Management of Biological Invasions (2013) Volume 4, Issue 1: 25–36
doi: http://dx.doi.org/10.3391/mbi.2013.4.1.04

Research Article

Is there a need for a more explicit accounting of invasive alien species under the Water Framework Directive?

Jochen Vandekerkhove[1], Ana Cristina Cardoso[1]* and Philip J. Boon[2]

1 *European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, I-21027 Ispra (VA), Italy*
2 *Scottish Natural Heritage, Silvan House, 3rd Floor East, 231 Corstorphine Road, Edinburgh, EH12 7AT, United Kingdom*
E-mail: *jochenvdk@hotmail.com* *(JV),* *ana-cristina.cardoso@jrc.ec.europa.eu* *(ACC),* *Phil.Boon@snh.gov.uk* *(PB)*
Corresponding author

Received: 27 June 2012 / Accepted: 17 December 2012 / Published online: 29 January 2013

Handling editor: Vadim Panov

Abstract

Through ratification of the Water Framework Directive (WFD), EU Member States committed themselves to a pressure-based assessment of the ecological status of their water bodies. Invasive alien species (IAS) constitute a major pressure in many aquatic ecosystems, yet are not explicitly accounted for by the majority of WFD assessment methods. Most Member States argue that no explicit assessment of IAS is required, assuming that significant IAS pressures will affect the WFD biological quality elements (BQEs), and be detected by generic WFD status assessments. We tested this assumption for a selection of country-by-surface-water category combinations, covering nearly 40,000 water bodies. For each of the combinations, the pressure by high-impact IAS is higher in water bodies with ecological status varying from bad to moderate than in water bodies in good or high ecological status. Most high-impact IAS show strong associations with low status class categories. Of the 17 most frequently occurring high-impact IAS, only *Mustela vison* (Schreber, 1777) and *Potamopyrgus antipodarum* (Gray, 1853) are disproportionately frequent in high status water bodies. The sensitivity of WFD methods varies across BQEs, with macrophyte-based methods showing a consistently high sensitivity to IAS pressures. However, significant pressures are observed in a number of high status water bodies. This points to a need for further optimization of existing methods so that they address the full range of pressures exerted by IAS.

Key words: ecological status; classification; invasive alien species; Water Framework Directive; pressure-impact relationship; indicator species

Introduction

The EC Water Framework Directive (WFD; 2000/60/EC) was adopted in 2000 and remains the single most important legislative instrument for the protection and management of European surface waters and groundwaters. Good ecological and chemical status should be achieved for all rivers, lakes, transitional and coastal waters within the European Union by 2015. Many methods have been developed to assess the ecological status of water bodies (Birk et al. 2012). These methods compare observed with reference biological communities and should respond to human pressures affecting the structure and functioning of water bodies.

The sensitivity of WFD methods has been quantified for a variety of pressures, including eutrophication (Kauppila 2007; Donohue et al. 2009; Marchetto et al. 2009), acidification (Rossaro et al. 2007; McFarland et al. 2010), hydromorphological changes (Borja et al. 2009), pollutants (Borja et al. 2009; Josefson et al. 2009; Sfriso et al. 2009; Delpech et al. 2010), habitat destruction (Borja et al. 2009), tourism (Romero et al. 2007) and water regulation (Pall and Moser 2009).

One pressure which, at a European level, has been largely overlooked in the context of the WFD is that exerted by invasive alien species (IAS). IAS are recognized as the second greatest threat to global biodiversity (CBD 2001) through their impacts on habitat structure (e.g. *Caulerpa* *racemosa* (Forsskål) J.Agardh, 1873: Klein and Verlaque 2008), alterations of the nutrient cycle (e.g. *Dreissena polymorpha* (Pallas, 1771): Naddafi et al. 2009) and shifts in food-web structure (e.g. *Mnemiopsis leidyi* Agassiz, 1865: Kideys 2002). Despite their ecological relevance, IAS are not mentioned in the WFD text. They were formally recognized as a pressure to be considered under the WFD only in 2002, when a working group published a non-legally binding and practical guidance for the identification of pressures and assessment of impacts, according to Article 5 of the WFD (IMPRESS 2002).

Since then, only a few Member States have incorporated alien species pressures explicitly in their WFD status assessments. Both the Republic of Ireland and the United Kingdom produced a guidance document on the issue (EPA 2004; UK TAG 2004). These documents are accompanied by a list of IAS, categorized according to impact, which are used in WFD risk assessment and for downgrading ecological status according to the alien species pressure. A similar approach is being used by Catalonia in high mountain lakes, where downgrading follows introduction of fish species (Agència Catalana de l'Aigua 2003). Others account for alien species pressures in a less explicit way. For example, alien species are part of a multimetric index to assess the ecological status of Basque estuaries (Borja et al. 2004). In Belgium, WFD fish metrics evaluate the proportion of alien species biomass in lakes and certain river zones. Another approach is followed in Germany, where alien species are attributed lower scores than native species in a species-based scoring system developed to assess the status of large rivers (Schöll et al. 2005). IAS are (partly) removed from reference communities when assessing the status of benthic communities in coastal and transitional waters by means of the Benthos Ecosystem Quality Index (BEQI; Van Hoey et al. 2007) and of rivers in the Austrian Fish Index (Gassner et al. 2005).

The vast majority of methods do not discriminate between native and alien species. Most Member States argue that there is no need for an explicit assessment of the pressure exerted by IAS, thereby assuming that their biological assessment methods are sensitive to a variety of pressures, including IAS (Vandekerkhove and Cardoso 2010).

Irrespective of the way WFD methods account for alien species pressures, either direct or indirect, their sensitivity needs to be confirmed using empirical data. Van Hoey et al. (2007) could associate changes in the macrobenthos-based BEQI score of certain Dutch brackish waters with an increase in dominance of invasive species, in particular *Ensis directus* Conrad, 1843 and *Crassostrea gigas* (Thunberg, 1793). Padisák et al. (2006) found a significant correlation between the ratio of alien species to total biomass and a phytoplankton assemblage metric developed for use under the WFD. The most comprehensive analysis thus far involved a pressure and impact assessment in 122 sites within three European invasion corridors (Arbačiauskas et al. 2008). BMWP (Biological Monitoring Working Party – a metric commonly used to assess ecological status based on macro-invertebrates; Wright et al. 2000) decreased significantly with increasing relative abundance and richness of alien invertebrates. MacNeil et al. (2010) repeated this for sites in the Isle of Man (British Isles), and confirmed that those with a greater relative abundance of macro-invertebate IAS tend to have lower water quality.

