysis

Subsequent data analysis was performed by trace formation, which is also known as fish tracking. In this context, the term ‘trace’ is synonymous with ‘fish’, each being composed of a number of echoes. All results presented here refer to the night-time survey.

Trace formation was carried out using SonarData Echoview Version 3.40.47.1551 (Myriax, Hobart, Australia, www.echoview.com) with a target threshold of -70 dB. This process was applied individually to each transect of the night-time surveys.

Mean target strength of each trace produced by Echoview was converted to fish length using the relationship described by Love (1971),

$$TS = (19.1 \log L) – (0.9 \log F) – 62.0$$

where TS is target strength in dB, L is fish length in cm, and F is frequency in kHz.

Mean target strength of each trace was then categorised into ‘small’ (i.e. -52 to -45 dB, length 40 to 99 mm), ‘medium’ (-44 to -37 dB, length 100 to 249 mm) or ‘large’ (greater than -37 dB, length equal to or greater than 250 mm) length classes, with the addition of a length class of ‘very small’ (i.e. less than -52 dB, length less than 40 mm) to contain the remaining traces. The latter may be significantly contaminated by non-fish echoes and are not considered further here. Traces of each transect were also categorised into 1 m deep strata from a depth of 2 m below the water surface down to the lake bottom. Such counts were then converted to fish densities expressed as individuals per hectare of lake surface area by the use of a spreadsheet incorporating the insonification volume for each depth stratum.

The average density of fish during each night-time survey was calculated as the geometric mean with 95% confidence limits of the component transects.

Estimates of the abundance of all species were converted to estimates for gwyniad using offshore (i.e. simple unweighted pooling of offshore bottom and offshore surface) community composition data from the gill-netting surveys of 2003 reported in Winfield *et al.* (2003a), in which gwyniad comprised 92% of all fish by numbers. This gwyniad population density estimate was then converted to an absolute population estimate by scaling it up to the total surface area of the lake (414 ha).

Finally, the mean with 95% confidence limits percentage contribution by small (assumed to be 0+/1+ age class) individuals to the total gwyniad population was calculated for each site using arcsine transformed data from each transect on which fish were recorded.

4.3. Oxygen and temperature profiles and Secchi depth

Oxygen and temperature profiles to a maximum depth of approximately 39 m were taken at the location specified in Fig. 1 and Table 1 at approximately 14.45 hours on 26 August 2014 using an Oxi 340i Handheld Oxygen Meter (Wissenschaftlich-Technische Werkstätten GmbH & Co KG, Weilheim, Germany). A Secchi depth reading was taken immediately afterwards at the same site using a standard Secchi disc. This sampling location (National Grid Reference SH 90520 33189) was immediately adjacent to the Lake Dynamics

Monitoring Station (LDMS) installed in Llyn Tegid on 18 October 2006 (Lamb et al., 2007).

4.4. Assessment of conservation status

Criteria to be used to assess the condition of a gwyniad, or any other whitefish (*Coregonus albula* and *C. lavaretus*), population specified by the protocol of Bean (2003) were based on abundance, population demographic structure, maintenance of habitat quality, and presence of alien species, with the first two criteria being applied to hydroacoustic data.

For abundance, the protocol noted that because variation among the abundance levels of whitefish (*Coregonus albula* and *C. lavaretus*) recorded at lakes in the U.K. and elsewhere in Europe is so great, reference values must be calculated for each site. However, the historical lack of extensive and directly comparable data on gwyniad abundance in Llyn Tegid means that such calculations cannot be performed robustly. Consequently, this aspect of the population's status can only be interpreted in terms of its relation to earlier data from Llyn Tegid and from whitefish (*Coregonus lavaretus*) populations recorded elsewhere as considered in more detail in Winfield *et al.* (2005a).

For population demographic structure, to achieve favourable condition the protocol of Bean (2003) requires a gwyniad population to have 90% of individuals in the 0+/1+ age class, corresponding to gwyniad in the small length class of 40 to 99 mm. For each hydroacoustic survey, statistical significance of this assessment was performed by t tests on arcsine transformed data of gwyniad population percentage composition from each night-time transect on which fish were recorded, against an expected value taken as the above criterion.

The above hydroacoustic assessments were then used to produce a new overall assessment of conservation status using data relevant to the last two criteria of Bean (2003) collected by or summarised from Winfield (2001) and Millband *et al.* (2002) by Winfield *et al.* (2003a). These same sources of information were also used to make an assessment under the criteria of the appropriate favourable condition table of JNCC (2005a), although with the age class structure criterion of 90% as originally formulated by Bean (2003).

Although such assessment following Bean (2003) has now been effectively superseded by the criteria of JNCC (2005a), its results are still presented here to facilitate direct comparisons with earlier assessments at Llyn Tegid and elsewhere in the U.K. which used only the assessment procedure of Bean (2003).

5. Results

5.1. Hydroacoustic survey

Surface water temperature was 15.6 ° C. The surveys each achieved a coverage ratio of 4.3:1 with respect to total surface, while for the area actually surveyed this figure was 5.3:1.

Fig. 2 presents abundance estimates for small, medium and large fish recorded during the survey. Data are also given in numerical form in Table 2, where conversions to the abundance of gwyniad are also presented.

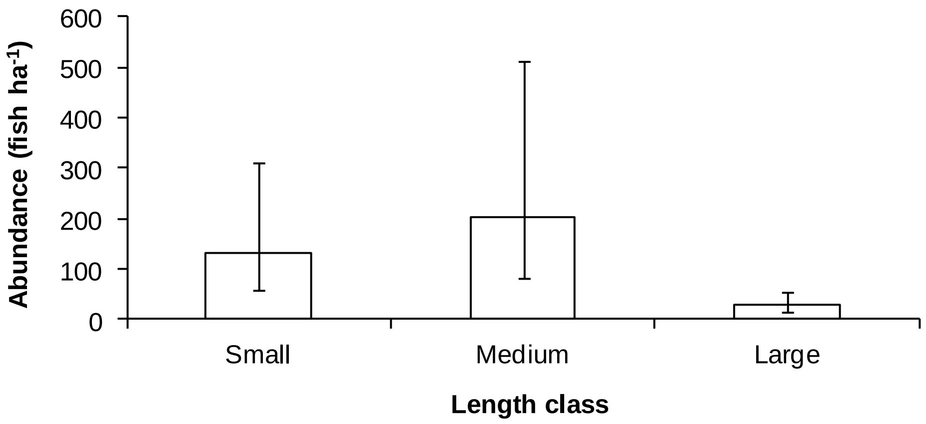


Figure 2 Abundance estimates (geometric means with 95% confidence limits) by length class for small (length 40 to 99 mm), medium (length 100 to 249 mm) and large (length equal to or greater than 250 mm) fish recorded on 26 August 2014.

