Effects of hydraulic engineering restoration measures on invasive gobies in a large river (Danube, Austria)

David Ramler · Hubert Keckeis

Received: 28 June 2018 / Accepted: 25 September 2019 / Published online: 29 September 2019
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Abstract Invasive gobies can have severe detrimental effects on local fish communities, however, direct methods for population control are often insufficient (i.e. fishing) or not feasible (i.e. poisoning). Indirect methods, such as habitat modifications in the course of restoration programs, appear promising but are poorly studied. In this study, we investigate the effects of different restoration measures on the abundance and occurrence of non-native gobies in the main stem of a free-flowing section of the Danube and attempt to disentangle these measures from general large-scale trends by applying a Before-After-Control-Impact design. We found three invasive goby species (racer, bighead, and round goby) in the sampling area, partly with very high abundances. Four to six years after the installation, the measures had negative (riprap removal), neutral (side arm reconnection), or positive (groyne field adaptations) effects on goby abundances. We conclude that the impact of the measures depends on the type of intervention, is species-specific, and is largely related to substrate composition. Independent from the effect of the measures, abundances of

bighead and round goby dropped in the project and reference sections after the pre-survey. This general decline probably indicates a stabilization phase of the goby populations on a lower level, but may also be influenced by a major flood event. Nevertheless, our results indicate a high potential of shoreline modifications for invasive species control, calling for considering and incorporating them in river restoration programs.

Keywords BACI · Bank restoration · Groyne adaptation · Riprap removal · Side arm reconnection · Side channel construction

Introduction

Since about 3 decades, several goby species (Teleostei: Gobiidae) of Ponto-Caspian origin are spreading over Europe and North-America (Ahnelt et al. 1998; Kornis et al. 2012; Ricciardi and MacIsaac 2000). Today, all major European waterways are invaded by one or more goby species (Borcherding et al. 2011; Kornis et al. 2012; Roche et al. 2013). Rapid dispersal is driven by a mix of long-range introductions via ballast water and active short-range migrations. It is also facilitated by river modifications, such as straightened shores with riprap-reinforced banks (Gozlan et al. 2010; Kornis et al. 2012; Roche et al. 2013).

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10530-019-02101-x>) contains supplementary material, which is available to authorized users.

D. Ramler (✉) · H. Keckeis
Department of Limnology and Bio-Oceanography,
University of Vienna, Vienna, Austria
e-mail: david.ramler@univie.ac.at

While most of the ecological functions of the natural banks were lost, these artificial, largely uninhabited structures match the habitat preferences of many goby species, further promoting their expansion. Different goby species may be dominant in different river stretches based on temporal (e.g. first arrival, duration of invasion) and autecological (e.g. habitat preference, reproduction strategy) traits (Borcherding et al. 2013; Erős et al. 2005; Kováč et al. 2009; Roche et al. 2013). Gobies can reach very high abundances within a very short time after settling and are therefore among the most abundant fishes in many invaded rivers (Borcherding et al. 2011; Loisl et al. 2014; Szalóky et al. 2015). Scientists soon raised concerns about the negative effects on native species (Charlebois et al. 2001; Janssen and Jude 2001; Ricciardi and MacIsaac 2000), although later studies also showed neutral or even positive effects (Janáč et al. 2016; Kornis et al. 2013; Piria et al. 2016; Płachocki et al. 2012). Nevertheless, field observations and laboratory experiments continue to show that local fish populations may be at risk by goby invasions (Brandner et al. 2013; Jermacz et al. 2015; Števo and Kováč 2016; van Kessel et al. 2011). Therefore, the protection of characteristic or endangered fish species also calls for control measures on goby populations (i.e. reduction of abundance) and for preventing new introductions. In heavily used European waterways such as the Danube or Rhine, however, new introductions are virtually unpreventable, and direct interventions on goby abundances are insufficient, costly and labor-intensive, or come at unintentional, high ecological costs (Kornis et al. 2012; N'Guyen et al. 2018).

More promising, but poorly studied, are indirect methods such as habitat modifications in the course of restoration programs (e.g. Dorenbosch et al. 2017). Invasive gobies are opportunistic generalists that can cope with a wide range of ecological conditions, but they also show species-specific preferences for certain habitats (Ahnelt et al. 1998; Borcherding et al. 2013; Didenko 2013; Jakubčinová et al. 2017). Rocky habitats in particular are readily colonized by bighead and round gobies, two of the most widespread invasive species, and the ever increasing proportion of shores stabilized by riprap contributes significantly to their invasion success (Polačik et al. 2008; Ray and Corkum 2001; Wiesner 2005). Consequently, although primarily targeted at promoting native fishes, restoration

measures have also a high potential for limiting the spread and abundance of non-native gobies.

One of the largest river restoration projects in Central Europe is the “Integrated River Engineering Project” (IREP), which will be carried out along the free-flowing stretch of the Danube east of Vienna. The IREP has an inter-disciplinary approach and is designed to integrate improvements for navigation, hydraulic engineering, and ecological restoration (Reckendorfer et al. 2005). A pilot project to test several hydraulic engineering measures is already being implemented. It is accompanied by a large-scale monitoring program including scientific investigations with extensive sampling efforts before and after the measures, incorporating the pilot project section as well as unchanged reference sections. From a fish-ecological point of view, the focus of the pilot project, and the IREP as a whole, is to improve conditions for characteristic and endangered fluvial fish species. Importantly, the sampling design also enables an in-depth examination of general trends of the total fish assemblage and the invasive species pool, as well as autecological characteristics of occurring species.

