Oceanological and Hydrobiological Studies

International Journal of Oceanography and Hydrobiology

Volume 50, No. 3, September 2021
pages (247-258)

sciendo

ISSN 1730-413X
eISSN 1897-3191

Establishment and range expansion of non-native fish species facilitated by hot springs: the case study from the Upper Sakarya Basin (NW, Turkey)

by

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DOI: **10.2478/oandhs-2021-0021**
Category: **Original research paper**
Received: **March 1, 2021**
Accepted: **March 26, 2021**

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Abstract

Non-native species can enter new habitats and ecosystems in a variety of ways. Suitable ecological conditions must exist for non-native species to reproduce in newly colonized habitats. Hot springs are suitable habitats for tropical, aquarium, and ornamental fish species. This paper presents the results of research on the distribution of non-native and native species in relation to environmental factors in the Upper Sakarya Basin, where several such springs are present. The fish fauna in the basin includes native (60% – 21 species, 14 of which are endemic) and non-native (40% – 14 species) fish species. Most of the non-native species (seven species) were found only in warm springs (minimum water temperature 16°C). In addition, 75 fish species belonging to 26 families were found throughout the Sakarya Basin. Hot springs were found to play an important role in the establishment of non-native species. The Kernel Density Estimation (KDE) results revealed that the non-native species density was high in the Upper Sakarya Basin where hot springs are common. This confirms that minimum and maximum temperatures are the main drivers of changes in the distribution of non-native fish species. Two aquarium fishes, *Bujurguina vittata* and *Xiphophorus* spp., are reported for the first time in the present study for inland waters of Turkey.

Key words: water temperature, aquarium species, Kernel Density Estimation, DISTLM, climate change, aquatic ecosystems

online at www.oandhs.ug.edu.pl

1. Introduction

Temperature is one of the most important abiotic factors governing physiological limits in many taxa, including fish and other poikilothermic organisms (Magnuson et al. 1997). In the description of species distributions, temperature tolerance was shown to be the most important factor (42%), followed by human footprint (23%; Gallardo et al. 2015). Climate change through global warming has been predicted to affect the health of freshwater systems worldwide (Chu et al. 2005). Atmospheric CO_2 modeling scenarios indicate an average global temperature rise of 1–7°C over the next hundred years, while regional atmospheric CO_2 scenarios predict sudden and irreversible changes in regional precipitation patterns and storm paths over the next hundred years (Ficke et al. 2007). As a result of global warming, wind density and direction, evaporation rate, stream flows, and lake water levels are expected to change (Lehtonen 1996). Specifically, the predicted increases in water temperature and climate change will affect the distribution of thermal habitats and fish species, leading to significant changes in aquatic ecosystems (Sharma et al. 2007).

The spread and establishment of invasive fish species in new areas are known to be one of the main threats to global and local freshwater ecosystems and biodiversity (Mamun et al. 2018). Non-native fish can affect freshwater ecosystems, including reduction of native fish fauna through mechanisms of predation, competition, hybridization, habitat change, the introduction of diseases or parasites, and trophic change (Miller et al. 1989; Allendorf et al. 2001; Gozlan et al. 2005). However, fish species continue to be introduced worldwide due to society's demand for food, aquaculture fish products, ornamental fish, sport fisheries (Fuller 2003; Gozlan 2008). Hundreds of non-native fish species, especially in Europe and North America, are being spread through human influence, such as escapees from aquaculture and aquariums (pets, human commensals; Jeschke & Strayer 2006).

Turkey is a significant hotspot in terms of diversity and freshwater fish endemism (Fricke et al. 2007). The geographic location of Turkey and the presence of transboundary river systems increase the risk of introducing non-native fish to Turkey from both Asia and Europe (Tarkan et al. 2015). There are 30 non-native freshwater fish species in Turkey (Tarkan et al. 2015; Çiçek et al. 2015). In addition, some ornamental fishes – *Poecilia reticulata* (Türkmen 2019), *Hemichromis letourneuxi* (İnnal & Sungur 2019), and *Clarias batrachus* (Emiroğlu et al. 2020) – have recently been reported from inland waters of Turkey, increasing the total number of non-native species to 33. To date, 384 freshwater fish species have been reported from Turkish inland waters, of which 208 species (54.2%) are endemic (Çiçek et al. 2020).