This paper examines the association between alien species pressure and ecological status in nearly 40,000 water bodies, spread across four countries and covering all four surface water categories.

Methods

Ecological status

In 2011, 10 Member States reported the ecological status of a total of 75,027 water bodies to the European Environment Agency (EEA: http://www.eea.europa.eu/). Ecological status is generally obtained by applying the 'one-out all-out' principle, with the overall ecological status corresponding to the lowest of the BQE-specific status classes. Occasionally, the reported status includes a correction based on supporting conditions and water body type. The results reported are mainly for rivers (77.7%) and lakes (19.2%), but also some coastal waters (2.6%) and transitional waters (0.5%). From the data reported to the EEA, the following were extracted for each water body: ecological status (bad, poor, moderate, good or high), the surface water category (river, lake, coastal or transitional water), the coordinates (WGS84 latitude and longitude), the country code and the unique identifier (ObjectID).

For a subset of the water bodies (n=10,961), more detailed results are published by national environmental agencies within the United

Kingdom (http://www.sepa.org.uk/; http://www.environment-agency.gov.uk/). The most recent results (2009) were used for the analysis. Because of the limited availability of biological data in coastal and transitional waters, only data for lakes and rivers were analysed at BQE level. Not all BQEs were assessed in each water body, only those that had been used in classifying at least 500 water bodies. These BQEs included benthic invertebrates, phytobenthos and macrophytes (lakes and rivers), phytoplankton (lakes) and fish (rivers).

High-impact invasive alien species

Following the rationale of other WFD pressure assessments, only species that might significantly alter the structure and/or functioning of aquatic ecosystems should be considered when quantifying the pressure from alien species. At a European level, 166 such species/species groups were identified by a SEBI expert group (Streamlining European 2010 Biodiversity Indicators; EEA 2007). The experts claimed that the list contains the most harmful IAS in Europe, across ecosystems and major taxonomic groups, with respect to their impacts on European biodiversity and their changing abundance or range. From the list only aquatic taxa were retained. All three listed bird species were excluded because these easily migrate across water bodies. Atlantic salmon (*Salmo salar* Linnaeus, 1758) was excluded also, as the occurrence data do not discriminate between introduced and native lineages. Within the UK, a Technical Advisory Group (UK TAG) has produced and manages a dynamic list of IAS for use under the WFD (UK TAG 2013). The species are classified according to their impacts on native habitats and biota (high, low, unknown). The list used on the analysis, and published in 2009 before its recent update, included 34 high-impact species associated with aquatic habitats, referred to here as ‘HI-IAS’.

For each of the aquatic HI-IAS listed by SEBI and UK TAG, occurrence data were retrieved through the Global Biodiversity Information Facility (GBIF: http://data.gbif.org/). GBIF may not be the most complete information source for individual water bodies, but it is not restricted to species which are part of a BQE. These species are not systematically monitored under the WFD. From the downloaded data, the georeferenced records within the 10 countries with reported ecological status results were selected. Old records (before 1990) and records with low coordinate precision (>100m) were deleted.

Analyses

Each of the occurrence records was assigned to a water body using the software ArcGIS 9.2 (ESRI, California). First, shape files (*.shp) were created with the latitudes and longitudes of the HI-IAS occurrence records and of the water bodies. For an accurate calculation of distances, both layers were re-projected from a World Geodetic System projection (in particular WGS84) into Lambert Azimuthal Equal Area (LAEA) Projection. The distance from an occurrence record to the nearest water body was calculated using the NEAR function.

Further calculations were limited to the eight country × surface water category combinations with the most comprehensive status results and GBIF coverage. For water bodies within these combinations, the pressure by HI-IAS was estimated by counting the number of HI-IAS within a 1 km perimeter around the water body coordinates. The results were visualized using histograms created with Sigmaplot 2000 (Systat Software Inc., San Jose).

For individual species, the analyses are based on occurrence data at the level of the water body. Abundance data are not readily available for most water bodies, and would add disproportionate weight to microscopic organisms. In addition, all selected species are short-listed on a European list of the worst invasive species. For these species, we believe that the detection of the species is almost as informative as the quantification of its abundance.

A quantitative estimate of the sensitivity of a (group of) method(s) was obtained through calculation of an index, hereby termed the Non-native Species Sensitivity Index (NSSI). The NSSI score is calculated by taking the mean percentage of water bodies in bad, poor and moderate ecological status with HI-IAS, and dividing this by the mean percentage of water bodies in good and high ecological status with HI-IAS. Note that the index score is independent of the distribution of water bodies over status classes, and can also be calculated in regions and/or surface water categories with low density of HI-IAS. A significance value is added to the NSSI score by testing if the percentages of water bodies in bad, poor and moderate ecological status with HI-IAS are significantly higher than the percentages of water bodies in good and high ecological status (1-tailed Student's t-Test, calculated in Statistica (Statsoft Inc., Tulsa), and only reported if $p<0.05$. Status classes with fewer than 10 water bodies are not included in the calculations, graphs and statistics.

For each shortlisted HI-IAS the degree of association with each status class was calculated. This was done by dividing the observed number of records by the expected number of records per status class, i.e. in the absence of any status association. The level of association was not calculated for species present in fewer than 10 water bodies.

Results

The presence of HI-IAS was assessed for 37,927 water bodies. Overall, HI-IAS become increasingly rare as ecological status improves (Figure 1). Ecological status is a multi-pressure assessment; water bodies may have a low ecological status even in the absence of a pressure by alien species. It is of greater relevance to check whether alien species pressures are low in good, and especially high ecological status water bodies. HI-IAS, as defined by the SEBI expert group, are found in 3.2% (moderate) to 3.9% (bad) of the low status water bodies. In contrast, in water bodies at good and high ecological status HI-IAS are present in only 1.4 and 1.1%, respectively. In total, 31 of the water bodies assessed at high ecological status contain HI-IAS. Most of these are coastal waters in the UK, mainly with *Potamopyrgus antipodarum* (Gray, 1853) (n=17), but also *Mustela vison* (Schreber, 1777) (n=3) and *Cordylophora caspia* (Pallas, 1771) (n=1). When using the UK TAG list as a reference, only two water bodies at high ecological status are inhabited by HI-IAS – a river with Canadian pondweed *Elodea canadensis* Michx. and a coastal water body with the amphipod *Crangonyx pseudogracilis* Bousfield, 1958.