Survey date	Species	Component of offshore community (%)	Abundance (fish ha^{-1}) Small	Medium	Large	All	Contribution by small (0+/1+) gwyniad (%)
26 August 2014	All	100	134.0 (57.5, 312.4)	204.2 (81.4, 512.3)	28.8 (15.0, 55.2)	354.8 (131.2, 959.5)	
	Gwyniad	92	123.3 (52.9, 287.4)	187.9 (74.9, 471.3)	26.5 (13.8, 50.8)	326.4 (120.7, 882.7)	36 (30, 43)

Table 2 Abundance estimates (geometric means with lower and upper 95% confidence limits) by size class for all fish and for gwyniad (adjusted using offshore community composition data from gill-netting surveys of 2003 reported in Winfield *et al.* (2003a)), and percentage contribution (means with lower and upper 95% confidence limits) by small (assumed to be 0+/1+ age class) individuals to the total gwyniad population recorded on 26 August 2014.

The geometric mean abundance of all sizes of all fish was 354.8 fish ha^{-1}, with lower and upper 95% confidence limits of 131.2 and 959.5 fish ha^{-1}, respectively. Gwyniad comprised 92% of the offshore community and so these figures converted to a gwyniad abundance of 326.4 fish ha^{-1}, with lower and upper 95% confidence limits of 120.7 and 882.7 fish ha^{-1}, respectively. In turn, this gwyniad population density estimate converted to an absolute population estimate of 135,119 individuals, with lower and upper 95% confidence limits of 49.958 and 365,451 individuals, respectively.

The mean percentage contribution by small (assumed to be 0+/1+ age class) individuals to the total gwyniad population was 36%, with lower and upper 95% confidence limits of 30% and 43%, respectively. These data are also given in Table 2.

The gwyniad population abundance estimate for 2014 is compared with corresponding data from 2003 (single summer survey), 2004 (single summer survey), 2005 (spring, summer and autumn surveys), 2006 (spring, summer and autumn surveys), 2007 (spring, summer and autumn surveys), 2008 (single summer survey), 2009 (single summer survey) and 2012 (single summer survey) in Figure 3 and Table 3.

The percentage contribution by small individuals to the total gwyniad population in summer 2014 is compared with corresponding data from the summers of 2003 to 2012 in Figure 4 and Table 4.

5.2. Oxygen and temperature profiles and Secchi depth

Oxygen and temperature profiles are given in Fig. 5. Values observed for oxygen levels and temperatures ranged from 9.3 mg L^{-1} and 15.6 °C at the surface to 3.1 mg L^{-1} and 9.2 °C at the bottom of the water column (approximate depth 39 m), respectively. The oxygen profile showed a discontinuous decrease in concentration with depth including almost no fall in the upper 10 m, while the temperature profile showed a strong thermocline at approximately 15 m. Secchi depth was 3.7 m.

5.3. Assessment of conservation status

As in 2003 (Winfield *et al.*, 2003a), 2004 (Winfield *et al.*, 2005a), 2005 (Winfield *et al.*, 2006a), 2006 (Winfield *et al.*, 2007a), 2007 (Winfield *et al.*, 2008a), 2008 (Winfield *et al.*, 2009a), 2009 (Winfield *et al.*, 2010a) and 2012 (Winfield *et al.*, 2013a), the values for gwyniad abundance observed in Llyn Tegid in 2014 were generally higher than values reported for whitefish (*Coregonus lavaretus*) populations elsewhere in the U.K. (see Winfield *et al.* (2013b)), although as noted earlier Bean (2003) warned that inter-lake comparisons are of limited value for this highly variable species. In addition, comparisons with data from whitefish (*Coregonus lavaretus*) populations on the European mainland are further complicated because such populations are usually subject to considerable fishing and stocking activities.

The mean total gwyniad abundance of 326.4 fish ha^{-1} observed in Llyn Tegid in 2014 was considerably higher than a geometric mean of 197.9 fish ha^{-1} recorded in the Wahnbach Reservoir, Germany (Brenner *et al.*, 1987), and comparable with 449 fish ha^{-1} recorded for Lake Constance, Germany