Many of Turkey's major industrial companies, residential areas and agricultural areas are located in the Sakarya Basin. Approximately 10% of Turkey's population lives in the Sakarya River Basin (TUIK, 2020). High density of residential areas (Ankara, Bilecik, Eskişehir, Kütahya, Sakarya), agricultural activities and industrial production impact the Sakarya River, which is one of the largest rivers in Turkey (Aksu et al. 2018) hosting high fish species diversity (Özuluğ et al. 2007; Aksu et al. 2018; Reis et al. 2018). Commercial and amateur fishing activities are common throughout the basin. In the upper basin of the Sakarya River, there are areas with high water temperature, resulting from groundwater discharges. It has been reported that aquarium fish that are released into hot springs may cause habitat degradation (Tarkan et al. 2015; Emiroğlu et al. 2016). Some non-native species have been recorded in the basin due to the release of ornamental fish into areas with high water temperatures (Emiroğlu et al. 2016; Emiroğlu et al. 2020).

Our objective was to characterize the diversity of freshwater fish in the Upper Sakarya Basin based on data obtained from sampling in the Sakarya River watershed in the cities of Ankara, Bursa, Eskişehir, Bilecik, Kütahya and Sakarya, as well as searching the related literature. The specific objectives of the study were: (i) to inventory native and non-native fish species occurring in the Upper Sakarya Basin, (ii) to identify fish communities based on the habitats they occupy and relate them to environmental factors, (iii) to determine which niche is more intensively occupied by these communities, and (iv) to compare the results obtained between the upper and lower Sakarya in order to determine the potential impact of hot springs in the upper basin on the diversity and density of non-native fish species.

2. Materials and methods

2.1. Study area

The Sakarya River is the third largest river in Turkey, with a total length of 810 km (Emiroğlu 2011). The Upper Sakarya Basin covers a large area (Fig. 1). The Sarıyar, Gökçekaya, and Yenice reservoirs constitute physical barriers between the upper and lower basins of the Sakarya River. The upper tributaries of the Sakarya River are the Seydisuyu, Porsuk, Kargın, and Sarısu streams. In the Upper Sakarya Basin, there are warm (Sakaryabaşı, Sarısu, Yenisofça, and Balıkdamı)

