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Flow requirements of non-salmonids

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Abstract Research into the relationships between non-salmonid fish population dynamics and discharge is in its infancy compared with salmonids, thus compromising the ability to manage flows in rivers and maintain ecological status. This study reviews the potential role of 'natural' hydrographical variability on fish life-history characteristics and develops a fish typology based on flow preference and conservation importance criteria that can be used to underpin the needs of hydrological management to support these fish community types. It highlights important characteristics of the natural flow regime that need to be maintained to ensure sustainability of populations of these species and offers a mechanism to categorise the fish community types, thus allowing generic management scenarios to be developed rather than complex single-species scenarios that are impractical.

KEYWORDS: cyprinids, discharge, lamprey, migration, recruitment.

Introduction

The European Union Water Framework Directive (WFD: 2000/60/EC) requires that surface waters are managed to improve and protect their ecological status. This is to be achieved by the implementation of river basin management plans that implement a programme of measures that maintain good ecological status, but also mitigate for human pressures that have caused deterioration of ecological status to less than good. Within the WFD, ecological status of a water body is defined according to how far the community characteristics of a number of biological quality elements (BQEs; of which fish is an important group) have deteriorated compared with reference community structures (structure at pristine/high status) (see Schmutz *et al.* 2007). Therefore, river basin characterisation, identification of appropriate reference conditions and assessment of current status are important stages in the WFD process.

Given that the WFD is the legislative driver of river basin management, future management of river flows and abstractions/discharge needs to take account of the natural diversity in BQEs, including fish species and communities, and their difference flow requirement needs, as well as setting of environmental standards that ensure hydrological regimes that support good ecological status. In this context, the concept of environmental flows is well established (Poff *et al.* 1997; Arthington *et al.* 2006), but most of the applications are for rivers in general or for specific target species. However, the parts of the hydrograph that are required for different species groups (communities) are poorly defined (Acreman *et al.* 2008). Such a requirement is needed if fisheries are to be given due consideration in any water resources management assessment and to meet obligations under the WFD.

Fish-based typologies and fish community–based reference conditions have been used in the development of ecological tools for the implementation of the WFD

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(Pont *et al.* 2006, 2007; Melcher *et al.* 2007; Noble *et al.* 2007; Schmutz *et al.* 2007) and in the evaluation of flow and level criteria for the management of hydrological regimes (Cowx *et al.* 2004; Noble *et al.* 2007). In all cases, the fundamental concept is that the appropriate reference community of a site or reach of river (against which appropriate management targets, decisions and legislation could be made) can be predicted using an appropriate suite of abiotic variables. However, whilst typological analysis of fish community structure has revealed the broad fish communities present, the hydrological requirements of each fish species/community are not well understood, and studies have mainly focussed on salmonid fishes (Milner *et al.* 2012a). This study reviews the potential role of 'natural' hydrographical variability on fish life history characteristics and develops a fish typology based on flow preference and conservation importance criteria that can be used to underpin the needs of hydrological management to support these fish community types.

Hydrological drivers of fish recruitment in rivers

Although more than 100 cyprinid and other non-salmonid species are presented in European continental waters, and they represent important fisheries and conservation resources, knowledge about their habitat requirements and the role hydrology plays in regulating fish recruitment is weak compared with salmonids (see Table 1, e.g. of typical information available for UK fish species).

In general, evidence suggests that the 'bottlenecks' to the development/recruitment of non-salmonid fish populations, as with salmonids, relate principally to the presence of, and access to, appropriate spawning sites, to spawning success, and to the growth and survival of newly hatched larvae (Cowx & Welcomme 1998). This is largely because adult fish, especially cyprinids, tolerate a wider range of river conditions, especially flow, than their 0-group life stage. Recruitment success is notably dependent on availability and quality of suitable spawning habitat as well as the hydrological regime, especially around the time of spawning and early life (larval life stages) of the target species.

Non-salmonids are known to migrate considerable distances during the spawning season to access such habitats (Lucas & Baras 2001); thus, similar to salmonids (Milner *et al.* 2012b), any major obstacle on the migration route could prevent access to spawning grounds. This can have serious implications for the reproductive success of the species and can lead to demise in the extant populations. Consequently, if modification of a flow regime reduces the likelihood of upstream migrating fish accessing spawning and nursery areas, this can compromise recruitment and sustainability of the stocks.