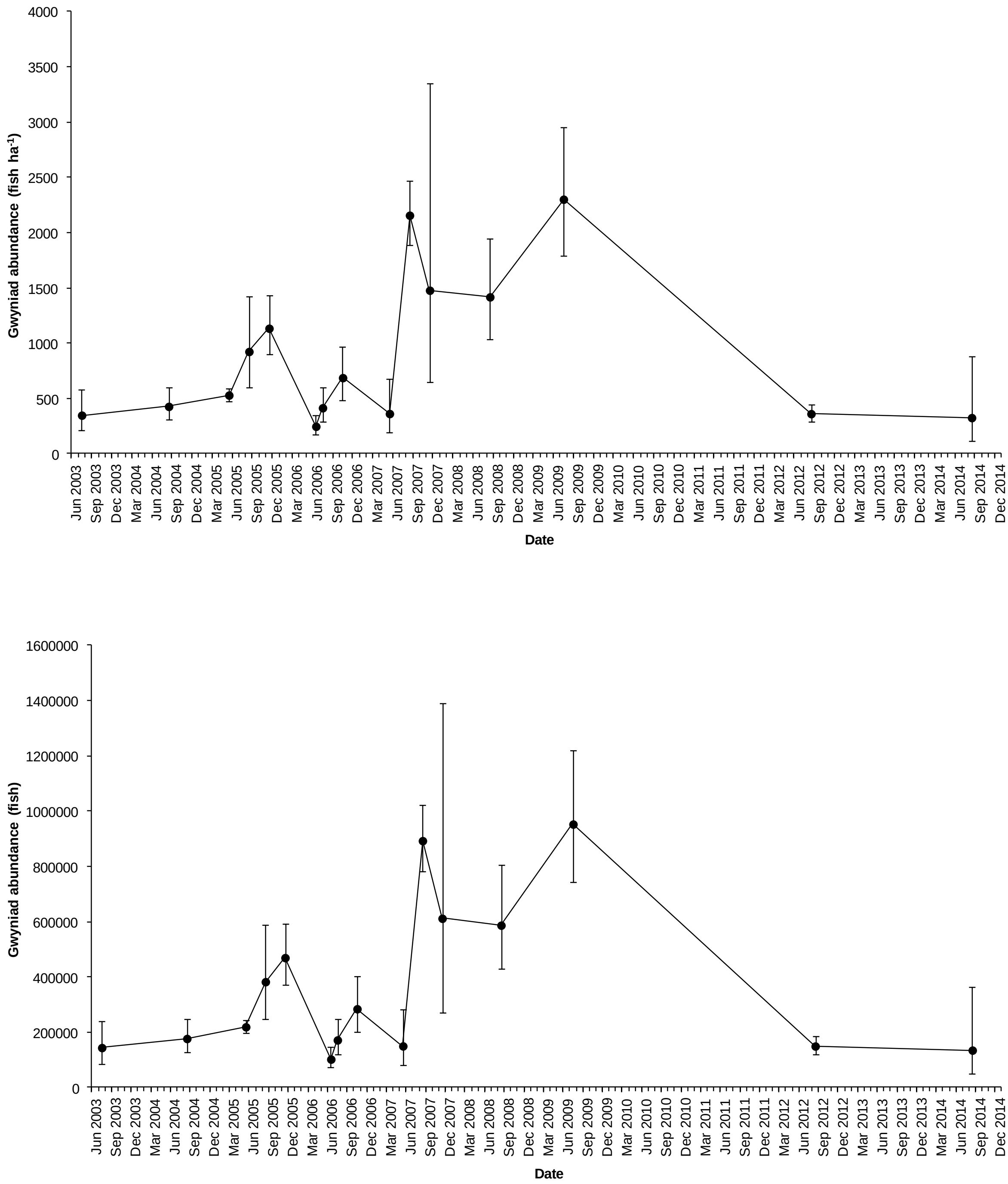


Figure 3 Abundance estimates (geometric means with 95% confidence limits) for all size classes of gwyniad expressed as population density (upper graph) and absolute number (lower graph) recorded between 2003 and 2014. Note that surveys were not carried out in 2010, 2011 and 2013. Figure sourced from present data and earlier surveys summarised in Winfield *et al.* (2013a).

Date	Abundance (fish ha^{-1})	Abundance (fish)
1 July 2003	348.6 (208.5, 583.0)	144,316 (86,295, 241,349)
5 August 2004	428.0 (307.0, 596.8)	177,203 (127,093, 247,070)
26 May 2005	530.3 (477.9, 588.4)	219,536 (197,855, 243,592)
1 August 2005	924.8 (600.2, 1,424.8)	382,860 (248,503, 589,858)
8 November 2005	1,135.1 (898.9, 1,433.2)	469,913 (372,168, 593,329)
5 June 2006	247.7 (174.6, 351.5)	102,567 (72,301, 145,503)
18 July 2006	415.5 (287.7, 600.2)	172,028 (119,089, 248,500)
23 October 2006	687.9 (488.0, 969.6)	284,787 (202,035, 401,434)
24 May 2007	363.1 (194.2, 678.9)	150,353 (80,399, 281,065)
13 August 2007	2,157.4 (1,885.6, 2,468.4)	893,164 (780,638, 1,021,918)
6 November 2007	1,478.8 (651.6, 3,355.9)	612,223 (269,762, 1,389,343)
28 August 2008	1,418.7 (382.5, 523.8)	587,326 (158,370, 216,840)
28 July 2009	2,302.2 (1,795.8, 2,951.4)	953,119 (743,465, 1,221,894)
6 August 2012	362.1 (292.0, 449.0)	149,911 (120,893, 185,894)
26 August 2014	326.4 (120.7, 882.7)	135,119 (49,958, 365,451)

Table 3 Abundance estimates (geometric means with lower and upper 95% confidence limits in parentheses) for all size classes of gwyniad expressed as population density and absolute number recorded between 2003 and 2014. Note that surveys were not carried out in 2010, 2011 and 2013. Table sourced from present data and earlier surveys summarised in Winfield *et al.* (2013a).

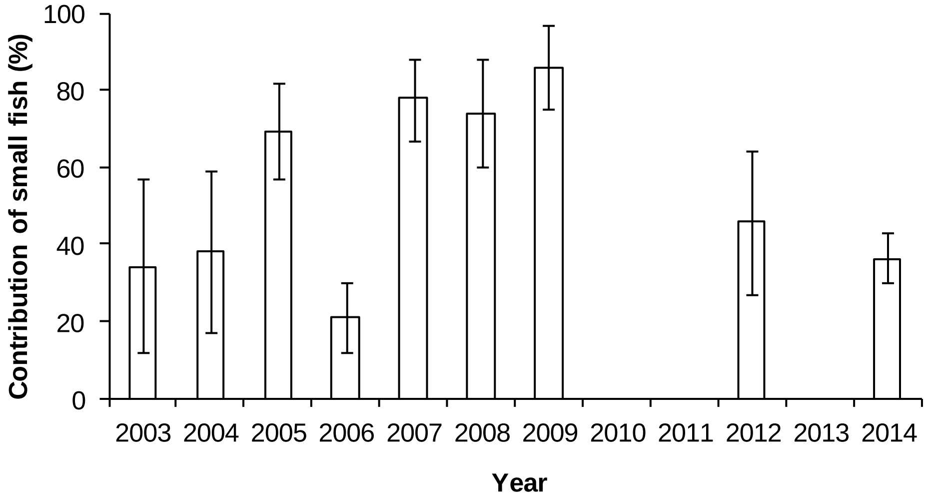
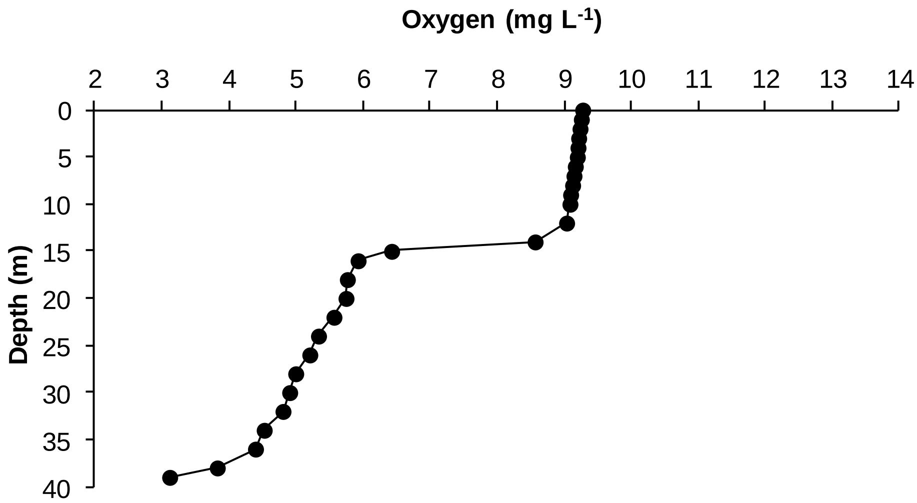


Figure 4 Percentage contributions (means with 95% confidence limits) by small individuals to the total gwyniad population in summer recorded between 2003 and 2014. Note that surveys were not carried out in 2010, 2011 and 2013. Figure sourced from present data and earlier surveys summarised in Winfield *et al.* (2013a).