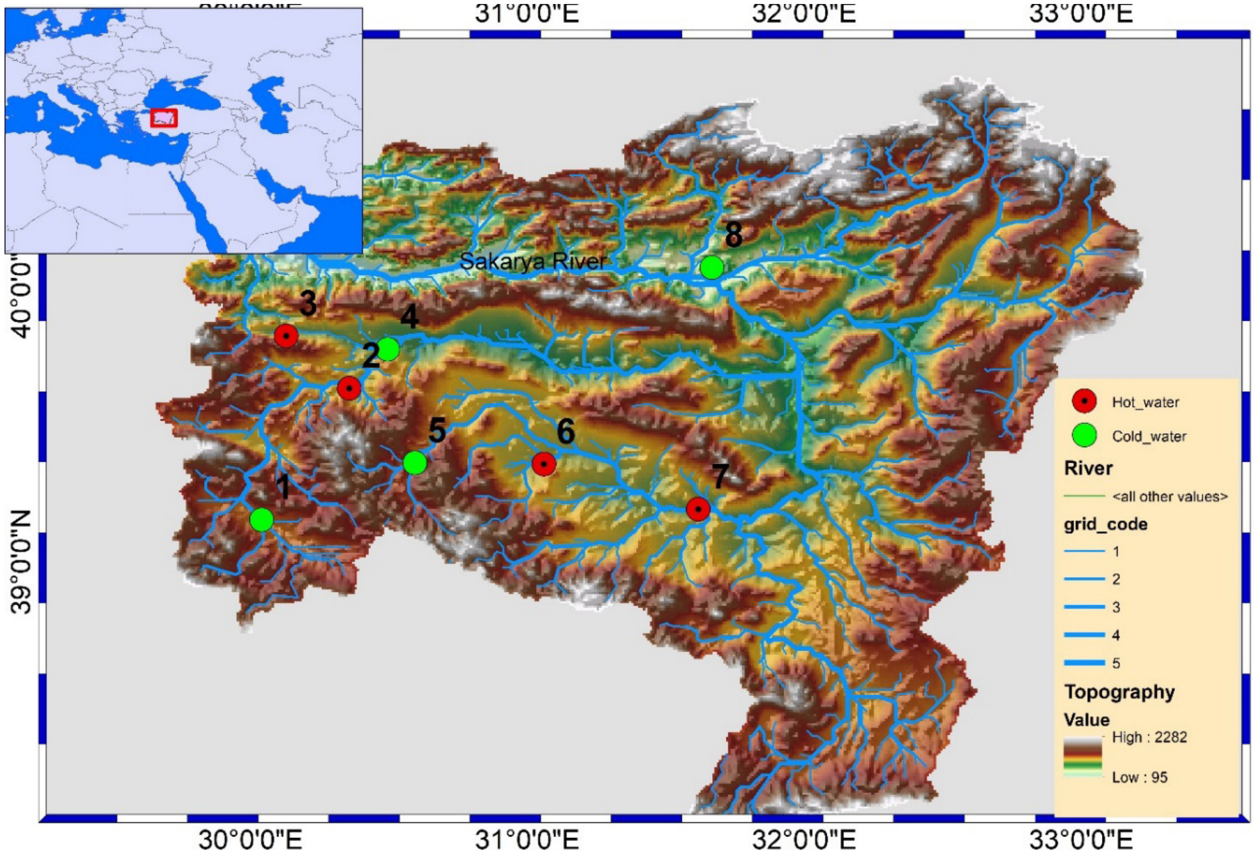

Figure 1

Sampling locations in the Upper Sakarya Basin

and cold water springs that form the source of the river (Table 1).

2.2. Sampling

Several sampling campaigns were conducted for this study along with a complementary literature review in 2014–2020. Fish were collected by electrofishing and standard multi-mesh gillnets. Sampling was carried out at eight locations, four of which were hot springs (sites 2, 3, 6, 7) and four cold water sources (1, 4, 5, 8) in the Upper Sakarya River Basin. Physicochemical measurements at the sampling locations were made using a HQ40D device.

Table 1

Sampling locations in the Sakarya Basin

	Location	Typology	Longitude	Latitude
1	Altıntaş	Stream	30.040537	39.151980
2	Yenisofça	Spring	30.356515	39.627796
3	Sarısu	Spring&Stream	30.128475	39.816556
4	Eskisehir	Stream	30.485606	39.762885
5	Seydisuyu	Stream	30.593632	39.357843
6	Sakaryabaşı	Spring&Stream	31.059387	39.353635
7	Balıkdamı wetland	Spring&Stream	31.617270	39.190264
8	Sarıyar	Reservoir	31.666131	40.064000

2.3. Fish identification

Species were identified according to the following references: Rosen & Bailey (1963), Rodriguez (1997), Geldiay & Balik (2007), Kottelat & Freyhof (2007) and Schmitter-Soto (2007). Valid scientific names of species were obtained from Fishbase (Forese & Pauly 2021) and the Catalog of Fishes (Fricke et al. 2021).

2.4. Distribution and density modeling

Kernel Density Estimation (KDE) starts by placing a grid (with n equal-sized cells) on top of the working area and measuring an intensity estimate based on center points of each grid cell and the distance between each grid cell of an event with the center, followed by a specific interpolation method (e.g. kernel function) and weighted bandwidth (e.g. search radius; Hart & Zandbergen 2013). Kernel density is the point density within the circle of a certain bandwidth radius. The occurrence of the species was mapped in five categories: springs, main body, lake, warm water and dams, and literature (Supplementary material). In this study, bandwidth (radius of action) and K (Kernel) functions were estimated for each site (Marceniuk et al. 2019). Fish species identified at the sampling sites in the upper Sakarya were included in the KDE analysis, whereas the literature was used for fish species from the lower Sakarya.

The kernel density calculation formula is given below (Silverman 1986):

$$\hat{f}(x) = \frac{1}{nh} + \sum_{i=1}^{n} K(\frac{x - X_i}{h})$$

$\hat{f}(x)$ – density value (x, y)
n – number of fish species
x-X_i – distance and location between points (x, y)
h – bandwidth
K – density function

Kernel density analysis was performed using ArcMap 10.8 software.