The pressure by alien species varies substantially across countries and surface water categories. Although part of the variation is attributable to regional variations in sampling and reporting effort, it is noteworthy that a much lower fraction of Swedish and French rivers are invaded by HI-IAS than British and Dutch rivers (HI-IAS in 0.7% and 0.5% vs. 4.9% and 18.1%, respectively). Within the UK, rivers and lakes experience a lower alien species pressure than coastal and transitional waters (HI-IAS in 4.9% and 6.8% vs. 9.6% and 27.1%, respectively).

For all country × surface water category combinations with sufficient data, the NSSI score is consistently above 1.00. This means that the proportion of water bodies with HI-IAS is higher in the bad to moderate status categories than in the good and high status categories. This is true both when identifying HI-IAS according to the SEBI list and the UK TAG high-impact list. The highest NSSI score (12.61) is given to the method for coastal waters in the UK, with identification of HI-IAS according to UK TAG. Here, HI-IAS are present in a disproportionately high fraction of moderate status water bodies, compared with good or high status coastal water bodies. The high NSSI score is attributable to a strong association of *Crepidula fornicata* (Linnaeus, 1758) with moderate status coastal waters. The NSSI score for coastal waters based on the SEBI list is lower (1.85), because *Potamopyrgus antipodarum*, a species exclusive to this list, is strongly associated with high status coastal waters. Because of a lack of British coastal waters in bad or poor status, no significance value can be calculated for the NSSI score. Significant NSSI scores are only found for lakes in the UK ($NSSI_{SEBI}$=5.07, p=0.044; $NSSI_{UK\ TAG}$=5.07, p=0.041). Except for coastal waters, the NSSI scores are largely comparable for the two HI-IAS lists (linear regression of UK NSSI scores: r=47; p=0.024). This is expected, as the SEBI list and the UK TAG list are largely overlapping: of the 30 high-impact alien taxa found within 1 km from a UK water body based on GBIF, 47% are listed both by SEBI and UK TAG. The most noticeable differences are the absence from the UK TAG high-impact list of *Elminius modestus* Darwin, 1854 ($n_{UK\ TAG}$ = 118), *Potamopyrgus antipodarum* ($n_{UK\ TAG}$ = 89), *Oncorhynchus mykiss* (Walbaum, 1792) ($n_{UK\ TAG}$ = 49) and *Mustela vison* ($n_{UK\ TAG}$ = 33), and the absence of *Crangonyx pseudogracilis* from the SEBI list (n_{SEBI} = 47).

Based on the SEBI list, 5.7% of the UK water bodies contain one or more HI-IAS, while species from the more restricted UK TAG list are found in 3.9% of the UK water bodies. The majority of these water bodies are overlapping (59% of water bodies with HI-IAS). For 2.5% (n=272) of the UK water bodies the presence of high-impact aliens varies according to the list that is used. Most of these water bodies (79.4%) are either classified as good or moderate ecological status. The presence of HI-IAS is dependent on the species list for 28 water bodies classified as high ecological status. Only in one

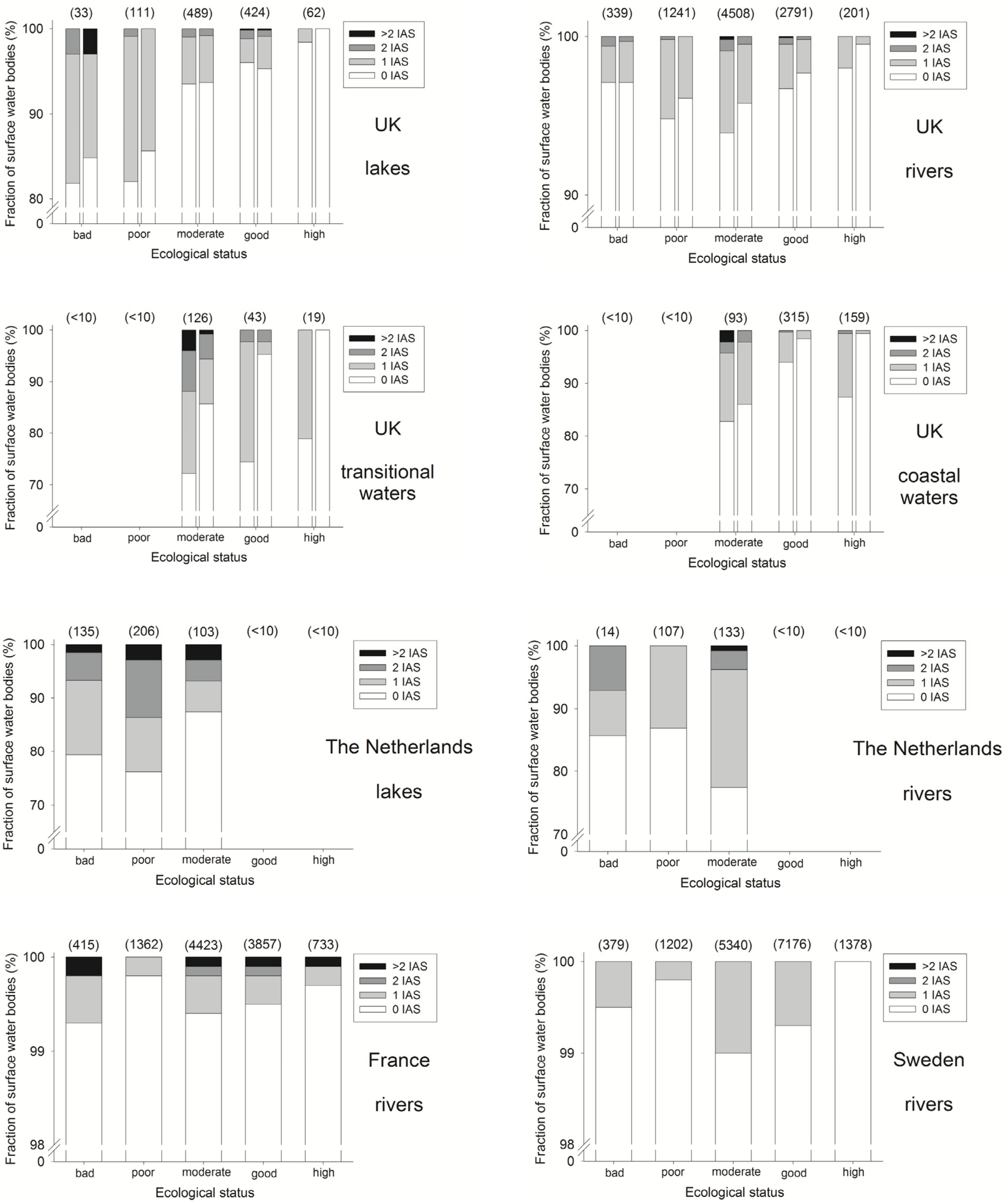

Figure 1. Bar charts showing the fraction of water bodies with one or more aquatic high-impact alien species (HI-IAS) within each of the WFD status classes. Status classes are integrative assessments based on different biological quality elements. HI-IAS are identified by the working group 'Streamlining European Biodiversity Indicators' (SEBI), and for water bodies within the UK by the UK Technical Advisory Group (UK TAG). Numbers between brackets above the bars indicate the number of water bodies within that status class, provided there are at least 10.

of these water bodies species exclusively present in the UK TAG list are recorded.