To our knowledge, this is one of the first studies to simultaneously investigate the effects of several different types of shoreline and river modifications on the occurrence and abundance of invasive species in a large river. Herein, we address the following research questions: Which non-native goby species occur in the study area and how abundant are they? What are their habitat preferences? How does each goby species respond to the different restoration measures? Specifically, we assume [1] that, as invasions are strongly facilitated by artificial banks made of rubble (riprap), measures that are accompanied by an exchange of this substrate type have a higher impact than measures that only change abiotic parameters, such as flow velocity or water depth; and [2] that due to differences in habitat/substrate preference, the restoration measures will have different effects on the respective goby species. The outcome of this study will contribute to the handling options for population control of invasive goby species and serves as a basis for future restoration projects.

Methods

General

Sampling was carried out in the Danube east (downstream) of Vienna, between river kilometers 1893.5 to 1880.5, close to the Slovakian border (Fig. 1). This stretch is a part of the “Alluvial Zone National Park” (Nationalpark Donau-Auen) which is, although impacted by river engineering measures, one of the two last remaining free-flowing sections of the Austrian Danube. Within this stretch, we sampled three sections: the project section near Bad Deutsch-Altenburg in which the restoration measures of the pilot project of the IREP were implemented and two reference sections near Witzelsdorf and Hainburg. Sampling took place before the measures in 2006/07 (termed “pre-survey”), shortly afterwards in 2014/15 (“post-survey 1”), and again in 2017 (“post-survey 2”). Sampling periods extended from March to December, each section being sampled twice a month from March to May and once a month afterwards. The initially designated reference section in Witzelsdorf

had to be changed due to unforeseeable water engineering emergency measures within this section shortly after the pre-survey. Nonetheless, samples taken at the same time during a 3-month period show that the mesohabitats in both references are similar enough (e.g. regarding choriotope structure, abiotic parameters, species composition) to be combined (see also Loisl et al. 2014). Accordingly, overlapping months were treated as replicates.

Mesohabitats and restoration measures

We assigned river stretches to five a priori defined characteristic mesohabitat types: riprap, groynefield, gravel bar, side arm, and side channel. They were classified visually based on structural and hydromorphological conditions of the shoreline and are the basis of the sampling design and comparisons. All mesohabitat types were represented at least once in each section.

The restoration efforts of the pilot project span over 3 km and included four river engineering measures with a modified length ranging from ca. 500 to 1200 m (Table 1; see also Reckendorfer et al. 2005): [1] groyne adaptation I: side channel formation by removing the inshore parts of a groynefield section and constructing a gravel island; [2] groyne adaptation II: groynefield adaptation by cutting groynes at their roots to enable a bank-side flow, lowering the groyne height and declinant positioning; [3] bank restoration: removal of riprap and new construction/extension of a gravel bar; [4] side arm reconnection: reconnection of a former side arm to the main stem of the Danube. The first two measures may be seen as two types of groynefield adaptations of different intensity: the flow velocity is increased in both concerned mesohabitats, but in one (measure 1) also the substrate is changed to more natural conditions (from riprap to small stones and finer substrate), while the other (measure 2) remains highly artificial.

The mesohabitats sampled as side arms in the reference were bay-like remnants of former inlets of now disconnected side arms and were characterized by lentic conditions. Thus, they correspond to the side arm in the project section prior to reconnection. Generally, the mesohabitat types that were sampled as references always correspond to the mesohabitats in the project section before the measure have been implemented (Table 1). In addition to the

Fig. 1 Sampling area of the pilot project of the Integrated River Engineering Project. **a** Map of Austria with black rectangle indicating sampled section. **b** Sampling area with pilot project and reference sections. Arrows indicate direction of flow. **c** Close-up of the project section showing the location of the measures (see text for details). The numbers indicate the river kilometer; shades of blue water depth

Table 1 Evaluated measures and sampling effort

Measure	Mesohabitat before	Mesohabitat after	Modified length (m)	Project section			Reference section			
				PRE	POST1	POST2	PRE	POST1	POST2	
<i>Wading electrofishing—littoral zone</i>										
[1] Groyne adaptations I	Groynefield	> Side channel	500	12	11	12	24/6	6/22	0/24	
[2] Groyne adaptations II	Groynefield	> Mod. groynefield	500	12	12	12	24/6	6/22	0/24	
[3] Bank restoration	Riprap	> Gravel bar	800	12	12	12	12/3	3/12	0/12	
[4] Side arm reconnection	Lentic side arm	> Lotic side arm	1200	12	12	12	12/3	3/12	0/12	
<i>Longline sampling—benthic zone</i>										
[2] Groyne adaptations II	Groynefield	> Mod. groynefield	500	11	9	12	22/6	3/12	0/24	
[4] Side arm reconnection	Lentic side arm	> Lotic side arm	1200	11	12	12	7/3	3/13	0/12	

The mesohabitat sampled in the reference section always corresponds to the mesohabitat in the project section before the measure was implemented. Modified length gives the approximate length of the modified river stretch for each measure. Sampling effort is expressed as the number of temporal replicates (i.e. sampling dates) for each survey. Sampling effort in the reference is given in the order Witzelsdorf/Hainburg (see text for further details). PRE—pre-survey in 2006/07; POST1—post-survey 1 in 2014/15; POST2—post-survey 2 in 2017

mesohabitats used for the analyses of the restoration measures, we have also sampled additional (unmodified) mesohabitats in the project and reference section to address more basic general questions like, for instance, habitat preferences of gobies.