2.5. Species–environment relationship

The relationship between the fish community and physicochemical factors was determined using the distance-based multivariate analysis for a linear model (DISTLM; Mcardle & Anderson 2001), which assesses the relationship between a multivariate data cloud for multiple predictor variables (Anderson et al. 2008). First, forward selection and sequential conditional distance-based redundancy analysis (dbRDA; Mcardle & Anderson 2001) were used to explain the variation in the zero-adjusted Bray–Curtis dissimilarity matrix of the square-root-transformed data on fish assemblages with 9999 permutations under a reduced model (Anderson & ter Braak 2003). Next, stepwise selection with sequential conditional tests was employed using DISTLM to determine the number of variables (n) that could be reasonably included in a parsimonious model. Finally, the best n-variable model was identified on the basis of the direct multivariate analogue to the small-sample corrected Akaike information criterion (AICc; Anderson et al. 2008) to obtain an overall parsimonious model. The dbRDA was used to visually interpret the resulting model in the multidimensional space. The direction and length of vectors indicate the strength of the relationship between the dbRDA axes and a given variable. The significance of the test was evaluated for heuristic purposes at $\alpha = 0.10$ (Kline 2013).

3. Results

Physicochemical parameters measured in the Upper Sakarya Basin during our study are presented in Table 2. In the Upper Sakarya Basin, there are areas with high water temperatures, resulting from groundwater discharges, exceeding 15°C in the coldest season of the year. These are Sakaryabaşı, Sarısu, Balıkdamı and Yenisofça. The tropical species found in these waters are: *Clarias gariepinus* and *Oreochromis niloticus* in Sakaryabaşı (Emiroğlu 2011) and in Balıkdamı (Emiroğlu 2011; Keskin 2014), *Poecilia* cf. *reticulata*, *Xiphophorus* cf. *maculatus*, *Bujurguina vittata* in Yenisofça (Fig. 2) and *Pterygoplichthyes disjinctivus*, *Pterygoplichthyes pardalis*, *Clarias batrachus* (Emiroğlu et al. 2016; 2020) in Sarısu (Fig. 3).

In this study, 75 species from 26 families were identified throughout the Sakarya Basin as a result of a literature review and field sampling. Fourteen of these species occurred only in the Upper Sakarya Basin, eight of which were non-native (Table 3, Supplementary material). A total of 35 fish species (14 non-native, 21 native, including 14 endemic) were identified in the

Table 2

Physicochemical parameters of water in the Upper Sakarya Basin

Localities	Minimum Temperature (°C)	Maximum Temperature (°C)	pH	Conductivity (µS cm^{-1})	Dissolved Oxygen (mg l^{-1})	Salinity (PSU)
1	2.2	27.5	8.50	670	7.82	0.21
2	19.1	25.3	8.50	540	7.45	0.22
3	15.8	26.9	7.46	495	7.65	0.24
4	3.6	23.8	7.98	580	8.40	0.35
5	2.0	24.5	7.45	450	8.50	0.26
6	15.2	25.4	8.02	726	7.40	0.46
7	16.0	26.0	7.05	1041	7.02	0.54
8	2.0	27.0	8.38	929	8.56	0.50