Date	Contribution of small fish (%)
1 July 2003	34 (12, 57)
5 August 2004	38 (17, 59)
1 August 2005	69 (57, 82)
18 July 2006	21 (12, 30)
13 August 2007	78 (67, 88)
28 August 2008	74 (60, 88)
28 July 2009	86 (75, 97)
6 August 2012	46 (27, 64)
26 August 2014	36 (30, 43)

Table 4 Percentage contributions (means with 95% confidence limits) by small individuals to the total gwyniad population in summer recorded between 2003 and 2014. Note that surveys were not carried out in 2010, 2011 and 2013. Figure sourced from present data and earlier surveys summarised in Winfield *et al.* (2013a).



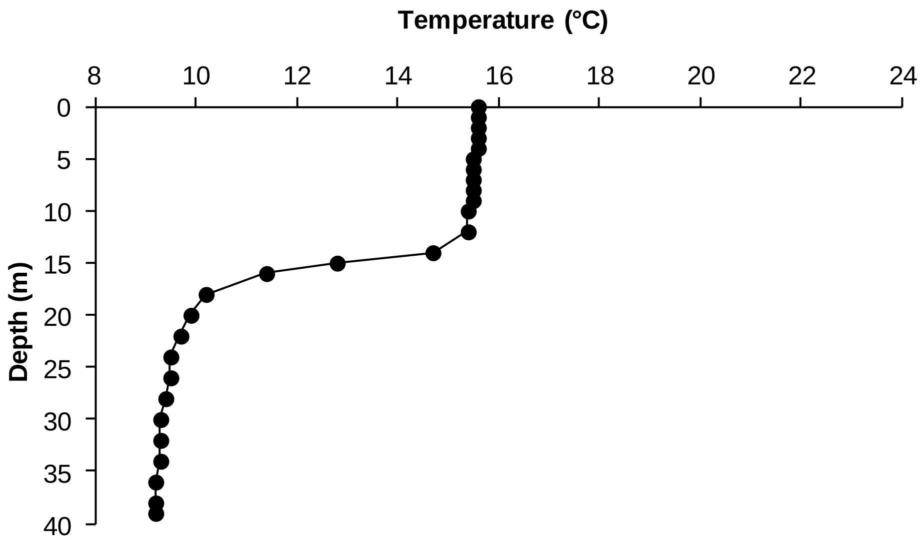


Figure 5 Oxygen (upper graph) and temperature (lower graph) profiles recorded on 26 August 2014.

(Eckmann, 1995), although the latter survey was not designed as a population assessment and so was not extensive. For adult gwyniad taken as individuals of length in excess of 150 mm, abundances recorded in Llyn Tegid during 2014 were probably (a full analysis was not undertaken due to time limitations) also considerably greater than a geometric mean of 51.6 adult fish ha^{-1} in the Wahnbach Reservoir, Germany (Brenner *et al.*, 1987), 90 adult fish ha^{-1} in Lake Constance, Germany (Eckmann, 1995), a range of 10.4 to 70.2 adult fish ha^{-1} between 1986 and 1993 in Lake Osensjoeen, Norway (Linloekken, 1995), and a mean of 1.2 adult fish ha^{-1} in July 2006 in Haweswater, U.K., where the local population has been severely impacted by water abstraction and predation by cormorants (*Phalacrocorax carbo*) (Winfield *et al.*, 2007c).

Under the protocol given by Bean (2003) and judged against the above background information, in 2014 this aspect of site assessment, i.e. gwyniad abundance, passed its performance indicator as it did in 2003 (Winfield *et al.*, 2003a), 2004 (Winfield *et al.*, 2005a), 2005 (Winfield *et al.*, 2006a), 2006 (Winfield *et al.*, 2007a), 2007 (Winfield *et al.*, 2008a), 2008 (Winfield *et al.*, 2009a), 2009 (Winfield *et al.*, 2010a) and 2012 (Winfield *et al.*, 2013a).

For population demographic structure, in August 2014 the observed percentage contribution (mean 36%, lower 95% confidence limit 30%, upper 95% confidence limit 43%) of small gwyniad defined as individuals of length between 40 and 99 mm (-52 dB to -45 dB) to the total population was significantly lower than the criterion of 90% (t test, $t = 24.22$, $df = 13$, $p < 0.001$).

Under the protocol given by Bean (2003), the population demographic structure aspect of site assessment failed its performance indicator as it did in 2003 (Winfield *et al.*, 2003a), 2004 (Winfield *et al.*, 2005a), 2005 (Winfield *et al.*, 2006a), 2006 (Winfield *et al.*, 2007a), 2007 (Winfield *et al.*, 2008a), 2008 (Winfield *et al.*, 2009a) and 2012 (Winfield *et al.*, 2013a). The only assessment to have met this criterion was that of 2009 (Winfield *et al.*, 2010a).

For maintenance of habitat quality, the re-examination by Winfield *et al.* (2003a) of environmental data summarised by Winfield (2001) showed that at least two of the specified problems of Bean (2003) were present at Llyn Tegid, i.e. nutrient enrichment and gravel exposure. However, it was and continues to be more difficult to determine their degree. The oxygen and temperature profiles collected during the present study revealed generally good conditions for the gwyniad during August 2014. The lowest oxygen level of 3.1 mg L^{-1} at the bottom of the water column was considerably higher than the lower tolerance level of 2.0 mg L^{-1} considered by Winfield (2001), while the highest temperature of 15.6 °C at the surface of the water column was only just above the upper tolerance level of 15.0 °C considered by Winfield (2001). There were no obvious impacts from either extreme value on gwyniad vertical distribution (see discussion). With the earlier conclusion of Winfield *et al.* (2006a) that gravel exposure was unlikely to be a major problem and in the absence of any data giving a clear indication to the contrary, habitat quality is thus again classified as being in favourable condition in terms of site assessment under the protocol given by Bean (2003).