Sampling

Fishes were caught using wading electrofishing and longline sampling. Electrofishing is a reliable and often used method for sampling the inshore fish coenosis (littoral zone), while longline sampling targets offshore, bottom-dwelling fishes (benthic zone; Kubečka et al. 2012; Loisl et al. 2014). The fish monitoring program of the pilot project also included electrofishing from a boat but, due their benthic life style, gobies were only rarely caught with this method (ca. 1% of total goby catch), impeding any detailed analyses. Electrofishing was carried out in all five mesohabitats in each section using stationary electrofishing equipment (3 kW, 300/500 V, 13/9 A; EL62II Hans Grassl GmbH). Mesohabitats were divided in five transects of 20 m length, which were treated as replicates. Longlines were laid in three mesohabitat types in each section (groynefield, gravel

bar, side arm). Longline sampling was not applicable in the riprap mesohabitats due to very high flow velocities, which dislocated the lines, as well as in the side channel due to low water levels. Each longline was approximately 50 m long, with one hook on a trace every meter. We used hooks of sizes 4, 6, and 8, baited with worms or maggots. Lines were laid in the morning and remained in the water overnight (mean exposure time 22.0 ± 1.6 h). All caught fish were measured (total length) to the nearest millimeter, identified at species level, and released again (see also Loisl et al. 2014; or Ramler and Keckeis 2018 for details on sampling methods).

Throughout all surveys, we measured water temperature and conductivity and estimated the choriotope structure (electrofishing only). To better characterize the mesohabitats, we calculated a relative water temperature, which we defined as the difference of the water temperature measured by us within a mesohabitat and the daily mean water temperature measured at a hydrological station. During the post-surveys, we also measured water depth and flow velocity (electrofishing only). Additional information on water level, discharge, and water temperature of the Danube was provided by the federal waterway

operator (viadonau) from the nearest hydrological stations in Wildungsmauer and Hainburg.

Data analysis

To assess the sediment composition, the choriotope structure was estimated following Moog et al. (1999). In order to determine if this structure truly corresponds to the mesohabitat types, we visually compared the proportions of choriotope types for all sections and sampling years and performed principal component analyses (PCA), also including other abiotic parameters. For details on PCAs and further analyses concerning choriotope structure see Online Resource 1.

All abundance data were standardized to catch-per-unit-effort (CPUE) values by dividing the number of caught fish by the sampling duration. For the statistical analyses, abundance data were normalized by the log-transformation $b = \log(x + d) - c$, in which x is the original CPUE value, d a decimal constant, and c a constant indicating the order of magnitude (following McCune et al. 2002). Size data was normalized by a square root transformation. For better interpretation, untransformed data are shown in the figures.

To disentangle the effects of the measures from general large-scale trends, we used a Before-After-Control-Impact design (BACI; Smith 2002) in which we compared mesohabitats in the project section before and after the measures and against the corresponding mesohabitats in a reference section. To analyze the overall effect of the measures and abiotic parameters on goby abundance we conducted a general linear model with the log-transformed CPUE values of all three goby species as response variables, *section* (project vs reference section), *survey* (pre- vs post-surveys), and *mesohabitat* (riprap, groynefield, gravel bar, side arm, side channel) as factors, *discharge* and *water temperature* as covariates, and *sampling month* as a random variable. Furthermore, general linear models were conducted for each measure using the log-transformed CPUE values of all three goby species as response variables, *section* and *survey* as factors, and *sampling month* as a random variable. An additional general linear model was conducted to analyze the effect of the measures on goby size in the littoral zone, with square root-transformed total lengths of bighead and round goby as response variables and *section* and

survey as factors. Statistical significance of the effects of the respective measures on goby abundance or size are revealed by the interaction term *section* x *survey* (Mahlum et al. 2018). The level of significance was set at 5%. Statistical analyses were conducted using IBM SPSS Statistics 23 (© IBM Corporation, Armonk, NY).

Results

General

All mesohabitat types showed a characteristic and consistent composition of choriotope classes (Online Resource 1), irrespective of section and sampling year. A gradient of decreasing grain size is apparent from ripraps to groynefields to gravel bars. Side arms and side channels shared many similarities, in particular a high proportion of sand, mud, and soil; they also had the highest amounts of macrophytes and deadwood of all mesohabitat types. Side channels were, however, more strongly correlated to stony substrates than were side arms. In the project section, average water temperature values dropped substantially in the side arm after the reconnection, due to the flowing conditions. The groyne modifications led to increased variability in water temperature and partially also in conductivity (Online Resource 2). Among the mesohabitats, high flow velocities were found in gravel bars and ripraps, the lowest in side arms. Lowest relative water temperatures were measured in ripraps.