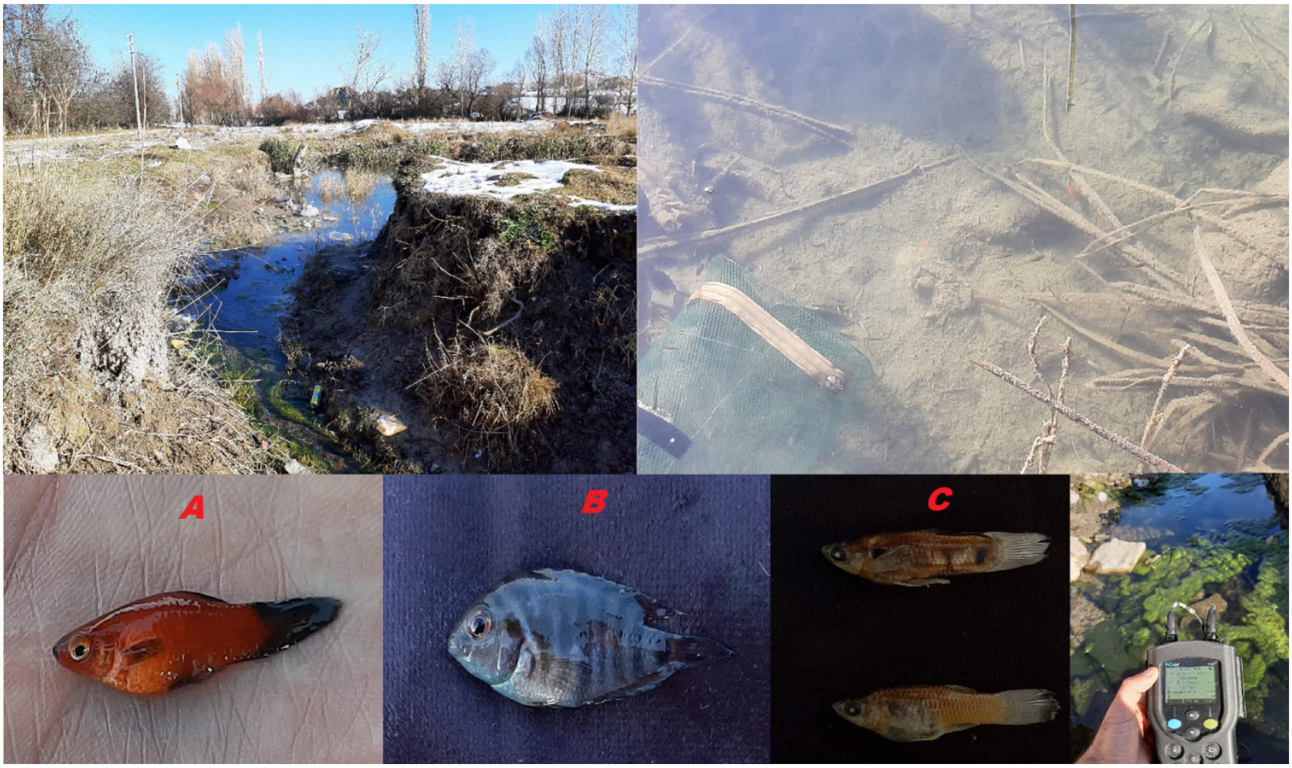

Figure 2

Aquarium fish found in hot springs in Yenisofça (A – *Xiphophorus* sp., B – *Bujurguina vittata*, C – *Poecilia* cf. *reticulate*) by Sadi Aksu

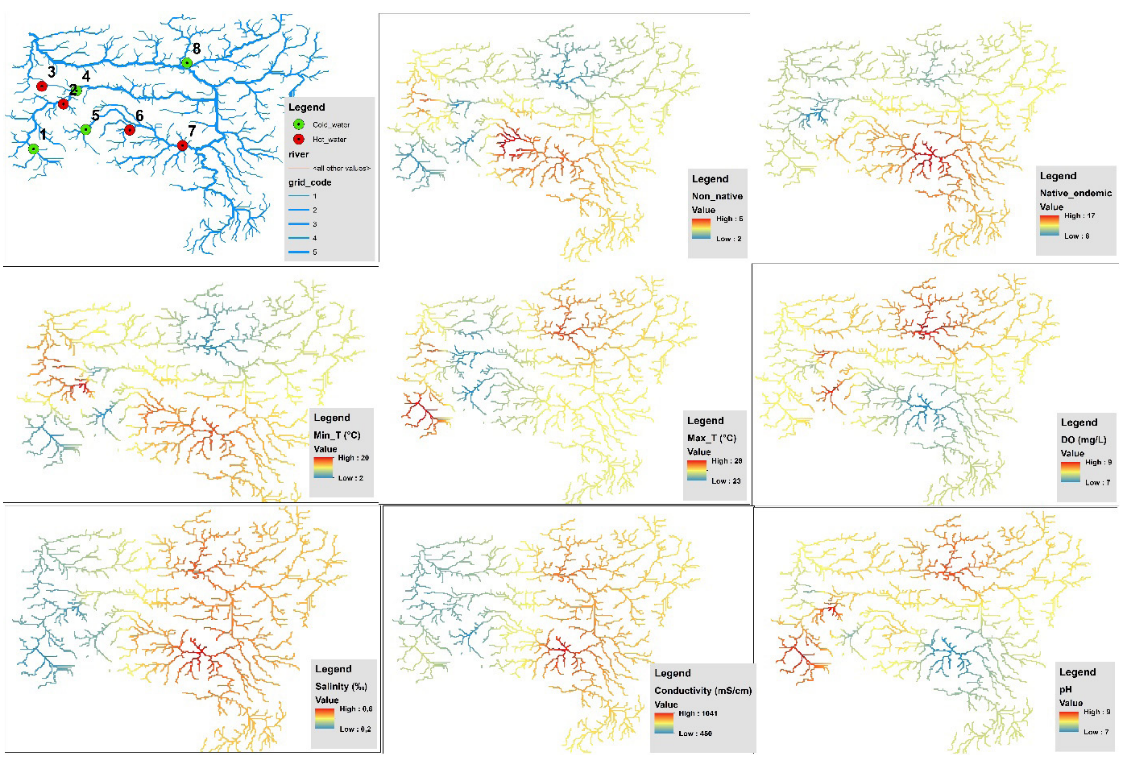

Figure 3

Variation in physicochemical values in water samples collected from the Upper Sakarya Basin