For British rivers and lakes, available information on HI-IAS and ecological status allowed the responsiveness of different WFD assessment methods to alien species pressures to be compared (Figure 2).

(a) *Macrophytes (MP)*: MP-based methods appear highly sensitive to alien species pressures. Indeed, the NSSI scores are consistently high, and vary from 1.98 (for lakes using the UK TAG list) to 4.10 (for rivers using the UK TAG list).

(b) *Benthic invertebrates (BI)*: The results for BIs are mixed, because of a low occurrence of HI-IAS in rivers and differences between SEBI and UK TAG in listing the riverine HI-IAS. In the 1968 rivers for which the status is assessed using BI, only five HI-IAS were recorded, with a total of only 33 occurrences. Not all species are present in both lists, which explains the difference in performance of the SEBI list ($NSSI_{SEBI}$ = 3.13, p=0.043) and the UK TAG list ($NSSI_{UK\ TAG}$ = 1.29). In lakes, an opposite pattern was observed, with more HI-IAS in the good to high status water bodies than in the moderate status water bodies ($NSSI_{SEBI}$ = 0.63 $NSSI_{UK\ TAG}$=0.63).

(c) *Phytobenthos (PB)*: PB-based methods are very sensitive to alien species pressures in rivers ($NSSI_{SEBI}$=2.84; $NSSI_{UK\ TAG}$=7.32). For lakes, the proportion of water bodies with HI-IAS is not associated with the status based on PB assessments ($NSSI_{SEBI}$=1.30; $NSSI_{UK\ TAG}$=1.06).

(d) *Phytoplankton* (*PP*): A relatively large proportion of lakes categorized as high or good ecological status based on PP assessments contain HI-IAS ($NSSI_{SEBI}$=0.77; $NSSI_{UK\ TAG}$=0.35).

(e) *Fish*: HI-IAS are over-represented in rivers for which fish data indicate a bad ecological status, but proportionately divided over the other status categories ($NSSI_{SEBI}$=1.19; $NSSI_{UK\ TAG}$=1.04).

Overall, most HI-IAS are over-represented in low status water bodies (see status association values in Table 1). Of the 17 most common HI-IAS, seven species are strongly associated (status association value >2) with a low status class category (*Azolla filiculoides* Lam. 1783, *Crangonyx pseudogracilis, Crepidula fornicata, Elodea canadensis, E. nuttallii* (Planch.) H. St. John, *Lepomis gibbosus* (Linnaeus, 1758) and *Pacifastacus leniusculus* (Dana, 1852)). Only two are disproportionately frequent in good or high status water bodies (*Mustela vison and Potamopyrgus antipodarum*).

Discussion

A correct understanding of pressure−impact relationships is vital for the successful implementation of the WFD (IMPRESS 2002). In recent years, significant progress has been made, mainly in the context of the EU projects REBECCA ('Relationships between ecological and chemical status of surface waters'; FP6 SSPI-CT-2003-502158; www.environment.fi/syke/rebecca) and WISER (“Water bodies in Europe: Integrative Systems to assess Ecological status and Recovery”; FP7 226273; www.wiser.eu). Thus far, focus has been on eutrophication, acidification and habitat degradation. Efforts to relate IAS pressures to ecological status have been limited in geographic scale (except Arbačiauskas et al. 2008) and restricted to single BQEs. The analysis described here, covering nearly 40,000 water bodies across different countries and surface water categories, reveals the sensitivity of a range of WFD methods to IAS pressures.

A decreasing pressure by HI-IAS with increasing ecological status was observed for most of the country by surface water category associations examined, with NSSI scores consistently higher than 1. These results are broadly in line with expectations that significant IAS pressures should result in impacts detectable by generic WFD methods. It should be noted that the results are conservative as they are based on absolute HI-IAS numbers and not on the ratio of HI-IAS to native species richness or abundance. Many WFD assessment methods respond positively to increases in native species richness, so that stronger associations would be expected if HI-IAS were to be compared with native richness. Such alien to native ratios are frequently used to assess the pressure by alien species (Olenin et al. 2007; Arbačiauskas et al. 2008; Panov et al. 2009), but may mask IAS pressures in diverse ecosystems.

With the exception of the UK, none of the countries included in this analysis makes an explicit assessment of alien species pressures (Vandekerkhove and Cardoso 2010). The UK issued guidance for downgrading ecological