Three invasive goby species were caught: racer goby *Babka gymnotrachelus* (Kessler, 1857), bighead goby *Ponticola kessleri* (Günther, 1861), and round goby *Neogobius melanostomus* (Pallas, 1814). Round and bighead goby were found in very high numbers (up to 4 individuals per minute), especially during the pre-survey (Fig. 2). For each sampling year and method, they comprised between 23 and 54% of the total catch and more than 96% of the total catch of non-native species. Round and bighead gobies were and are among the most abundant fishes in the sampling area. Only one native species, the bleak *Alburnus alburnus*, was caught more often (Ramler and Keckeis 2018). Another member of the Gobiidae was the tubenose goby *Proterorhinus semilunaris* (Heckel, 1837), which is native in this part of the Danube (Ahnelt 1988) and is therefore not further discussed here. Bighead and round

Fig. 2 Changes of goby abundance throughout the surveys. **a** Total abundances across all mesohabitats for all goby species in the littoral (green, upper diagram) and benthic zone (yellow, lower diagram). **b** Changes in abundance and composition of

goby showed substantial declines in both sampling methods in post-survey 1 compared to the pre-survey (Fig. 2). This decline is expressed in the project and reference sections and constitutes the sharpest decrease in numbers of all occurring fish species. Bighead goby abundances increased slightly again in post-survey 2, while round goby abundances continued to drop, although at much lower rates. Racer goby abundance was generally low and remained constant through all surveys. In round and racer goby, changes in abundance were reflected in all size classes. In bighead goby, however, the size classes declined or increased disproportionally. As a result, medium-sized fishes constituted 90% of the total catch of bighead gobies in the latest survey in contrast to a more balanced size distribution in the pre-survey (Fig. 2b).

All gobies showed distinct preferences for certain mesohabitats (Online Resource 3). Round and bighead goby primarily utilized mesohabitats with coarse substrate (riprap and groynefields), while racer goby used mainly mesohabitats characterized by fine sediment (side arm and side channel). The proportion of round gobies in the benthic zone was between 10 and 20% higher compared to the littoral zone (Online Resource 4A).

In the littoral zone, discharge had a significant effect on overall abundance for all goby species. This also applies to water temperature, with the

different size-classes of gobies. PRE—pre-survey in 2006/07; POST1—post-survey 1 in 2014/15; POST2—post-survey 2 in 2017

exception of racer goby. No significant effect of discharge or water temperature was found in the benthic zone (Table 2). Also sampling month had a significant effect on overall goby abundance in the littoral zone, but only for bighead goby in the benthic zone (Table 2). The effect of sampling month within the measures was, however, highly variable (Table 3).

Effects of restoration measures

The four restoration measures had different effects on goby abundances (Figs. 3, 4). Generally, the groyne adaptations (measures 1 + 2), showed similar developments in abundance in the benthic and littoral zone. Contrary to the substantial decline in the reference section, the abundances of all goby species were on a comparable level during the pre-survey and post-survey 2 in measure 1 (side channel) and 2 (modified groynefield). However, all goby species had their lowest abundances during post-survey 1 in measure 1; bighead goby also in measure 2. A significant interaction term (section x survey) was found for both measures for round goby in the littoral zone (Table 3). The bank restoration (measure 3) was followed by decreased abundances for bighead and round goby. Significantly lower abundances compared to the reference and a significant interaction term were,

Table 2 Results of the general linear models for the total effect of the measures on goby abundance in the littoral (wading electrofishing) and benthic zone (longline sampling), using log-transformed CPUE values as response variable, mesohabitat, section, and survey as factors, discharge and water temperature as co-variables, and sampling month (time) as a random variable

Method	Regression coefficient	Racer goby				Bighead goby				Round goby			
		F	df	h ²	P	F	df	h ²	P	F	df	h ²	P
Littoral zone	Intercept	3.587	1 (266)	0.013	0.059	0.000	1 (266)	0.000	0.983	4.084	1 (266)	0.015	0.044*
	Discharge	9.254	1	0.034	0.003**	16.063	1	0.057	< 0.001***	44.684	1	0.144	< 0.001***
	Water temperature	0.019	1	0.000	0.890	22.299	1	0.077	< 0.001***	12.612	1	0.045	< 0.001***
	Time	2.168	1	0.068	0.025*	11.600	9	0.282	< 0.001***	6.532	9	0.181	< 0.001***
	Mesohabitat	4.680	1	0.066	0.001**	7.315	4	0.099	< 0.001***	18.473	4	0.217	< 0.001***
	Section	0.080	1	0.000	0.778	2.936	1	0.011	0.088	4.446	1	0.016	0.036*
	Survey	6.300	1	0.045	0.002**	31.457	2	0.191	< 0.001***	0.302	2	0.002	0.740
	Section x mesohabitat	10.027	1	0.070	< 0.001***	6.933	2	0.050	0.001**	15.591	2	0.105	< 0.001***
	Survey x mesohabitat	0.695	1	0.018	0.676	3.224	7	0.078	0.003**	2.488	7	0.061	0.017*
	Section x survey	0.494	1	0.004	0.611	1.763	2	0.013	0.174	14.439	2	0.098	< 0.001***
Benthic zone	Section x survey x mesohabitat	1.635	1	0.012	0.197	0.338	2	0.003	0.714	4.836	2	0.035	0.009**
	Intercept	1.299	1 (139)	0.009	0.256	2.312	1 (139)	0.016	0.131	0.841	1 (139)	0.006	0.361
	Discharge	0.114	1	0.001	0.736	0.449	1	0.003	0.504	2.834	1	0.020	0.095
	Water temperature	0.746	1	0.005	0.389	0.461	1	0.003	0.498	0.295	1	0.002	0.588
	Time	1.789	9	0.104	0.076	3.701	9	0.193	< 0.001***	0.499	9	0.031	0.873
	Mesohabitat	2.907	2	0.040	0.058	5.543	2	0.074	0.005**	11.745	2	0.145	< 0.001***
	Section	0.104	1	0.001	0.748	2.428	1	0.017	0.121	13.593	1	0.089	< 0.001***
	Survey	26.986	2	0.280	< 0.001***	4.322	2	0.059	0.015*	0.596	2	0.009	0.552
	Section x mesohabitat	0.137	1	0.001	0.711	0.760	1	0.005	0.385	2.141	1	0.015	0.146
	Survey x mesohabitat	5.487	2	0.073	0.005**	0.965	2	0.014	0.384	1.340	2	0.019	0.265
Section x survey	0.740	2	0.011	0.479	3.885	2	0.053	0.023*	1.250	2	0.018	0.290	
	Section x survey x mesohabitat	0.002	1	0.000	0.963	1.299	1	0.009	0.256	0.197	1	0.001	0.658