An example of such an issue was elucidated by Nunn *et al.* (2008) with respect to recruitment of river lamprey, *Lampetra fluviatilis* (L.), in the Yorkshire River Ouse, UK. River lamprey is an EU Habitats Directive protected species, and thus, it is important to facilitate

Table 1. Habitat preferences and requirements for reproduction of nine UK cyprinids with a wide range of distribution in rivers. R_{50} refers to 50% central range of variable utilisation by species

Species	Depth (cm)	Water velocity (cm s^{-1})	Substratum (∅ mm)	Vegetation	Optimum temperature (°C)
Abramis brama (L.)	variable	<20	>5	*Glyceria*, *Sagittaria*, *Nuphar*	12–20
Barbus barbus (L.)	R_{50} = 14–22	R_{50} = 35–49	R_{50} = 20–50	Absent	>14
Blicca bjoerkna (L.)	Variable	<20	indifferent	Hydrophytes Helophytes	16–25
Cyprnus carpio L.	Variable	<5	Indifferent	Submerged riparian or floodplain veg., *Carex*, *Glyceria*, *Phragmites*	>18
Gobio gobio (L.)		10–80	3–30	Hydrophytes (occasional)	>17
Leuciscus cephalus (L.)	10–30	20–50 R_{50} = 15–75	>5	Hydrophytes (occasional)	14–20
Leuciscus leuciscus (L.)	25–40	20–50	30–250	Hydrophytes, rootwad (occasional)	6–9
Phoxinus phoxinus (L.)	10–25	>20 R_{50} = 25–45	20–100	Absent	
Rutilus rutilus (L.)	15–45	>20 R_{50} = 35–60	50–150	*Fontinalis* moss, *Elodea*, *Salix*, *Scirpus*	14–18

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population recruitment. River lamprey spawns throughout the Ouse catchment but access to important spawning areas is restricted in some tributaries by artificial weirs, especially under low-flow conditions during the spawning migration. This is evident through comparison of length frequency distributions of juvenile (ammocoete) life stages (Fig. 1) from two adjacent tributaries, one with few obstructions (River Swale) and another with several large weirs (River Ure). On the River Swale, clear modes between approximately 20–40 mm (0+ ammocoetes) and 40–65 mm (1+ ammocoetes) and 65–120 mm size ranges were evident. These modes likely correspond to successive year classes (in this case, the 2004, 2003 and 2001 + 2002 year classes). By contrast, on the River Ure, definitive modes were apparent between approximately 20 and 45 mm (0+ ammocoetes), representing the 2004 year class and between 70 and 120 mm (representing the 2001 + 2002 year classes), but recruitment in 2003 was poor (few ammocoetes in the 45–70 mm size range). This failure of recruitment on the River Ure in 2003 was the result of large weirs in the lower reaches impeding upstream migration in 2003 during a period of atypically low spring flows (note flows in 2002 and 2004 were adequate to enabled upstream migration). This shows the importance of maintaining appropriate flows in rivers during critical periods of a fish's life cycle, in this case for lamprey during upstream migration in spring.

River flows also play an important role in determining recruitment success in non-salmonid fishes through direct and indirect interaction, especially at the juvenile life stages (Nunn *et al.* 2003, 2007). Historically, higher than average ambient water temperature in the first year of life was considered responsible for strong cohorts of adult cyprinid fish (e.g. Mills & Mann 1985). However, Nunn *et al.* (2002) indicated that whilst temperature explains much of the variation in year-class strength (YCS), it is not the only influential factor as high temperature does not necessarily yield strong year-classes. Furthermore, years in which a strong year class is prevalent in one species do not necessarily result in strong year-classes in other coexisting species (Nunn *et al.* 2002), suggesting other biotic and abiotic factors are important in regulating recruitment success. It appears that YCS (a surrogate for recruitment) is positively correlated with mean 0-group fish length at the end of the summer, and mean length of 0-group fish at the end of the summer is positively correlated with water temperature (cumulative degree days >12°C) and negatively correlated with river discharge (cumulative discharge days above basal discharge rate) (see Fig. 2). In addition, water temperature was negatively correlated with river discharge. It is also likely that there are 'critical periods' in the first summer of life when fish may be more susceptible to increases in river discharge. For example, YCS of roach and chub is strongly correlated with discharge in the period from June to September inclusive, while YCS of dace was most significantly correlated to discharge in August (Nunn *et al.* 2003). Thus, river discharge (rather than water temperature) appears to be the key factor in determining YCS, either directly (through discharge-induced mortality) or indirectly (via reduced growth at lower water temperatures, discharge-associated increases in energy expenditure or reduced food availability). Indeed, Nunn *et al.* (2007) concluded that water temperature determines potential YCS while discharge determines realised YCS.