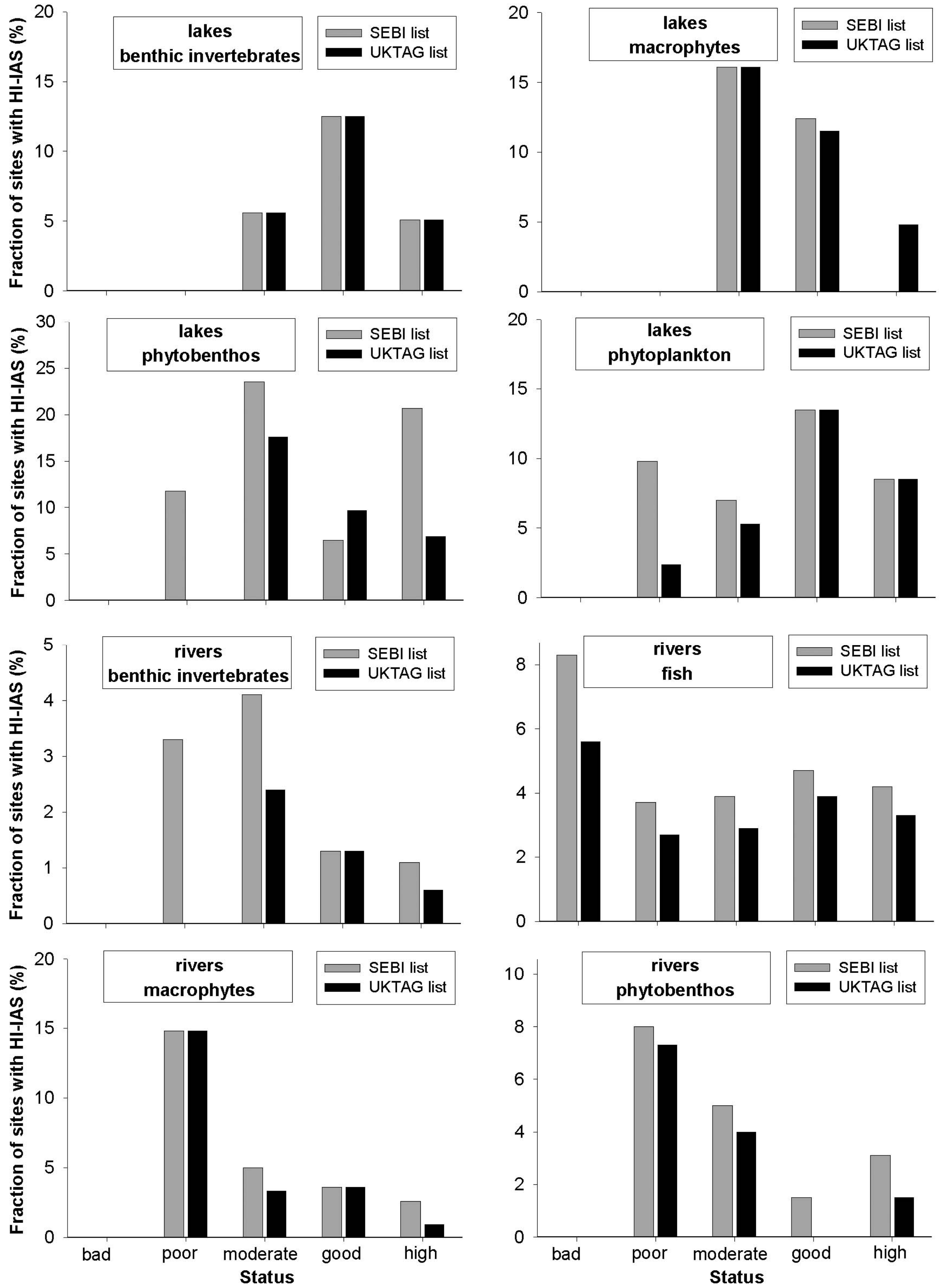

Figure 2. Bar charts showing the fraction of water bodies in the UK with one or more aquatic high-impact alien species (HI-IAS) within each of the WFD status classes. Status classes were obtained from assessments targeting different biological quality elements. HI-IAS are identified by two working groups ("Streamlining European Biodiversity Indicators" (SEBI) and UK Technical Advisory Group (UK TAG)). No bars are shown if fewer than 10 water bodies are available.

status based on the presence of HI-IAS, following two principles: (1) A water body classified as being at high status (i.e. in reference condition) should contain no established alien species known to cause serious impacts to water bodies, and (2) a water body that demonstrates more than a slight adverse impact from one or more established alien species on the high-impact list is considered to be failing to achieve good status (UK TAG 2007). These downgrading rules have only been applied to a small fraction of the UK water bodies (<5% of the 10,961 water bodies). For example, in the first river basin management cycle, the Environment Agency in England and Wales did not downgrade water bodies at good ecological status based on alien species. The review of the British data indicates that the downgrading procedure resulted in a lowering of the status class for about 40 water bodies. The small proportion of downgraded water bodies may indicate that most of the IAS pressures in British waters are already detected by the BQE-specific assessment tools. However, this conclusion needs to be treated with caution as recent evidence suggests that interactions between invasive and native species may lead to incorrect assumptions about ecological status. A study by Gallardo et al. (in press) investigated the impact of *Dikerogammarus villosus* on Average Score Per Taxon (ASPT), one of the standard invertebrate metrics used for assessing ecological status in British rivers. They concluded that the impact of *D. villosus* on high-scoring taxa such as mayflies and blackflies would reduce ASPT scores in river sections at high and good status and inflate them in sections at poor status. They concluded that the potential effectiveness of current WFD monitoring strategies could be improved by including a measurement of 'bio-contamination' within biological communities.

Ecological status classification under the WFD should be based on an integrated assessment of all major pressures. At the water body level, not all pressures are equally significant, and the overall ecological status may not reflect the pressure from IAS. However, the observed presence of HI-IAS in high status water bodies calls into question both the accuracy of IAS pressure assessments and/or that of existing WFD assessment methods. Some mismatches may have been caused by the way species records were attributed to water bodies. Indeed, not all HI-IAS found within a 1 km perimeter around a water body will occur within the water body itself. In addition, species recorded in the early 1990s may have been eradicated before the WFD assessment. However, in other studies only samples collected within water bodies were analysed, simultaneously with the status assessment, and a significant pressure of IAS was still observed in a number of waters at high status (Arbačiauskas et al. 2008; MacNeil et al. 2012). The percentage of water bodies with a mismatch between ecological status and IAS pressure is low in all studies, so that the added value of making changes to assessment methods may be limited. On the other hand, the number of HI-IAS responsible for the mismatches is low, and their pressures may be recorded with relatively little extra effort.

There are a number of arguments that can be made against a more explicit accounting of IAS under the WFD. First, changes or additions to existing WFD methods would involve extra cost and effort. Second, ecological status is directly linked to programmes of measures which are elaborated in River Basin Management Plans. However, for a number of IAS there are currently no effective eradication or control measures, so that downgrading ecological status based on their presence may not help in removing the problem. On the other hand it can be argued that WFD status assessments may contribute to highlighting the problem, and eventually stimulate action to prevent the further spread of established IAS. Another criticism is that a more explicit accounting for IAS pressures, in particular through a post-assessment downgrading, adds (in some cases) disproportionate weight to them. For this reason, UK TAG adopted very stringent criteria for the identification of HI-IAS, listing only the few species which are all known to have a serious impact on ecosystem structure and functioning. Finally, the accuracy of IAS pressure assessments is constrained by the limited knowledge on short- and longer-term impacts. For many alien species, the impacts are not known or only partially documented, and it is critically important to assess the potential impacts of IAS case by case. Some IAS may appear to have a positive impact on specific aspects of ecosystem functioning (e.g. zebra mussel *Dreissena polymorpha* reducing the levels of phytoplankton in nutrient-enriched waters: Ludyanskiy et al. 1993) and this may introduce bias into assessments of ecological status.