The degrees of freedom (*df*) in brackets in the row of the intercept are the *df* for the Error. Asterisks indicate level of significance: *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$

Table 3 Results of the general linear models for the effect of each measure on goby abundance in the littoral (wading electrofishing) and benthic zone (longline sampling), using log-transformed CPUE values as response variable, section and survey as factors, and sampling month (time) as a random variable

Method	Regression coefficient	Racer goby			Bighead goby			Round goby			Effect	P	Effect	P	Effect	
		F	df	η^2	P	Effect	F	df	η^2	P						Effect
Littoral zone	Measure 1: Groyne adaptations I															
	Intercept	21.745	1 (99)	0.657	0.001***		32.229	1 (99)	0.775	< 0.001***		64.746	1 (99)	0.869	< 0.001***	
	Time	1.886	9	0.146	0.063		11.035	9	0.501	< 0.001***		5.738	9	0.343	< 0.001***	
	Section	15.625	1	0.136	< 0.001***	↑	3.425	1	0.033	0.067	–	4.859	1	0.047	0.030*	
	Survey	3.150	2	0.060	0.047*	↑	22.215	2	0.310	< 0.001***	↓	8.613	2	0.148	< 0.001***	
	Section x Survey	1.522	2	0.030	0.223	–	2.960	2	0.056	0.056	–	7.514	2	0.132	0.001*** (†)	
	Measure 2: Groyne adaptations II															
	Intercept	43.768	1 (101)	0.729	< 0.001***		51.598	1 (101)	0.847	< 0.001***		95.408	1 (101)	0.906	< 0.001***	
	Time	0.555	9	0.047	0.831		10.824	9	0.491	< 0.001***		4.230	9	0.274	< 0.001***	
	Section	8.681	1	0.079	0.004**	↑	0.731	1	0.007	0.395	–	0.040	1	0.000	0.842	
	Survey	2.305	2	0.044	0.105	–	34.706	2	0.407	< 0.001***	↓	5.270	2	0.094	0.007***	
	Section x Survey	2.350	2	0.044	0.101	–	0.885	2	0.017	0.416	–	4.223	2	0.077	0.017* (†)	
	Measure 3: Bank restoration															
	Intercept	12.592	1 (63)	0.556	0.005**		53.960	1 (63)	0.853	< 0.001***		76.001	1 (63)	0.889	< 0.001***	
	Time	0.803	9	0.103	0.615		2.570	9	0.269	0.014*		1.812	9	0.206	0.083	
	Section	0.234	1	0.004	0.630	–	0.426	1	0.007	0.516	–	7.356	1	0.105	0.009**	
	Survey	4.521	2	0.126	0.015*	↑	41.900	2	0.571	< 0.001***	↓	7.904	2	0.201	0.001***	
	Section x Survey	0.693	2	0.022	0.504	–	0.472	2	0.015	0.626	–	3.251	2	0.094	0.045* ↓	
	Measure 4: Side arm reconnection															
	Intercept	20.052	1 (63)	0.680	0.001**		32.555	1 (63)	0.777	< 0.001***		58.482	1 (63)	0.860	< 0.001***	
	Time	1.894	9	0.213	0.069		2.480	9	0.262	0.017*		1.673	9	0.193	0.114	
	Section	6.217	1	0.090	0.015*	↓	9.218	1	0.128	0.003**	↓	28.370	1	0.310	< 0.001***	
	Survey	0.099	2	0.003	0.906	–	4.459	2	0.124	0.015*	↓	1.434	2	0.044	0.246	
	Section x Survey	0.752	2	0.023	0.476	–	1.098	2	0.034	0.340	–	14.523	2	0.316	< 0.001*** (↔)	