These examples demonstrate the importance of river discharge in regulating fish population success in non-

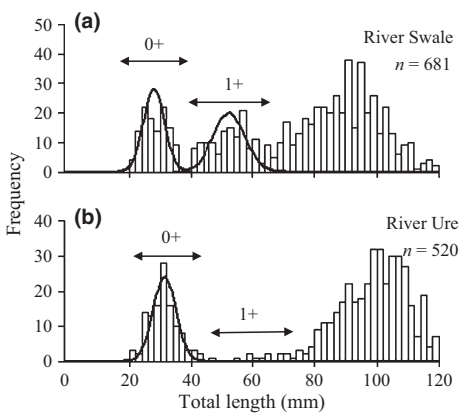

Figure 1. Length distributions of *Lampetra* spp. ammocoetes captured from (a) an unimpounded and (b) an impounded river. The approximate length ranges of the 0+ and 1+ age classes are illustrated (modified from Nunn *et al.* 2007).

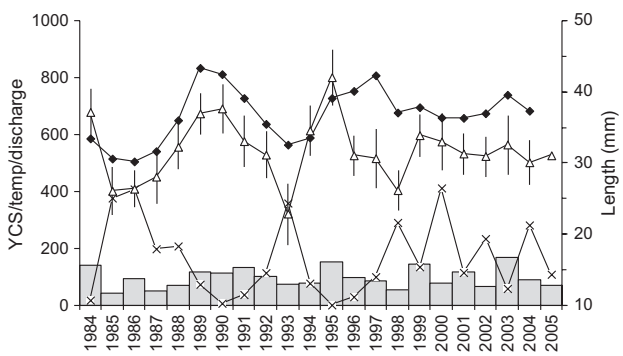

Figure 2. Relationships between roach year-class strength (YCS), water temperature (Temp; cumulative degree days >12°C, April–September inclusive), river discharge [Dis; cumulative discharge days above the basal discharge rate ($m^3 s^{-1} \div 10$), April–September inclusive] and 0+ roach growth [Length; mean fork length (mm ± SD) in September] in the Yorkshire Ouse, 1984–2005 inclusive (modified from Nunn *et al.* 2003).

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salmonid fishes and highlight the need to protect natural flow regimes or elements of the natural flow regime. However, non-salmonid fish species often exhibit highly plastic life-history strategies that proffer potential resilience to modified flow regimes. Nevertheless, to manage flow regimes for multiple species within typical fish communities is problematic, and there is a need to develop a fish community typology that can be used to underpin the needs of hydrological management to support these fish community types. The switch from a typical species-based model to one derived from species grouped into classes based on flow preference and conservation importance allows the typology to be directly related to flow characteristics and to other legislation linked to the conservation of specific species (e.g. salmon). Additionally, the use of guilds based on flow preference also has the potential to overcome the problems presented by the restricted range of some species due to post-glacial distribution factors (Wheeler 1977; Noble *et al.* 2007).

Hydrological regime characteristics of fish community types

The development of the fish community typology and sensitivity rating to flow modification for England and Wales was based on fish community data from Environment Agency (EA) monitoring sites sampled between 2000 and 2005. Overall, more than 12 000 sampling occasions were extracted from the EA's National Fisheries Population Database (NFPD). For all surveys, the number of individuals captured in the first run of the survey was used to determine the relative abundance of each species captured [this was done to allow data from single-run catch-per-unit-effort (CPUE) data and data from multiple-run (depletion) surveys to be used in the same analysis]. All these monitoring sites were fitted to a derived GIS river network for calculation of abiotic catchment and site data following the method of Coley (2003).