Table 1. List of aquatic high-impact alien species listed by the working group 'Streamlining European Biodiversity Indicators' (SEBI) and UK Technical Advisory Group (UK TAG), for which records were found through the Global Biodiversity Information Facility (GBIF) in the vicinity of water bodies with reported ecological status results. Birds and salmon are excluded from the list (see text for details). For each species the number of water bodies is given where the species is found within a 1 km perimeter around reported water body coordinates. For species with at least 10 records, the degree of association with a status class is given between brackets (observed number of records divided by number of records expected in the absence of any status association).

Species	SEBI	UK TAG	bad	poor	moderate	good	high
Asparagopsis armata Harvey 1855	X		0	0	2	6	0
Azolla filiculoides Lam. 1783	X	X	8 (5.0)	24 (4.7)	12 (0.7)	2 (0.1)	0 (0.0)
Beröe cucumis Fabricius, 1780	X		0	0	1	0	0
Carassius auratus (Linnaeus, 1758)	X	X	0 (0.0)	1 (0.9)	4 (1.0)	4 (1.0)	1 (1.5)
Cordylophora caspia (Pallas, 1771)	X		0	0	2	1	1
Crangonyx pseudogracilis Bousfield, 1958		X	4 (2.4)	1 (0.2)	21 (1.1)	20 (1.1)	1 (0.3)
Crassostrea gigas (Thunberg, 1793)		X	0	1	8	0	0
Crassula helmsii (Kirk) Cockayne	X	X	1	0	2	5	0
Crepidula fornicata (Linnaeus, 1758)	X	X	0 (0.0)	1 (0.1)	56 (2.2)	7 (0.3)	0 (0.0)
Cyprinus carpio Linnaeus, 1758	X	X	5 (1.4)	14 (1.3)	63 (1.6)	17 (0.4)	1 (0.1)
Didemnum spp./ *D. lahillei* Hartmeyer, 1909		X	0	0	1	0	0
Dreissena polymorpha (Pallas, 1771)	X	X	0	1	3	1	0
Elminius modestus Darwin, 1854	X		0 (0.0)	2 (0.2)	81 (1.7)	34 (0.7)	1 (0.1)
Elodea canadensis Michx.	X	X	10 (1.9)	38 (2.3)	74 (1.2)	27 (0.5)	1 (0.1)
Elodea nuttallii (Planch.) H. St. John	X	X	31 (6.1)	62 (3.8)	47 (0.8)	7 (0.1)	0 (0.0)
Ensis americanus (Gould, 1870)	X		0	0	3	0	0
Ficopomatus enigmaticus (Fauvel, 1923)	X	X	0	0	1	0	0
Gambusia affinis (Baird and Girard, 1853)	X		0	0	1	1	0
Gammarus tigrinus Sexton, 1939	X		0	1	1	1	0
Hydrocotyle ranunculoides L.f.	X	X	0	2	1	1	0
Hydroides elegans (Haswell, 1883)	X		0	0	2	0	0
Lagarosiphon major (Ridl.) Moss		X	1	0	1	2	0
Lepomis gibbosus (Linnaeus, 1758)	X		1 (2.6)	0 (0.0)	5 (1.1)	5 (1.2)	0 (0.0)
Ludwigia peploides (Kunth) Raven	X		1	1	1	1	0
Mustela vison (Schreber, 1761)	X		1 (0.9)	2 (0.5)	13 (1.0)	12 (0.9)	5 (2.3)
Myriophyllum aquaticum (Vell.) Verdc.		X	0	0	2	1	0
Oncorhynchus mykiss (Walbaum, 1792)	X		2 (0.8)	11 (1.4)	31 (1.1)	25 (0.9)	0 (0.0)
Orconectes limosus (Rafinesque, 1817)	X	X	0 (0.0)	0 (0.0)	7 (1.2)	6 (1.1)	1 (1.1)
Pacifastacus leniusculus (Dana, 1852)	X	X	3 (1.0)	21 (2.2)	47 (1.4)	13 (0.4)	0 (0.0)
Petricola pholadiformis (Lamarck, 1818)	X		0	0	6	2	0
Potamopyrgus antipodarum (Gray, 1853)	X		3 (0.9)	9 (0.9)	44 (1.2)	12 (0.3)	23 (3.8)
Procambarus clarkii (Girard, 1852)	X	X	0	0	5	1	0
Pseudorasbora parva (Temminck and Schlegel, 1846)	X	X	2	0	1	0	0
Ruditapes philippinarum (Adams & Reeve, 1850)	X		1	0	1	0	0
Salvelinus fontinalis (Mitchill, 1814)	X		2 (0.6)	2 (0.2)	47 (1.3)	38 (1.1)	0 (0.0)
Sargassum muticum (Yendo) Fensholt, 1955	X	X	0 (0.0)	1 (0.3)	19 (1.7)	8 (0.7)	0 (0.0)
Silurus glanis Linnaeus, 1758	X		1	0	1	0	0
Styela clava Herdman, 1881	X	X	0 (0.0)	1 (0.5)	12 (1.8)	4 (0.6)	0 (0.0)

Ecological status assessments combine the results obtained for different BQEs following specific combination rules. Each BQE method is assumed to reflect a particular pressure (or set of pressures), and the outputs are generally combined using the “one-out all-out” principle. The results of this study point to a differential sensitivity of the BQEs to alien species pressures. Consistently strong sensitivity was observed for status assessments based on analyses of macrophyte assemblages. Macrophytes are the single most important group of HI-IAS, both in the number of species listed (UK TAG: 15 of 34 species, SEBI: 41 of 166 species), and their occurrence in water bodies (366 of the 1201 occurrences; Table 1). Macrophytes are known to be good ecological indicators because they provide a spatially and temporally integrated picture of the overall status. Their assessment may not just reveal pressures by invasive macrophytes, but also by other IAS. Indeed, macrophytes interact closely with many other groups of organisms, for example by serving as a food source for herbivores, as a refuge for zooplankton and juvenile fish, or by offering a substratum for sessile organisms and for egg deposition.

While this study quantifies the sensitivity of WFD methods to pressures by IAS, it does not resolve the causality of the observed correlations. There is increasing evidence that IAS can adversely affect the structure and functioning of aquatic ecosystems (Kideys 2002; Krisp and Maier 2005; Klein and Verlaque 2008). Alternatively, a change in structure and functioning may also facilitate the introduction and spread of alien species. A reduction in native species richness – for example, caused by hydromorphological changes – may affect the resilience of communities to invasions (Dunstan and Johnson 2006), or eutrophication may dramatically alter the food-web structure in favour of non-native species. The latter is true for many shallow lakes, where increased nutrient levels have induced a shift from a top-down to a bottom-up regulated food web structure, with reduced control of invasive planktivorous and benthivorous fish (Scheffer 1998). The effects of IAS and other pressures are likely to reinforce each other, potentially resulting in an invasional meltdown at the water body level (Ricciardi 2001). At the regional scale, positive feedback mechanisms might explain the observed exponential increase in the numbers of alien species (DAISIE 2009).