Table 3 continued

Method	Regression coefficient	Racer goby			Bighead goby			Round goby			Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P	η^2	Effect	P
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The degrees of freedom (*df*) in brackets in the row of the intercept are the *df* for the Error. Asterisks indicate level of significance: *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$. Arrows indicate if overall abundances were higher/lower in the pilot project section compared to the reference (Section); if overall abundances increased/decreased during the post-surveys compared to the pre-survey (Survey); or the general effect of the measure on goby abundance (Section x Survey)

Fig. 3 Abundances of invasive gobies before and after restoration measures 1 and 2 in the littoral (green, left diagrams) and benthic zone (yellow, right diagrams). In measure 1 the former groynefield was converted to a gravel island with a side channel behind it; in measure 2 the groynefield was only modified. Black line—median; whiskers—25/75 quartiles; dots—5/95 percentiles. PRE—pre-survey in 2006/07; POST1—post-survey 1 in 2014/15; POST2—post-survey 2 in 2017. M1/M2—measure 1/2 implemented in the project section (light); REF—reference sections (dark)

however, only found for round goby, but not for bighead goby. The numbers of racer goby were low before and after the measures, without significant changes (Fig. 4). The effects of the side arm reconnection (measure 4) on goby abundances was generally minimal. Abundances of all three goby species were low or zero in the littoral and benthic zone before

and after the reconnection. An exception is the racer goby which showed relatively high abundances during the pre-survey in the benthic zone. Significant interaction terms were found for round goby (littoral) and bighead goby (benthic; Table 3). Goby abundances were generally higher in the reference side arm, especially during the pre-survey, resulting in

Fig. 4 Abundances of invasive gobies before and after restoration measures 3 and 4 in the littoral (green, left and middle diagrams) and benthic zone (yellow, right diagrams). In measure 3 the former riprap section was replaced by a gravel bar; in measure 4 a former side arm was reconnected to the main

stem. Black line—median; whiskers—25/75 quartiles; dots—5/95 percentiles. PRE—pre-survey in 2006/07; POST1—post-survey 1 in 2014/15; POST2—post-survey 2 in 2017. M3/M4—measure 3/4 implemented in the project section (light); REF—reference sections (dark)

significant differences between sections in most cases (Fig. 4, Tables 2, 3).

The effect of the measures on size was variable (Fig. 5, Online Resource 5). For bighead goby a

significant interaction term was found for groyne adaptation I and the side arm reconnection (measure 1 + 4) and for round goby for groyne adaptation I and the bank restoration (measures 1 + 3). It is apparent

Fig. 5 Size distribution of bighead and round goby before and after the measures in the littoral (green, upper diagrams) and benthic zone (yellow, lower diagrams). Abundances in the project zone (left, lighter colors) are mirrored by the

corresponding abundances in the references section (right, darker colors) of each survey. PRE—pre-survey in 2006/07; POST1—post-survey 1 in 2014/15; POST2—post-survey 2 in 2017

that smaller round gobies used the side channel during the post-surveys and also the former groynefield during the pre-survey compared to the reference groynefields. The same may be true for the new gravel bar and the reconnected side arm, however, simultaneously also abundances decreased drastically. In bighead goby, the size distribution patterns remained generally similar to the references.

Discussion

Our study showed that shore restoration measures can be used to limit goby abundances. It depends on the type of measure, though; some measures may also foster goby populations. Restoration projects should therefore carefully consider which measures are implemented. If the goal is to reduce goby abundances, the projects must ensure that an extensive multi-annual monitoring of treatment and reference sections is realized, in order to be able to correctly judge the effectiveness of the measure(s).

General

Independent of the restoration effects (discussed below), we found a strong general decline in goby abundance in the project and reference sections. There are several potential causes for this decline, which probably also act in combination. First, it may indicate that the population boom following the successful invasion of this part of the Danube in the 1990s is over. Gobies rapidly reproduce and may colonize entire rivers and lakes very soon after the first occurrence (e.g. summarized for round goby in Kornis et al. 2012). In many cases, one or more invasive goby species were among the most common fishes of a given water body within a few years (Borcherding et al. 2011; Jurajda et al. 2005; Szalóky et al. 2015; Wiesner 2005). Due to their sheer numbers and biomass, gobies are not only competitors to native species, but also constitute a potential new food source. Recent research has shown that native predatory species are able to adapt and shift their diet in favor of the ubiquitous gobies, possibly also