Given that factors other than hydrological regime determine the current structure and status of fish communities in British rivers (Cowx *et al.* 2004), the data set was screened in GIS against the EA's General Quality Assessment (GQA) data set, the River Habitat Survey (RHS) Habitat Modification Score (HMS) data set and LowFlow 2000 data. This was done to screen out sites whose fish community structure potentially reflected impacted systems. General Quality Assessment data were available as a GIS river-line data set, and the flow pressure data were available as a GIS waterbody layer. However, RHS data were only available on a site-specific basis. The data for HMS were therefore linked to a river typology-line GIS data set. This was done by spatially joining and averaging the data from sites that were closest to each river line. Four criteria were chosen for retention of sites for use in the typology analysis:

- General Quality Assessment biology class must be class 'C' or better – equivalent to fair or better;
- General Quality Assessment chemistry class must be class 'C' or better;
- Average HMS class score RHS must be <'4.5';
- Flow impact must be within ± 50% at Q95 (all data provided by EA).

The final (calibration) data set after screening comprised monitoring data from 3907 sites across England and Wales.

The fish community types were generated using manual classification of fish community structure based on ecological guilds of their flow preferences (Table 2; Aarts & Neinhuis 2003; Noble *et al.* 2007). The use of a manual classification scheme rather than multivariate techniques was prompted by the recognition that hierarchical cluster analysis is generally inappropriate when using very large data sets (Waite 2000). To do this in a logical way in relation to flow, species data from a calibration data set were analysed using canonical correspondence analysis (CCA; Fig. 3), a multivariate ordination technique, to identify the key environmental variables that relate to changes in the species structure of communities and groups of species that respond in similar ways to the abiotic catchment variables and flow, and are most often associated with each other. The data set was assessed using river slope and width together with flow variables. Flow data, as QN values, were transformed into flow per metre width values to standardise them against the size of the river. Additionally, two flow variables were derived to assess the difference between intermediate flows (QN70), low flows (QN95) and high flows (QN5). These were calculated as simple ratios to give some indication, together with base flow index (BFI), of the variability of flow at a site.

Analysis of the response of relative abundance of species within the fish community to the environmental and flow variables indicated that certain species were associated with each other based on the size of the river, its slope and the flow conditions (Fig. 3). The four groups labelled in Figure 3 relate to:

(A) Rheophilic minor species (stoneloach and minnow).
(B) Rheophilic cyprinids (dace, chub and Gudgeon).
(C) Eurytopic group 'a' (bream, roach, pike and perch).
(D) Eurytopic group 'b' (tench, bleak and silver bream).

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Table 2. Summary of the species/flow guilds used to classify the fish community types for England and Wales

Guild/species	Flow preference	Native species	Comment
Atlantic salmon	Lotic	Salmon, *Salmo salar* L.	Salmonid rheophil but appears to have different habitats/flow preferences to trout
Brown trout	Lotic	Trout, *Salmo trutta* L.	Salmonid rheophil but appears to have different habitats/flow preferences to salmon
Grayling	Lotic	Grayling, *Thymallus thymallus* (L.)	Salmonid rheophil which Huet used to describe a fish zone in European rivers
Rheophilic minor species	Lotic	Stone loach, *Barbatuala barbatula* (L.); Minnow, *Phoxinus phoxinus*	Sampling issues so not directly included in per cent abundance calculations – only used to classify some trout sites
Rheophilic cyprinids	Lotic	Dace, *Leuciscus leuciscus*; Chub, *Leuciscus cephalus*; Gudgeon, *Gobio gobio*	Group of cyprinids that have a high preference for higher flows and gradients than other cyprinids
Barbel	Lotic	Barbel, *Barbus barbus*	Exhibited a different correlation to other lowland species in relation to flow and abiotic characteristics. However, not native to all of England and Wales
Eurytopic 'a'	Lotic/ Lentic	Perch, *Perca fluviatilis* (L.); Pike, *Esox lucius* L.; Roach, *Rutilus rutilus*; Common bream, *Abramis brama*	Lowland river cyprinids. Perch and pike can probably tolerate more flow that roach and bream (see canonical correspondence analysis bi-plot)
Eurytopic 'b'	Lentic/ Lotic	Silver bream, *Blicca bjoerkna*; Tench, *Tinca tinca* (L.); Bleak, *Alburnus alburnus* (L.)	Species which only dominate catches in very large lowland rivers. Note tench are actually classed as a limnophil