For presence of alien species, it is evident from the gill netting of 2003 (Winfield *et al.*, 2003a) and seine netting of 2005 (Winfield *et al.*, 2005a), 2006 (Winfield *et al.*, 2006b) and 2007 (Winfield *et al.*, 2007b) that the introduced ruffe population first reported by Winfield *et al.* (1994a) remains well established in the inshore habitat of Llyn Tegid. Under the Site Condition Monitoring protocol given by Bean (2003) this aspect of site assessment is thus classified as being in unfavourable condition, but under the condition assessment of JNCC (2005a) the presence of ruffe only constitutes a form of environmental disturbance.

On the basis of the above assessments and in accordance with the protocol of Bean (2003), the overall condition of the gwyniad population in 2014 is considered to be unfavourable as it was in 2003, 2004, 2005, 2006, 2007, 2008 and 2012 by Winfield *et al.* (2003a), Winfield *et al.* (2005a), Winfield *et al.*

(2006a), Winfield *et al.* (2007a), Winfield *et al.* (2008a), Winfield *et al.* (2009a) and Winfield *et al.* (2013a). The only assessment to have reported favourable condition was that of 2009 (Winfield *et al.*, 2010a). In terms of site assessment, environmental conditions in Llyn Tegid in 2014 met the maintenance of habitat quality criterion for favourable condition, although they continue to give some cause for concern. However, the site failed the presence of alien species criterion for favourable condition. As a result, the site cannot be accorded favourable condition.

Having failed their respective criteria for favourable condition, the assessment categories available for the gwyniad population itself and for its environment comprise unfavourable (with sub-categories of declining, maintained or recovering), partially destroyed, or destroyed. Taking into consideration gwyniad and environmental data available from the 1990s and 2000s, a classification of unfavourable (maintained) is most appropriate for both the gwyniad and the site of Llyn Tegid.

This assessment of conservation status is summarised in Table 5 in terms of compliance with the targets for favourable condition specified by Bean (2003).

Finally, an assessment under the criteria of the appropriate favourable condition table of JNCC (2005a) is given in Table 6, for which the overall assessment was unfavourable. This assessment includes reference to contemporary annual mean data on pH and total phosphorus provided by NRW and presented in full in Table 7.

Attribute	Target	Pass / Fail	Comment
Abundance	Not specified	Pass	Although quantitative target not set, abundance is relatively high in evolving context of other UK whitefish populations
Population demographic structure	Percentage contribution of small (0+/1+ age class) individuals to comprise 90% of the population by numbers	Fail	Contribution of 36% (lower and upper 95% confidence limits of 30 and 43%). Note also that it is possible that the specified criterion is inappropriate as considered in the discussion
Maintenance of habitat quality			
Nutrient enrichment	Should not have occurred to any degree	Pass	Although some nutrient enrichment and associated impact on deepwater oxygen conditions is evident, there was no obvious impact on gwyniad distribution
Siltation	Should not have occurred to any degree	Pass**	No evidence to the contrary
Gravel exposure	Should not have occurred to any degree	Pass**	No evidence to the contrary
Loss of spawning substrate	Should not have occurred to any degree	Pass**	No evidence to the contrary
Presence of alien species	Established introduced populations of species such as ruffe should not be present	Fail**	Introduced ruffe population probably remains well established

Table 5 Summary for 2014 of Llyn Tegid gwyniad compliance with the targets for favourable condition specified by the generic whitefish assessment protocol of Bean (2003). A double asterix indicates that the feature was not specifically investigated in 2014 and so the assessment is based on earlier assessments.

Attribute	Target	Pass / Fail	Comment
Age class structure	Minimum requirement should be confirmation that coregonids are present and spawning successfully Juvenile fish (0+ and 1+) should comprise 90% of individuals in surveys carried out using quantitative hydroacoustics Targets for overall fish density will be set once reference values are calculated for each waterbody	Fail	Contribution of 36% (lower and upper 95% confidence limits of 30 and 43%). Note also that it is possible that the specified criterion is inappropriate as considered in the discussion
Water quality: oxygen*	Hypolimnion should not become anoxic; oxygen levels in the hypolimnion should exceed 4 mg L^{-1}	Fail	Hypolimnetic oxygen concentration observed to fall to 3.1 mg L^{-1}
Water quality: pH/ANC	pH>5.5	Pass	pH range of 6.35 to 7.11 observed from 9 January 2014 to 3 October 2014 giving an annual mean of pH 6.76 (Data from NRW)
Water quality: nutrients	Mean annual total phosphorus (TP) should be set at ≤ 20 µg L^{-1} or when hindcasting/paleolimnology are used the TP level should not exceed the error margin of the model applied	Pass	TP range of 6.8 to 33.5 µg L^{-1} observed from 9 January 2014 to 3 October 2014 giving an annual mean of 17.5 µg L^{-1} (Data from NRW)
Hydrology*	There should be a natural hydrological regime Levels should be stable during the winter spawning period	Fail**	Managed since 1955 as part of the River Dee regulation scheme, effectively increasing its catchment area and leading to unnatural water level fluctuations
Habitat composition*	Maintenance of littoral and pelagic zones with no barriers to movement between them Summer habitat: Well-oxygenated hypolimnion >20 m deep: high altitude lakes of lesser depth may be adequate	Fail	Hypolimnion was not well oxygenated (as defined above) during the summer, in addition levels have been observed to fall significantly in the autumn
Spawning habitat*	No increase in artificial structures Areas of clean gravel or winter macrophyte growth should be available for spawning during winter	Pass**	
Food supply*	Available littoral/benthic fauna (including *Asellus*, bivalves, chironomid larvae and gastropods) and open water zooplankton (especially *Daphnia* and *Bosmina* sp.)	Pass**	
Overall assessment		Unfavourable	

Table 6 Summary for 2014 of Llyn Tegid gwyniad compliance with the targets for favourable condition specified by JNCC (2005a). An asterisk indicates that the attribute is discretionary. A double asterix indicates that the feature was not specifically investigated in 2014 and so the assessment is based on earlier assessments. Note that the age class structure criterion has been corrected to the value of 90% specified by Bean (2003).