limiting/controlling their spread and abundance (Hempel et al. 2016; Mikl et al. 2017; Płachocki et al. 2012; Reyjol et al. 2010). Secondly, discharge, and thus the available volume of water, has an effect on the catchability of fishes and therefore influences abundance estimates (e.g. Ramler et al. 2016; Speas et al. 2004). During the pre-survey sampling, the average discharge was lower than at the post-surveys. It is highly improbable, though, that this difference in discharge and water level is the sole cause for the drastic reduction in numbers (up to – 90% reduction in mean CPUE in post-surveys). Furthermore, the decline is also apparent in the benthic zone (up to – 95%), which are not or less affected by discharge (Table 2). Lastly, an extreme flood event in June 2013 (i.e. the year before post-survey 1) in the Upper Danube Basin may have had an impact on gobies. This flood event, with a maximum discharge of ca. $11,000 \text{ m}^3 \text{ s}^{-1}$ (measured in Vienna), was the most severe flood since centuries (Blöschl et al. 2013), therefore it is plausible that it affected goby (and other species) abundances. The actual response of the fish community to floods is, however, ambiguous (Piniewski et al. 2017). Several studies reported that non-native species showed the most negative response to floods, which is usually explained by a lack of adaptation to flood regimes (Deboer et al. 2011; Piniewski et al. 2017). The non-native species in these studies were primarily salmonids, though. Furthermore, the native range of most invasive gobies also comprised running waters (e.g. Lower Danube, Prut, Siret, Dnieper; Roche et al. 2013), thus, they should not be completely naïve to floods, although this would also depend on where the invasive founding populations originate from. On the other hand, species like burbot (*Lota lota*), gudgeons (Gobioninae), or sculpins (*Cottus* spp.), which share many habitat preferences with round and bighead gobies (i.e. benthic, rocky habitats), were found to be not affected by floods or even increased in abundance afterwards (Deboer et al. 2011; Jurajda et al. 2006). Less is known on the effect of floods on early developmental stages, which appears to be also very variable and species-specific (Jurajda et al. 2006; Piniewski et al. 2017). There is indication that gobies react to perturbations by adapting life-history-traits, for instance by increasing oocytes number (Hôrková and Kováč 2015). Furthermore, due to their generally high fecundity, gobies should be able to rapidly compensate population

losses. At least for round goby, this was not the case. Accordingly, we suggest that the major flood event was not the main cause for the decline.

Overall, we consider our findings on the general trend of goby abundances to primarily reflect a stabilization on a lower level due to an adaptation of the local fauna (Ramler and Keckeis 2019). Nonetheless, round and bighead goby are still among the most abundant fishes in the sampling area. In any case, our results highlight the importance of a sampling design with reference sections: in the present case, the absence of such a section would have yielded an incorrect interpretation (overestimation) of the effects of the measures.

Effects of restoration measures

The restoration measures did have an effect on goby occurrence and abundances, ranging from positive, to neutral and negative. The effectiveness was partly species-specific and also linked to the mesohabitat types involved, which were found to be suitable units for analyzing and assessing restoration effects. Although the two groyne field adaptations differed in intensity, the effect on the goby community was surprisingly similar. The removal of large parts of the former groynes and the installation of a gravel island (measure 1) led to a drop of inshore abundances of all gobies during post-survey 1. In post-survey 2, however, numbers quickly recovered to equal or even higher magnitudes than during the pre-survey. This could be linked to the flood event in 2013 (see above), on the other hand, this measure was also the last one finished, with the first sampling date of post-survey 1 shortly afterwards. Conceivably, the lower abundances during post-survey 1 may be influenced by shorter colonization possibilities of the modified habitat. Adapting the groynes by cutting the roots and changing the height and position (measure 2) had almost no effect on goby abundance. Also, the size distribution patterns in the project and reference sections were similar in bighead and round gobies throughout all surveys. Apparently, adapting groynes is not a suitable measure to decrease goby abundances, irrespective of intensity. A significant interaction term was only found for round goby, which is, however, primarily due to decreased abundances in the reference section during the post-surveys. Gobies may thus even benefit from these measures. This is surprising

because side channels can be regarded as intermediate between side arms and gravel bars (concerning abiotic parameters), which are both habitats not preferred by bighead and round gobies. Thus, at least the side channel construction (measure 1) was expected to have a profound impact on them due to the change in substrate composition. However, abundances in a side channel sampled in the reference section were much lower (see also Online Resource 3). This difference of goby abundances in side channels is probably influenced by larger-scale factors such as different types of upstream habitats. In gobies, most dispersal is probably directed downstream, especially during the drift of early life stages, which is known to be an important dispersal mechanism in gobies (Borcherding et al. 2016; Janáč et al. 2013; Ramler et al. 2016). Accordingly, the higher abundance of gobies in the project section may be due to a higher upstream stock of gobies. Our interpretation is that side channels are not preferred habitats of gobies per se, but that goby abundances in this mesohabitat are also influenced by upstream habitat conditions.

Converting a riprap to a gravel bar (measure 3) is an appropriate method to reduce the abundance of round gobies. In fact, although all measures had a significant effect on round goby abundance in the littoral zone, this measure was the only one that led to an actual decrease in numbers. Abundances of all three goby species were low or zero in gravel bars during all surveys and all size classes, however, no significant differences between the project and reference section were found for racer and bighead goby. This is because racer gobies were only rarely found in ripraps at all, and the abundances of the latter dropped in this mesohabitat type during the post-surveys in both sections. The reason for this declining trend in bighead gobies is unclear because ripraps are actually readily utilized, often with equal or even higher abundances than round goby (e.g. Borcherding et al. 2011; Janáč et al. 2018). Possible explanations would be increased competition with round goby or increased (and selective) predation, driving bighead gobies to sub-optimal habitats. Nevertheless, if the shift in habitat preference is neglected, this measure appears to be also suitable to limit the abundance of bighead gobies.