In conclusion, this comprehensive study suggests a moderate to strong sensitivity to IAS pressures of the WFD methods examined. However, sensitivity is method-specific, and should ideally be assessed for all countries and surface water categories. The interaction of IAS with other pressures such as eutrophication and physical disturbance needs to be examined in order to comprehend the impact of alien species invasions on the structure and functioning of aquatic ecosystems. This knowledge should eventually feed into the river basin management plans.

Acknowledgements

We thank the European Environment Agency for giving us access to data on the ecological status of water bodies. We thank also the members of UK TAG, the ECOSTAT working group, and discussion meetings for constructive comments on draft versions of the manuscript, in particular by Kestutis Arbaciauskas, Maria Antonietta Pancucci-Papadopoulou, Beatriz Rodriguez-Labajos, Franz Schöll and Gert van Hoey. The WISER project partners provided unpublished information on WFD classification tools. Grazia Zulian is acknowledged for her help with the spatial analyses. We thank four anonymous reviewers for their valuable comments that helped us improve the manuscript.

References

Agència Catalana de l’Aigua (2003) Desenvolupament d’un índex integral de qualitat ecològica I regionalització ambiental dels sistemes lacustres de Catalunya. http://aca-web.gencat.cat/aca/documents/ca/directiva_marc/llacs.pdf (Accessed 14 October 2011)

Arbačiauskas K, Semenchenko VP, Grabowski M, Leuven RSEW, Paunović M, Son MO, Csányi B, Gumuliauskaitė S, Konopacka A, Nehring S, van der Velde G, Vezhnovetz V, Panov VE (2008) Assessment of biocontamination of benthic macroinvertebrate communities in European inland waterways. *Aquatic Invasions* 3: 211–230, http://dx.doi.org/10.3391/ai.2008.3.2.12

Birk S, Bonne W, Borja A, Brucet S, Courrat A, Poikane S, Solimini A, van de Bund W, Zampoukas N, Hering D (2012) Three hundred ways to assess Europe's surface waters: an almost complete overview of biological methods to implement the Water Framework Directive. *Ecological Indicators* 18: 31–41, http://dx.doi.org/10.1016/j.ecolind.2011.10.009

Borja A, Franco J, Valencia V, Bald J, Muxika I, Belzunce MJ, Solaun O (2004) Implementation of the European Water Framework Directive from the Basque Country (northern Spain): a methodological approach. *Marine Pollution Bulletin* 48: 209–218, http://dx.doi.org/10.1016/j.marpolbul.2003.12.001

Borja A, Muxika I, Rodriguez JG (2009) Paradigmatic responses of marine benthic communities to different anthropogenic pressures, using M-AMBI, within the European Water Framework Directive. *Marine Ecology* 30: 214–227, http://dx.doi.org/10.1111/j.1439-0485.2008.00272.x

CBD (Convention on Biological Diversity) (2001) Invasive alien species: report on existing international procedures, criteria and capacity for assessing risk from invasive alien species.

Convention on Biological Diversity. Subsidiary Body on Scientific, Technical and Technological Advice, Sixth Meeting, Montreal, 12-16 March 2001. UNEP/CBD/SBS TTA/6/INF/5

DAISIE (2009) Handbook of Alien Species in Europe. Springer, Dordrecht, 400 pp

Delpech C, Courrat A, Pasquaud S, Lobry J, Le Pape O, Nicolas D, Boët P, Girardin M, Lepage M (2010) Development of a fish-based index to assess the ecological quality of transitional waters: the case of French estuaries. *Marine Pollution Bulletin* 60: 908–918, http://dx.doi.org/10.1016/j.marpolbul.2010.01.001

Donohue I, Donohue LA, Ainín BN, Irvine K (2009) Assessment of eutrophication pressure on lakes using littoral invertebrates. In: Nõges P, van de Bund W, Cardoso AC, Solimini A, Heiskanen A-S (eds), Assessment of the Ecological Status of European Surface Waters. *Hydrobiologia* 633: 105–222

Dunstan PK, Johnson CR (2006) Linking richness, community variability, and invasion resistance with patch size. *Ecology* 87: 2842–2850, http://dx.doi.org/10.1890/0012-9658(2006)87[2842:LRCVAI]2.0.CO;2

EEA (European Environment Agency) (2007) Halting the loss of biodiversity by 2010: proposal for a first set of indicators to monitor progress in Europe. European Environment Agency, Copenhagen

EPA (Environmental Protection Agency) (2004) Alien Species Risk Analysis (Republic of Ireland): Guidance for the Assessment of Pressures and Impacts in accordance with Article 5 of the Water Framework Directive (WFD). Environmental Protection Agency, Kilkenny. http://www.lgp.ie/wfd (Accessed 28 October 2011)

Gallardo B, Dodd J, Aldridge DC (in press) A preliminary assessment of the impacts of *Dikerogammarus villosus* on ecological status for the Water Framework Directive. Environment Agency, Bristol

Gassner H, Wanzenböck J, Zick D, Tischler G, Pamminger–Lahnsteine B (2005) Development of a fish based lake typology for natural Austrian lakes >50 ha based on the reconstructed historical fish communities. *International Review of Hydrobiology* 90: 422–432, http://dx.doi.org/10.1002/iroh.200510798

IMPRESS (2002) Guidance for the analysis of pressures and impacts in accordance with the Water Framework Directive. Common Implementation Strategy Working Group 2.1. Office for Official Publications of the European Communities, Brussels

Josefson AB, Blomkvist M, Hansen JLS, Rosenberg R, Rygg B (2009) Assessment of marine benthic quality change in gradients of disturbance: comparison of multi-metric indices. *Marine Pollution Bulletin* 58: 1263–1277, http://dx.doi.org/10.1016/j.marpolbul.2009.05.008

Kauppila P (2007) Phytoplankton quantity as an indicator of eutrophication in Finnish coastal waters. Applications within the Water Framework Directive. *Monographs of the Boreal Environment Research* 31: 1–58

Kideys AE (2002) Fall and rise of the Black Sea ecosystem. *Science* 297: 1482–1484, http://dx.doi.org/10.1126/science.1073002