Table 3

Non-native species distribution in the Upper Sakarya Basin

Species	Distribution	Literature & Sampling (S)
Carassius auratus	3,5	S
Carassius gibelio	1,2,3,4,5,6,7	S
Gambusia holbrokii	7	S
Pseudorasbora parva	1,4,5,6,7	S
Poecilia cf. *reticulata*	2	S
Xiphophorus cf. *maculatus*	2	S
Oncoryhncus mykis	5	S
Pterygoplichthyes disjunctivus	3	S
Pterygoplichthyes pardalis	3	S
Clarias batrachus	2	S
Clarias gariepinus	5,6,7	S
Oreochromis niloticus	5,6,7	S
Bujurguina vittata	2	S
Pangasius sanitwongsei	4,8	(Yoğurtçuoğlu & Ekmekçi 2018)

Upper Sakarya Basin (Table 3, Supplementary material). Endemic fish species accounted for 40% of the fish in the Upper Sakarya Basin. Nine non-native species (*Pterygoplichthyes disjunctivus*, *Pterygoplichthyes pardalis*, *Clarias batrachus*, *Clarias gariepinus*, *Carassius auratus*, *Bujurguina vittata*, *Poecilia* cf. *reticulata*, *Oreochromis niloticus*, *Xiphophorus* cf. *maculatus*) were found only in hot springs. The KDE results indicated that the number of non-native species increased in the region with hot springs (Fig. 4), whereas the Lower Sakarya Basin hosted more native and endemic species (Fig. 5).

Of the parameters assessed, marginal tests revealed that only maximum temperature was significantly correlated with the variation in fish assemblages (p = 0.103; Table 4). However, sequential tests with stepwise selection across all potential predictor variables indicated that a parsimonious model explaining the variation in fish assemblage data based on all potential predictor variables would be obtained using only two variables: maximum (p = 0.097) and minimum (p = 0.101) temperatures, which were also the best two variables in the AICc models (maximum temperature: 61.428; minimum temperature: 62.946; Table 4). The model was visualized with the dbRDA ordination of fitted values (Fig. 6), whose first two axes explained the total fitted variation and only 30.8% of the total variation.

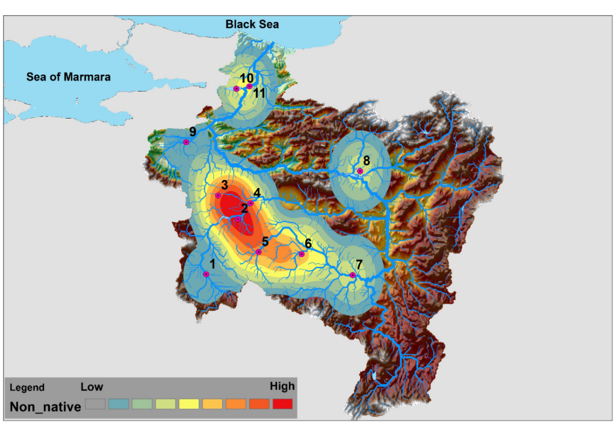

Figure 4

Kernel density analysis generated for non-native species in the upper and lower Sakarya Basin

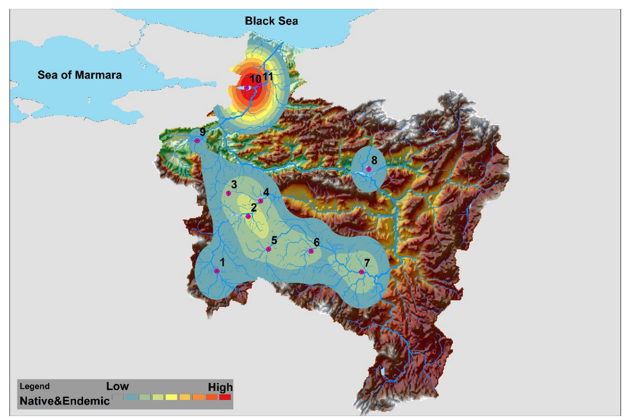

Figure 5

Kernel density analysis generated for native endemic species in the upper and lower Sakarya Basin

4. Discussion

The establishment of populations of non-native species released into a new environment relies on suitable conditions for life. When warm water intolerant fish species are released into any

Table 4

Results of distance-based multivariate analysis for a linear model (DISTLM) for physicochemical variables. Significant results are indicated in bold.