Attribute	Actual measurement	Date	Value
Water quality: pH/ANC	pH	9 January 2014	6.35
		6 February 2014	6.36
		7 March 2014	6.75
		7 April 2014	6.58
		8 May 2014	6.99
		30 June 2014	7.11
		31 July 2014	7.05
		24 September 2014	6.89
		3 October 2014	6.78
Water quality: nutrients	Total phosphorus (TP)	9 January 2014	17.7 µg L^{-1}
		6 February 2014	24.9 µg L^{-1}
		7 March 2014	33.5 µg L^{-1}
		7 April 2014	20.0 µg L^{-1}
		8 May 2014	20.0 µg L^{-1}
		30 June 2014	11.7 µg L^{-1}
		31 July 2014	7.6 µg L^{-1}
		24 September 2014	6.8 µg L^{-1}
		3 October 2014	15.2 µg L^{-1}

Table 7 Full 2014 data on pH and total phosphorus (TP) provided by NRW and used in the assessment presented in Table 6 of Llyn Tegid gwyniad compliance with the targets for favourable condition specified by JNCC (2005a). All sampling was undertaken at NRW Site 28860.

6. Discussion

6.1. Introduction

The present project essentially comprised a hydroacoustic survey, together with the simultaneous collection of associated environmental data, of the gwyniad population of Llyn Tegid. Such exercises were previously carried out at least annually between 2003 and 2009 (Winfield *et al.*, 2010a) and annually in 2012 (Winfield *et al.*, 2013a). Consequently, the present 2014 activities constitute the ninth year of such monitoring, although with breaks encompassing 2010, 2011 and 2013. As a result, the gwyniad of Llyn Tegid is now the second-most monitored *Coregonus lavaretus* population in the U.K. after that of Haweswater which has been followed for over 18 years (Winfield *et al.*, 2011; authors, unpublished data). In accordance with the reporting requirements, this discussion will be short and will first consider the hydroacoustic survey, followed by the oxygen and temperature profiles and Secchi depth, before moving on to interpret these data in terms of the assessment of the conservation status of the gwyniad population of Llyn Tegid

6.2. Hydroacoustic survey.

Bean (2003) rightly warned that inter-lake comparisons of whitefish (*Coregonus lavaretus*) abundance are of limited value for this highly variable species, which makes it difficult to produce robust abundance criteria for sites of different trophic status. This concern is particularly appropriate in the context of the gwyniad, which shows a quite different population biology from that of other U.K. whitefish (*Coregonus lavaretus*) populations (Winfield *et al.*, 1994a; Winfield *et al.*, 2013a). Nevertheless, it is encouraging that, as in previous hydroacoustic surveys of Llyn Tegid, the abundance estimate produced for gwyniad in 2014 was higher than or comparable with values reported from elsewhere in mainland Europe for this species. Furthermore, analysis by Winfield *et al.* (2005a) of extensive hydroacoustic data collected in 1992 for gwyniad in Llyn Tegid by Winfield *et al.* (1994a) and schelly in Ullswater by Winfield *et al.* (1994c), together with subsequent comparisons with the results of hydroacoustic surveys of powan in Loch Eck and Loch Lomond by Winfield *et al.* (2013b), confirmed that the population abundance of gwyniad is also relatively high when compared with appropriate U.K. data.

In terms of temporal trends, the mean abundance of gwyniad recorded in Llyn Tegid in 2014 of 326.4 fish ha^{-1} represents a considerable decrease from corresponding abundances recorded in 2009 (2,302.2 fish ha^{-1}), 2008 (1,418.7 fish ha^{-1}), 2007 (2,157.4 fish ha^{-1}) and 2005 (924.8 fish ha^{-1}), but was comparable with those recorded in 2006 (415.5 fish ha^{-1}), 2004 (428.0 fish ha^{-1}), 2003 (348.6 fish ha^{-1}) and most recently in 2012 (362.1 fish ha^{-1}). As discussed in more detail by Winfield *et al.* (2010a), these population fluctuations are driven primarily by changes in the summer abundance of small gwyniad.

6.3. Oxygen and temperature profiles and Secchi depth

Previous oxygen and temperature profiles recorded during 2003 to 2005, 2007 to 2009 and 2012 were all within the approximate environmental tolerance ranges of gwyniad as summarised by Winfield (2001), although profiles recorded during 2006 included relatively low hypolimnetic oxygen (minimum of 2.5 mg L^{-1}) and relatively high epilimnetic temperature (maximum of 22.7 °C) (Winfield *et al.*, 2010a). The profiles of 2014 similarly showed generally acceptable conditions in terms of gwyniad requirements. While a detailed analysis of hydroacoustic data to determine the quantitative vertical distribution of gwyniad was not carried out, a qualitative inspection of the relevant echograms showed numerous fish present at the bottom of the water column. This indicates that, as in previous years, the environmental conditions observed in 2014 did not restrict the spatial distribution of gwyniad within Llyn Tegid, but it is possible that deterioration in oxygen levels will significantly restrict their occupation of the lower hypolimnion. Although the present intermittent profiling of oxygen and temperature has great value, more frequent measurements are highly desirable and so the continued operation of the LDMS now installed on Llyn Tegid (Lamb *et al.*, 2007) will be invaluable in this context. The Secchi depth of 3.7 m observed in 2014 was remarkably greater than the 1.8 m observed in 2012 (Winfield *et al*., 2013b) and also greater than any values (maximum 3.2 m) recorded for the lake between 2003 and 2007 as reviewed by Winfield *et al.* (2008b). As such, the 2014 Secchi depth observation may be tentatively viewed as an indication of improved conditions with respect to the long-term eutrophication issues of Llyn Tegid (Thomas *et al.*, 2013).

6.4. Assessment of conservation status

This 2014 assessment of the conservation status of the gwyniad in Llyn Tegid has already been effectively discussed within the results section and so further consideration here will be brief. As in previous assessments, gwyniad abundance observed in Llyn Tegid in 2014 was generally higher than values reported for other whitefish (*Coregonus lavaretus*) populations and passed the appropriate population abundance performance indicator. In contrast, population demographic structure failed its performance indicator as it had done in all previous assessments with the exception of that of 2009.

Winfield *et al.* (2003a) first identified this frequent apparent contradiction between the results of hydroacoustic and survey gill-netting samplings, i.e. the former indicate a lower relative abundance of young fish than is acceptable for favourable condition under the protocol of Bean (2003), but the latter indicate a population composed of a relatively high number of year classes in apparently good condition. As reviewed in detail by Winfield *et al.* (2005a) and Winfield *et al.* (2006a), the only remaining possible explanations for this previously observed contradiction are that it is either a hydroacoustic sampling artefact resulting from the near-surface blind zone, or that the population demographic criterion of 90% is inappropriate. Although these issues have already been considered at length in Winfield *et al.* (2008a) and elsewhere, they are of such importance to the long-term monitoring of the gwyniad and other rare fish populations that their discussion will be repeated here.