In the pilot project section, goby abundances in the side arm were low or zero before and after the reconnection (measure 4), although abundances (in the littoral zone) slightly increased again during post-

survey 2. This is probably caused by the higher connection of the reconnected side arm with source habitats in the main stem; nonetheless, median abundances were zero for all goby species throughout all surveys. Side arms are avoided by larger bighead and round gobies individuals (although this habitat seems attractive for small individuals; Fig. 5, Online Resource 4B), irrespective of flow conditions, probably due the high amount of fine substrate or macrophytes cover. Racer gobies are known to cope well with the conditions in side arms (Didenko 2013; Jakubčinová et al. 2017; Kakareko et al. 2016) and also showed a preference for this habitat type in the study area regardless of size. This species is far less abundant than the other two gobies in the sampling area and the Upper and Lower Danube in general, which is also linked to its preference for habitats that have become rare (e.g. muddy, vegetated shores; Jakubčinová et al. 2017). Accordingly, it is only of marginal ecological concern. The abundances of all gobies were higher in side arms of the references compared to the pilot project section, especially during the pre-survey. The higher abundances are probably linked to the higher habitat diversity of the reference side arms, which also include parts of the shore stabilized with riprap, making this mesohabitat attractive for all goby species. While abundances remained low in the project section, without any apparent effect of the measure, abundances dropped to low or moderate levels in the reference.

Significant effects of the measures on mean sizes revealed a clear pattern in round goby. Only very small individuals (at or below 5 cm) were found in the side channel and gravel bar (measures 1 + 3) in the project section during both post-surveys and also in the reconnected side arm (measure 4, though without significance in this case). Therefore, although these mesohabitats may be used as nursery habitats, they do not constitute appropriate habitats for older, or rather, larger individuals of round goby (anymore), which are only found in groynefields and ripraps. The high numbers of small round gobies in the side channel may also lead to enhanced recruitment in adjacent areas. In contrasts, the effect of the measures on bighead goby was less consistent. Sizes of bighead gobies tended to increase in both sections during the post-surveys. The significant interaction terms found for bighead goby are probably based on small differences (without biological significance) that were detected because of

the high number of observations. Generally, the size distribution pattern in the pilot project mirrors that of the reference and are thus not indicating an effect of a measure. It is striking that almost exclusively medium sized bighead gobies (5–10 cm) were caught during the post-surveys, especially during post-survey 2, in both sections (Fig. 2b). Apparently, recently hatched bighead gobies must have settled in unsampled habitats. As we sampled a large variety of habitat types, the most likely explanation is a shift to deeper waters, which were inaccessible to wading electrofishing and, due to the small fish size, not effectively sampled by longlines. This shift may reflect increased competition with small round gobies, or size-dependent predation (Płachocki et al. 2012; Všeticková et al. 2018). Interestingly, Borcharding et al. (2011) and Didenko (2013) also found very few or no small individuals of bighead gobies in samples from the Rhine and Dnieper, respectively. Young gobies are frequently found in the drift, but only in a narrow size range, with most individuals drifting between 6 and 8 mm (Borcharding et al. 2016; Ramler et al. 2016). Larger young fish apparently settle in unknown habitats and reappear later. The whereabouts of young bighead gobies remains obscure, although the findings from the pre-survey suggest that the habitat shift is a relatively recent phenomenon.

Conclusions

Our study demonstrated that analyzing the effects of hydro-engineering measures for restoration requires intensive, large-scale monitoring efforts, even when focusing on a small group of fishes. Incorrect assessments of measures arise from the omission of reference sections and also a too early cessation of sampling may lead to misleading conclusions. Furthermore, general population trends may mask the effect of restoration efforts.

Our results largely support our assumptions that the restoration measures had different effects on gobies depending on type of measure and species. Bank restoration, by replacing a riprap with a gravel bar, was found to be the most suitable measure to lower the abundance of round and likely also bighead gobies. The side arm reconnection had little effect on gobies, however, abundances were generally low before and after the measure. Both measures can therefore be

recommended without restriction. Groyne adaptations, on the other hand, were unable to limit goby abundances and may even be beneficial for gobies, and can thus not be recommended in cases where high goby abundances are deemed problematic.

The effect on invasive species is only one element in judging restoration success, which needs to be evaluated against, and compared with, the effect on the native fauna or target species of restoration. Nonetheless, invasive species can pose a major threat to native communities, yet direct management options are often limited. Our study exemplified that restoration measures can be used for population control of invasive gobies and suggest that they are incorporated in the planning and implementation of future restoration projects.

Acknowledgements Open access funding provided by University of Vienna. The pilot project Bad Deutsch-Altenburg was commissioned and financed by the viadonau Österreichische Wasserstraßen-Gesellschaft mbH and the Federal Ministry for Transport, Innovation and Technology. Fish sampling was granted by the Lower Austrian Fishery Association (BNÖ LFV-E-04/12 NÖ Landesfischereiverband). We thank the Gutsverwaltung Petronell, the municipality and fishermen association of Hainburg, and the Nationalpark Donau-Auen GmbH for sampling permissions. We also like to extend thanks to Elisabeth Schludermann, Dominik Altmann, Vinzenz Bammer, Simon Götsch, Hansjörg Hoyer, Tim Kaminskas, Franz Lumesberger-Loisl, Reinhard Krusch, Maximilian Sehr, Astrid Toth, Holger Villwock, Bernhard Zens, Philip Kerschbaumer, Michael Schöffbenker, Sylvia Wanzenböck and Julia Weber for their participation in sampling and data entry. Michael Stachowitsch has improved the English.

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