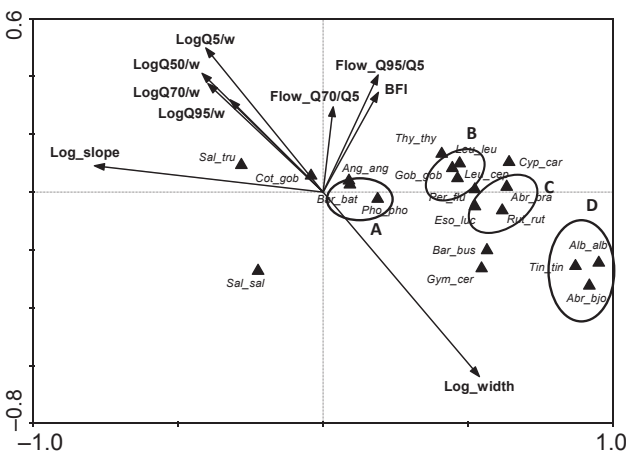

Figure 3. Canonical correspondence analysis bi-plot of species and abiotic flow variables. Arrows indicate environmental gradients which structure species composition. The direction and size of the arrows indicate the direction and size of the effect. All flows were modelled as QN flows. Circles highlight key associations or key individual species.

These groupings broadly followed the community guilds for flow preference presented by Aarts and Neinhuis (2003). This scheme broadly groups species into different rheophilic [all life stages confined to lotic (flowing) water], eurytopic [all life stages can occur in lentic (still) or lotic water] and limnophilic (all life stages confined to lentic waters) guilds. It should be noted, however, that salmon, trout, grayling and barbel (the latter being two other notable rheophilic species) did not appear to fit closely with these four groups of species. Therefore, these four distinctive rheophilic species were used in addition to the four groups to create eight flow guilds/species groups that were used to classify the data set rather than using all species individually. A summary of guild membership is presented in Table 2.

The relative abundance of each species/guild was calculated for each survey in the calibration data set as the abundance of the species/guild divided by the sum of abundance of all the species/guilds used (Table 3). The samples were classified based on the percentage abundance of salmon, trout, rheophilic cyprinids (B), eurytopic 'a', eurytopic 'b', barbel, grayling and rheophilic minor species. Due to the problems associated with the sampling of minor species such as bullhead, minnow and stoneloach, these species were not directly included in the calculations of relative abundance. However, their

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Table 3. Average per cent abundance of each species guild in each of the eight community types

	Fish community type							
	1 n = 896	2 n = 1068	3 n = 155	4 n = 738	5 n = 435	6 n = 426	7 n = 25	8 n = 47
% salmon	81	14	0	0	2	0	0	12
% trout	19	85	79	100	9	2	0	27
% grayling	0	1	1	0	2	0	0	49
% barbel	0	0	0	0	1	0	0	1
% rheo cyp	0	0	10	0	70	19	9	8
% eury_a	0	0	8	0	16	76	35	2
% eury_b	0	0	0	0	0	4	56	0

Table 4. Average values of abiotic characteristics of each of the eight fish community types

	Fish community type							
	1	2	3	4	5	6	7	8
Altitude (m)	117	108	56	137	38	31	29	53
Distance from source (km)	20	13	17	7	32	47	120	38
Slope (m km^{-1})	12.9	15.1	5.8	22.8	3.7	2.3	1.1	4.4
Width (m)	8.7	5.5	6.0	4.4	8.6	14.4	28.3	13.4
Upstream catchment area (km^2)	147	70	111	29	256	732	3312	398
Shreve river order	138	58	66	25	152	289	1145	270
QNmean ML day^{-1}	457.9	232.7	163.5	160.8	342.6	634.7	2980.7	712.3
QN5 ML day^{-1}	1565.8	775.4	515.1	533.8	1120.9	2080.2	9770.0	2197.5
QN50 ML day^{-1}	247.5	129.3	97.1	90.4	190.1	368.7	1778.0	422.7
QN70 ML day^{-1}	138.8	76.4	62.2	53.0	117.7	225.6	1054.6	275.0
QN95 ML day^{-1}	53.1	33.8	33.5	22.3	58.9	121.6	595.3	147.2
Base flow index	0.45	0.48	0.57	0.50	0.51	0.55	0.61	0.66

presence and abundance was used to validate groupings based on other species groups.