Even with recent developments in hydroacoustic techniques, it is still difficult to address the possibility that the previously observed under-representation of small gwyniad resulted from the near-surface blind zone sampling limitation of the hydroacoustic surveys. Two possible field approaches to this problem are to orientate the hydroacoustic beam vertically but in the opposing direction to a typical deployment, i.e. to place the transducer near the bottom of the water column and transmit sound upwards, or to orientate it horizontally and so insonify horizontally-distant parts of the near-surface where sampling volume is acceptable and disturbance is minimal. However, unless a submarine or remotely operated vehicle is available, an upward-looking system such as used by Axenrot *et al.* (2004) can only be deployed in a stationary configuration which although adequate for some behavioural studies is inappropriate for population abundance estimates. Horizontal deployments have the benefit of mobility in the same way as a typical vertical deployment, but pioneering studies in this developing technique such as those of Kubecka & Wittingerova (1998) and Knudsen & Saegrov (2002) have found that no or very low wind levels are essential for successful field deployment. Even then, a number of problems remain to be solved in terms of post-processing of such data. Such near-ideal wind conditions are likely to occur only rarely on Llyn Tegid and so this approach is unlikely to have routine survey applications at this or any other large lake. However, continued attempts to address the specific issue of the potential near-surface distribution of small gwyniad are recommended and would have a generic application to lake fish monitoring beyond Llyn Tegid.

As first noted by Winfield *et al.* (2005a), an alternative although less definitive approach to the potential frequenting of the near-surface zone by young gwyniad is appropriate fine-scale vertical analysis of data from surveys by CEH Lancaster of other whitefish (*Coregonus albula* and *C. lavaretus*) populations, in addition to that of data collected during the gwyniad surveys at Llyn Tegid. Such fine-scale analyses have been greatly helped by recent developments in post-processing software and would give a strong indication of the likelihood that near-surface distributions of fish are being missed, although they could not be definitive.

The only other potential explanation for the previously observed apparent contradiction between the results of hydroacoustic and survey gill-netting samplings is that the population demographic criterion of 90% is inappropriate, either because this figure is never shown by a whitefish (*Coregonus albula* and *C. lavaretus*) population in favourable condition or because it is not shown consistently. Within the present monitoring programme at Llyn Tegid, this parameter was estimated at 34, 38, 69, 21, 78, 74, 86, 46 and 36% for the summers of 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2012 and 2014, respectively. In addition, it is notable that at the only other two sites at which the protocol of Bean (2003) has been applied to whitefish, this criterion was failed at Loch Lomond with values of 37% in 2004 (Winfield *et al.*, 2006c) and 51% in 2007 (Winfield *et al.*, 2013b) but passed at Loch Eck with values of 90% in 2005 (Winfield *et al.*, 2006d) and 98% in 2007 (Winfield *et al.*, 2013b). This issue is clearly one of fundamental whitefish ecology, rather than one specific to the gwyniad of Llyn Tegid, and so it is beyond the remit of the present work to solve it. However, the evidence so far from Llyn Tegid is consistent with both parts of this explanation being correct, i.e. the value of 90% is inappropriate for gwyniad and the actual value varies significantly between years even though the population is in good condition. The issue of recruitment consistency in the gwyniad population of Llyn Tegid is clearly worthy of further investigation.

In terms of the habitat occupied by the gwyniad in Llyn Tegid, it should be noted that not all environmental criteria considered by Bean (2003) and JNCC (2005a) were addressed within the present project. Among the criteria specified by Bean (2003), siltation, gravel exposure, loss of spawning substate and presence of alien species were not investigated, although with respect to the latter it is relevant to note that a synthesis of information on U.K. ruffe introductions in the context of impacts on native coregonid populations by Winfield *et al.* (2007d) produced no conclusive evidence that such impacts have been significant. Among the environmental criteria specified by JNCC (2005a), hydrology, spawning habitat and food supply were not addressed but all of these criteria are only discretionary. Most of these environmental issues are considered below in terms of recommendations for further work.

On the basis of the above observations and a consideration of relevant environmental features, under the protocol of Bean (2003) the overall condition of the gwyniad population in 2014 was unfavourable (maintained). Furthermore, the overall assessment was also unfavourable under the protocol of JNCC (2005a).

7. Conclusions and Recommendations

7.1. Conclusions

The objectives of the present project were to collect and analyse hydroacoustic survey and associated environmental data during the summer of 2014, to interpret them with respect to similar data from earlier years, and to consider their implications for the current status of the gwyniad and its habitat in Llyn Tegid. These were achieved in full and led to the conclusions that under the protocol of Bean (2003) the overall condition of the gwyniad population in 2012 was unfavourable (maintained) and under the protocol of JNCC (2005a) the overall assessment was a fail.

7.2. Recommendations

Detailed recommendations for further work relating to the conservation of the gwyniad of Llyn Tegid were made by Winfield *et al.* (2008a) and reviewed by Winfield et al. (2013a). These require only minor modification in the light of the work and observations of 2014. Such recommendations were also a major component of a risk assessment for the gwyniad produced by Winfield (2001), when work was recommended in the following six areas;

1. The continuation of oxygen and temperature profiling,
2. An investigation of gwyniad spawning grounds,
3. An investigation of the fish community,
4. Preparation for the establishment of a refuge population,
5. A monitoring programme for gwyniad,
6. The management of allochthonous sediment sources.

Significant progress has been achieved for a number of these areas within the present project and its immediate predecessors, although item 6 lies outside the expertise of the authors and so is not considered further here. Items 3 and 4 have now been completed and a first assessment of the translocation to Llyn Arenig Fawr was made by Winfield *et al.* (2010b) as a component of the long-term monitoring plan for this site recommended by Winfield *et al.* (2008c). A second assessment was made in 2012 (Winfield *et al.*, 2013c). This leaves items 1, 2 and 5 for further consideration here.

Under item 1, it is recommended that at least monthly profiling of oxygen and temperature is undertaken in future years. This should be done at least from August to November, when the threat of hypolimnetic deoxygenation is greatest. Llyn Tegid's LDMS (Lamb *et al.*, 2007) will enable even more frequent appropriate measurements to be taken once it is fitted as planned with winch-mounted sensors to facilitate measurements of oxygen and temperature throughout the water column. The LDMS will also give a greater degree of protection from disruption arising from adverse weather conditions. This recommendation is given high priority.