Klein J, Verlaque M (2008) The *Caulerpa racemosa* invasion: a critical review. *Marine Pollution Bulletin* 56: 205–225, http://dx.doi.org/10.1016/j.marpolbul.2007.09.043

Krisp H, Maier G (2005) Consumption of macroinvertebrates by invasive and native gammarids: a comparison. *Journal of Limnology* 64: 55–59, http://dx.doi.org/10.4081/jlimnol.2005.55

Ludyanskiy ML, McDonald D, MacNeill D (1993) Impact of the zebra mussel, a bivalve invader. *BioScience* 43: 533–544, http://dx.doi.org/10.2307/1311948

MacNeil C, Briffa M, Leuven RSEW, Gell FR, Selman R (2010) An appraisal of a biocontamination assessment method for freshwater macroinvertebrate assemblages; a practical way to measure a significant biological pressure? *Hydrobiologia* 638: 151–159, http://dx.doi.org/10.1007/s10750-009-0037-x

MacNeil C, Boets P, Platvoet D (2012) 'Killer shrimps', dangerous experiments and misguided introductions: how freshwater shrimp (Crustacea: Amphipoda) invasions threaten biological water quality monitoring in the British Isles. *Freshwater Reviews* 5: 21–35

Marchetto A, Padedda BM, Mariani MA, Lugliè A, Sechi N (2009) A numerical index for evaluating phytoplankton response to changes in nutrient levels in deep Mediterranean reservoirs. *Journal of Limnology* 68: 106–121, http://dx.doi.org/10.4081/jlimnol.2009.106

McFarland BP, Carse F, Sandin L (2010) Littoral macro-invertebrates as indicators of lake acidification within the UK. *Aquatic Conservation* 20: 105–116, http://dx.doi.org/10.1002/aqc.1064

Naddafi R, Eklöv P, Pettersson K (2009) Stoichiometric constraints do not limit successful invaders: zebra mussels in Swedish lakes. *PLoS ONE* 4: e5345, http://dx.doi.org/10.1371/journal.pone.0005345

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

Padisák J, Borics G, Grigorszky I, Soróczki-Pintér E (2006) Use of phytoplankton assemblages for monitoring ecological status of lakes within the Water Framework Directive: the assemblage index. *Hydrobiologia* 553: 1–14, http://dx.doi.org/10.1007/s10750-005-1393-9

Pall K, Moser V (2009) Austrian Index Macrophytes (AIM) - Module 1 for lakes: a Water Framework Directive compliant assessment system for lakes using aquatic macrophytes. *Hydrobiologia* 633: 83–104, http://dx.doi.org/10.1007/s10750-009-9871-0

Panov VE, Alexandrov B, Arbačiauskas K, Binimelis R, Copp GH, Grabowski M, Lucy F, Leuven RSEW, Nehring S, Paunović M, Semenchenko V, Son MO (2009) Assessing the risks of aquatic species invasions via European inland waterways: from concepts to environmental indicators. *Integrated Environmental Assessment and Management* 5: 110–126, http://dx.doi.org/10.1897/IEAM_2008-034.1

Ricciardi A (2001) Facilitative interactions among aquatic invaders: is an "invasional meltdown" occurring in the Great Lakes? *Canadian Journal of Fisheries and Aquatic Sciences* 58: 2513–2525, http://dx.doi.org/10.1139/f01-178

Romero J, Martínez-Crego B, Alcoverro T, Pérez M (2007) A multivariate index based on the seagrass *Posidonia oceanica* (POMI) to assess ecological status of coastal waters under the Water Framework Directive (WFD*). Marine Pollution Bulletin* 55: 196–204, http://dx.doi.org/10.1016/j.marpolbul.2006.08.032

Rossaro R, Marziali L, Cardoso AC, Solimini A, Free G, Giacchini R (2007) A biotic index using benthic macroinvertebrates for Italian lakes. *Ecological Indicators* 7: 412–429, http://dx.doi.org/10.1016/j.ecolind.2006.04.002

Scheffer M (1998) Ecology of Shallow Lakes. Chapman and Hall, London, 358 pp

Schöll F, Haybach A, König B (2005) Das erweiterte Potamon-typie-ver-fahren zur ökologischen Bewertung von Bundes-wasserstraßen (Fließgewässertypen 10 und 20: kies- und sandgeprägte Ströme, Qualitätskompo - nente Makrozoo-benthos) nach Maßgabe der EG-Wasserahmen-richtlinie. *Hydrologie und Wasserbewirt-schaftung* 49: 234–247

Sfriso A, Facca C, Ghetti PF (2009) Validation of the Macrophyte Quality Index (MaQI) set up to assess the ecological status of Italian marine transitional environments. *Hydrobiologia* 617: 117–141, http://dx.doi.org/10.1007/s10750-008-9540-8

UK TAG (United Kingdom Technical Advisory Group) (2004) Guidance on assessment of alien species. United Kingdom Technical Advisory Group on the Water Framework Directive. http://www.wfduk.org/tag_guidance/Article_05/Folder.2004-02-16.5332/TAG%202004%20%28PR1-16-03-04%29 (Accessed 2 December 2011)

UK TAG (United Kingdom Technical Advisory Group) (2007) Recommendations on Surface Water Classification Schemes for the purposes of the Water Framework Directive. United Kingdom Technical Advisory Group on the Water Framework Directive. http://www.wfduk.org/UKCLASSPUB/LibraryPublicDocs/class%20report (Accessed 2 December 2011)

UK TAG (United Kingdom Technical Advisory Group) (2013) Revised classification of aquatic alien species according to their level of impact. United Kingdom Technical Advisory Group on the Water Framework Directive. http://www.wfduk.org/sites/default/files/Media/Assessing%20the%20status%20of%20the%20water%20environment/ALIEN%20SPECIES%20REVISED%20TAG%20TABLE-Jan%2013.pdf

Van Hoey G, Drent J, Ysebaert T, Herman P (2007) The Benthic Ecosystem Quality Index (BEQI), intercalibration and assessment of Dutch coastal and transitional waters for the Water Framework Directive: Final report. NIOO Rapporten, 2007–02

Vandekerkhove J, Cardoso AC (2010) Alien species and the Water Framework Directive - questionnaire results. JRC Scientific and Technical Research Series. Publications Office of the European Union, Luxembourg, http://dx.doi.org/10.2788/64083

Wright JF, Sutcliffe DW, Furse MT (eds) (2000) Assessing the biological quality of fresh waters. Proceedings of an International Workshop, 16–18 September, 1997, Oxford. Freshwater Biological Association: Ambleside, Cumbria