Abiotic variables that characterised the monitoring sites were then used in a multivariate discriminant analysis to identify the most appropriate suite of abiotic variables that could be used to predict the fish community typology for any given site/section of a river. The predictive typology was generated using a discriminant analysis model from the key abiotic site and catchment characteristics that were least susceptible to human alteration. These included site altitude (m), catchment area upstream of the site (km^2), river gradient (slope m km^{-1}), distance from source (km), Shreve river order and wetted width (m). Whilst width can be altered by human activity, it was still considered a very important predictor of fish community structure. The abiotic characteristics were log-transformed (log x + 1) and entered in a stepwise approach into a discriminant function analysis. A Wilks' Lambda approach using probability criteria for entry and removal was used (P of <0.05 for entry and >0.10 for removal). Prediction of group membership was not weighted using the original size of the groups as in theory any new site or data set for which predictions are made could have an equal probability of belonging to any group (Noble *et al.* 2007).

Model outputs

Eight major fish community types were identified that broadly followed the classical zonation theory (Huet 1959) with river gradient from upland salmonid to lowland cyprinid communities as follows:

Type 1 samples with >50% trout with salmon the next most common species;

Type 2 samples with >50% salmon and trout as secondary species;

Type 3 samples with >50% trout with rheophilic cyprinids and rheophilic minor species as next most common;

Type 4 samples with only brown trout recorded (validated by the absence of rheophilic minor species);

Type 5 samples with >50% rheophilic cyprinids;

Type 6 samples with >50% eurytopic 'a' species;

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Type 7 samples where eurytopic 'b' was the dominant guild;

Type 8 samples where grayling was dominant.

These river types were fundamentally characterised by different hydrological regimes, in addition to geomorphological conditions prevailing in the river reaches (Table 4). The stepwise discriminant function model retained six catchment/site level variables – catchment size, river slope, width, altitude, distance from source and Shreve river order – and resulted in six functions discriminating the eight fish community types, viz. catchment area, distance from source, slope, altitude, Shreve river order and width. The predicted fish community type for each site is presented in Figure 4. It should be noted that the discriminant model does not predict the community type with any reference to spatial location in England and Wales and as such does not make any reference to, or attempt to deal with, the problems posed by post-glacial distribution of species (Wheeler 1977). As such, the community types predicted are based on the general community structures of England and Wales, and the actual community present may not be that expected based on the habitat conditions, for example, in the north-east and south-west certain cyprinids are not found naturally. Therefore, where habitat might suggest a community type of rheophilic cyprinids, it may still be dominated by salmonids.

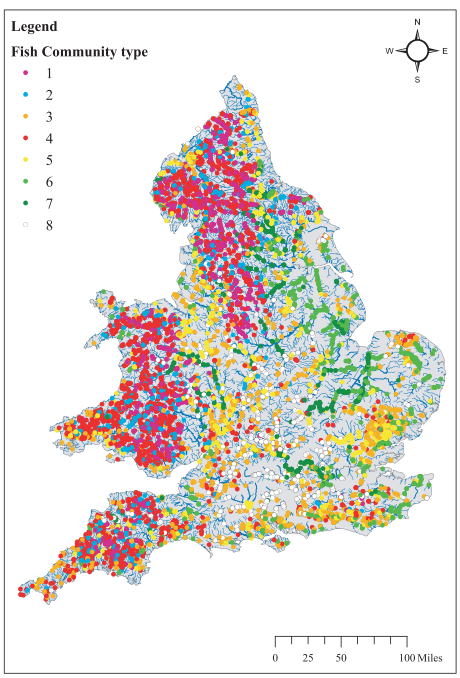

Figure 4. Predicted fish community typology for all EA monitoring sites in England and Wales monitoring database.