Under item 2, the thorough mapping and in particular the characterising of gwyniad spawning grounds beyond that already produced by Haram (1965) would require considerable resources, but the resulting information could be strategically valuable. Similar studies have recently recently been undertaken in Cumbria for Arctic charr spawning grounds in Crummock Water and Windermere by Winfield *et al.* (2014) and Miller *et al.* (2014), respectively, using novel hydroacoustic and underwater video techniques which have greatly reduced the amount of time required for such assessments. Such mapping and characterising is consequently given only a low priority. However, if a detailed inshore bathymetry is now available for Llyn Tegid, the analysis of historic lake level data in the context of gwyniad spawning requirements undertaken by Winfield *et al.* (2006a) could be usefully refined. In addition, the use of an underwater video or still camera system using a low-light or infra-red camera, and thus posing very little threat of disturbance, may be a cost-effective and acceptable means of locating at least some of the inshore areas of Llyn Tegid currently used by gwyniad for spawning. In addition, recent work on two Cumbrian whitefish populations has demonstrated that the spraints and prey remains of otters (*Lutra lutra*) can reveal the locations of whitefish spawning grounds (Hewitt & Winfield, 2013) and this technique may well have applicability to Llyn Tegid. This recommendation is given medium priority.

Under item 5, the present study continues a monitoring programme for gwyniad in Llyn Tegid begun in 2003, although with a break in 2010, 2011 and 2013. Continuation of the present monitoring as a single annual survey is highly desirable and this recommendation is given high priority. On a related subject, it was suggested by Winfield *et al.* (2003a) that the analysis of hydroacoustic data from the Windermere Arctic charr dataset (e.g. Winfield *et al.*, 2003e) could also make a useful contribution to determining the effect of sampling time window on the results of hydroacoustic surveys and was given a medium priority. Subsequently, such an analysis has been undertaken independently of the present project and a scientific manuscript describing the results has been published (Winfield *et al.*, 2007e).

Still under item 5 and in terms of hydroacoustic data analysis and interpretation, further work is urgently required on the vertical distribution of young gwyniad and in particular their frequenting of the near-surface zone which cannot be surveyed by vertical beam orientation. Some progress in this area may be made by appropriate fine-scale vertical analysis of data from surveys by CEH Lancaster of other whitefish (*Coregonus albula* and *C. lavaretus*) populations, in addition to the data collected during the 2003 to 2014 gwyniad surveys. This recommendation is given high priority. With respect to the same problem, the use of a horizontal beam orientation in lakes to remove the near-surface blind zone has still not yet reached the stage of routine deployment and requires further technical development but, under suitable weather conditions, such a survey on Llyn Tegid would be extremely informative. This recommendation is also given high priority. Finally in terms of the interpretation of hydroacoustic data in the context of the protocol of Bean (2003), the validity of the population demographic criterion of 90% is worthy of further investigation. Reflecting the fact that this issue continues to be a question of fundamental population biology, some progress has recently been made in this area with respect to vendace by Winfield *et al.* (2009c). Consequently, this recommendation is given low priority here. However, the work at Llyn Tegid could still make a significant contribution to such wider understanding of whitefish (*Coregonus albula* and *C. lavaretus*) population biology by making its hydroacoustic data readily available to other researchers on request. To this end, this recommendation is given high priority.

Also under item 5, the use of survey gill netting at 1, 3 or 5 year intervals to monitor the gwyniad population was recommended by Winfield (2001). However, with the exception of limited sampling in December 2008 by Colin W. Bean of Scottish Natural Heritage and Colin E Adams of the University of Glasgow (Winfield *et al.*, 2010a), which was not compliant with Bean (2003) because it was undertaken for other purposes, no such gill netting has been performed since the 2003 survey of Winfield *et al.* (2003a). It is possible that such sampling could be aligned with reporting requirements under the European Union Water Framework Directive, which could both reduce costs to NRW and maximise the benefit of understandably contentious lethal gill netting. If hydroacoustic monitoring continues, this netting is given high priority because the use of gill-netting data collected in 2003 in the analysis of any hydroacoustic data collected in 2014 and beyond is becoming increasingly inappropriate.

Finally as a new initiative under item 5, it is recommended that the long-term monitoring plan for the gwyniad translocation site of Llyn Arenig Fawr described by Winfield *et al.* (2008c), for which 2009 (Winfield *et al.*, 2010b) and 2012 (Winfield *et al.*, 2013c) surveys were the first and second steps, continues to be implemented. This recommendation is given high priority. These recommendations are summarised in tabular form in Table 8.

Research area	Specific activity	Priority
1	At least monthly profiling of oxygen and temperature, preferably more frequently by an automatic water quality monitoring system	High
5	Continuation of long-term monitoring plan for the translocation to Llyn Arenig Fawr	High
5	Further hydroacoustic surveys	High
5	Fine-scale vertical analysis of existing hydroacoustic data	High
5	Horizontal hydroacoustic survey	High
5	Making hydroacoustic data available to the wider research community	High
5	Further survey gill netting	High
2	Refinement of analysis of historic lake level data by consideration of fine-scale inshore bathymetry (if available)	Medium
2	Use of hydroacoustics, underwater camera(s) and/or otter feeding activities to locate current gwyniad spawning grounds	Medium
2	Thorough mapping and characterising of gwyniad spawning grounds	Low
5	Further assessment of the population demographic criterion	Low

Table 8 Summary of recommendations for future work. Unless specified otherwise, all activities relate to Llyn Tegid.

8. Acknowledgements

We are grateful to Rhian Thomas of Natural Resources Wales for her support during this project. We also thank Arwel Morris of the Snowdonia National Park Authority for his help with the logistics of the field work. We are indebted to Claire James of Natural Resources Wales for her provision of environmental data for Llyn Tegid. This work was funded by Natural Resources Wales.

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Data Archive Appendix

Data outputs associated with this project are archived as project 458, media 1519 on server–based storage at Natural Resources Wales.

The data archive contains

[A] The final report in Microsoft Word and Adobe PDF formats.

[B] Echoview analysed data supplied in Comma Separated Value (*.csv).format.

[C] Oxygen profiles, temperature profiles in .xls format

[D] Visual Acquisition raw data (*.dt4 format) derived from the echo sounder.

[E] Species abundance in .xls format. This will also be entered into Recorder 6

Metadata for this project is publicly accessible through Natural Resources Wales' Library Catalogue http://194.83.155.90/olibcgi by searching 'Dataset Titles'. The metadata is held as record no 115866.

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