Given that the eight fish community types represent the continuum from head water communities to lowland fish communities (plus the grayling community, which was fundamentally associated with groundwater-fed chalk streams) and also a continuum from rheophilic community to eurytopic community, it can be assumed that this will also represent a continuum of sensitivities to the effects of modifying flows, such as abstraction reducing low flows. This is under the assumption that the sensitivity to reductions in flow (discharge) is related to the degree of rheophily exhibited by the community and the type of habitat in which it occurs (ease of altering flow and habitat by abstraction, the relative effect of abstraction size and natural river discharge). As such, salmonid communities (Types 1, 2, 3 and 4) can be said to be the most sensitive to changes in low flows, whilst eurytopic fish communities will be less sensitive to changes in flow as they are more plastic in their flow preferences. Therefore, it follows that the rheophilic cyprinid community type (Type 5) will have an intermediate sensitivity to changes in flow, and the eurytopic groups lower sensitivity. The final grouping (8) contained grayling and was considered, through expert judgment, highly sensitive to abstraction (occurring predominantly in ground water fed rivers). This predictive typology can be applied to hydrological management, in particular abstraction management, by relating the typology and sensitivity rating to abstraction management frameworks. In the context of England and Wales, the typology can be translated into abstraction sensitivity band (ASB) classes, such as that used in the Resource Assessment stage of the Catchment Abstraction Management Strategies framework of the EA (EA 2010). The fish community typology and sensitivity rating was overlaid onto the WFD waterbody network for England and Wales (Fig. 5) to provide a tool for rapid assessment of a potential sensitivity of water bodies to abstraction, hence enabling the application of the most suitable abstraction management strategies

Discussion

Research into the relationships between non-salmonid fish population dynamics and discharge is in its infancy compared with salmonids. Nevertheless, non-salmonids represent the majority of fish species in most river systems across Europe and are characteristic of large lowland rivers, which are typically heavily impacted through river engineering, but more importantly through flow modification by abstraction, flow augmentation and regulation. It is thus critical to include these species or species groups in any flow management scenarios. In particular, it is important to ensure adequate flows are

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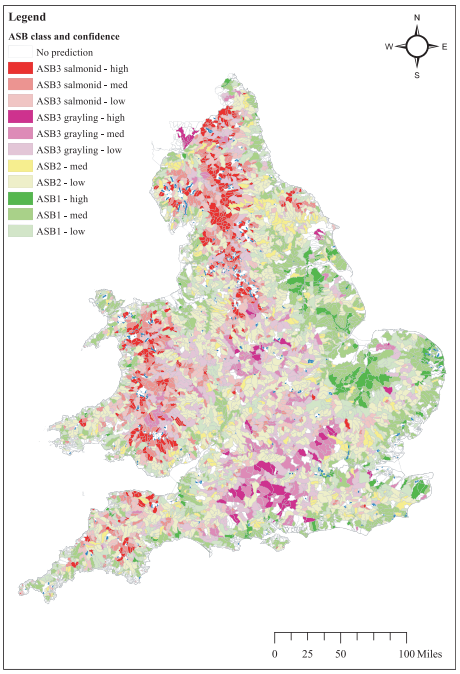

Figure 5. Predicted abstraction sensitivity (ASB) class and confidence level of prediction for each water body and subcatchment.

available to maintain longitudinal connectivity in river systems, and any flow modifications do not compromise recruitment dynamics.

The analysis presented shows that, whilst the species structure of fish community evolves along a continuum from headwaters to lowland river, it is possible to predict what the most likely fish community type is for any given site along this continuum. The link between distinctive fish community types and distinctive flow patterns indicates that it is not only the volume of flow but a combination of volume, rate, extremes and variability of flow that regulated fish community structure and dynamics, and probably population structure through habitat requirements of different life stages. It was concluded that the influence of flow and the potential impacts of abstractions and regulation should be considered within the context of each of the main fish assemblages identified, linking key species per community type to their functional ecology and flow requirements. The relationship between the rate of flow, the rate of change of flow, the duration of high/low flow events and their seasonal timing and their influence over the functioning of fish populations (spawning, recruitment and growth) therefore needs to be considered more fully when evaluating anthropogenic changes to flow patterns and establishing environmental flow regimes.

Whilst the typology presented here provides an approximation of the sensitivities of fish community types to flow regulation, there remain some uncertainties because of gaps in the fisheries or hydrological data, particularly in relation to lowland chalk streams that support salmonid and grayling fisheries. Expert judgment still needs to be used to override these vagaries, until such time as the models can be updated to include more comprehensive fisheries data. The methods now need to be moved forward to identify which components of the hydrograph are critical to discriminating the fish community, and such work is ongoing with cyprinids and fishes of high conservation value in relation to recruitment dynamics (e.g. Nunn *et al.* 2007, 2008).

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