Variable	Marginal test			Sequential test		
	SS (trace)	Pseudo-*F*	*p*	SS (trace)	Pseudo-*F*	*p*
Minimum Temperature (°C)	2996.4	1.914	**0.103**	2996.4	1.194	**0.101**
Maximum Temperature (°C)	830.8	0.431	0.889	2996.4	1.194	**0.097**
pH	1749.7	0.987	0.481			
Conductivity (µS cm^{-1})	1449.8	0.795	0.563			
Dissolved Oxygen (mg l^{-1})	2472	1.496	0.172			
DOS	1421.7	0.778	0.631			
Salinity (PSU)	1762.1	0.995	0.451			

environment, they must have the reproductive capacity to establish a population. Habitat modifications and non-native species are the main threat to native species (Giannetto et al. 2013). In addition, small ponds and reservoirs prevent fish from moving to other parts of the river (Pompei et al. 2018). It has been observed that aquarium fish can reproduce, even in a limited area, if the conditions under which they are released are suitable (Emiroğlu et al. 2016). Three large reservoirs were built on the Sakarya River (Sarıyar, Gökçekaya and Yenice). These artificial barriers have prevented non-native and native species from the upper basin from entering the lower basin. In the Sakarya Basin, there are springs with a minimum water temperature of 16°C (Arslan et al. 2007; Çiçek et al. 2018), which can sustain populations

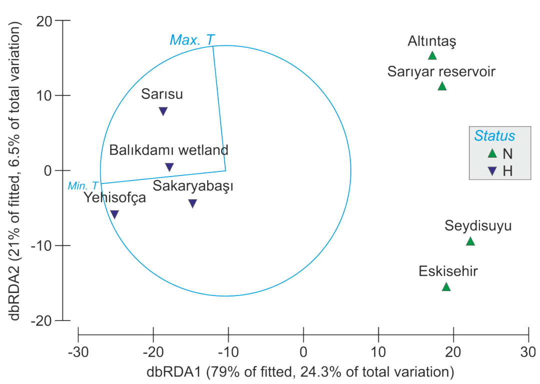

Figure 6

Constrained ordination relating fish species data to predictor variables. Distance-based redundancy analysis (dbRDA) of zero-adjusted Bray–Curtis dissimilarities calculated from presence/absence data vs minimum and maximum temperatures, identified as the best two variable model using the AICc selection criterion. Colors denote the sampling locations in the Sakarya River Basin. N – Normal, H – Hot springs

of aquarium and ornamental fish (Emiroğlu 2011; Emiroğlu et al. 2016; Emiroğlu et al. 2020). Our results strongly support previous studies that water temperature is the most critical factor limiting the establishment of tropical and subtropical fish species (Moore et al. 2013; Yamada et al. 2017). In terms of thermal water resources, the Central Anatolia Region is the second richest region in Turkey. Two major cities (Ankara and Eskişehir) occupy most of the Sakarya Basin and are the most important ones in terms of thermal sources in the region (Özşahin et al. 2013). The results of the present study also suggest that hot water resources in the Upper Sakarya Basin effectively provide suitable habitats for non-native tropical and aquarium fish during all seasons.

The percentage of non-native species in the Upper Sakarya Basin (40%) is almost ten times higher than the percentage for Turkey (3.9%; Çiçek et al. 2020). The literature review shows 60 fish species recorded from the Lower Sakarya Basin (Supplementary material). Five of these species are non-native and 56 are native and endemic species. Two aquarium fishes – *Bujurguina vittata*, *Xiphophorus* cf. *maculatus* – are reported for the first time in the present study for inland waters of Turkey (Fig. 2).

According to global climate change projections, the temperature increase in Turkey is expected to be between 1 and 6°C (Demircan et al. 2017). This change will increase the surface water temperature, which in turn will facilitate the spread of non-native species populations distributed over limited areas in warm water sources. Two such species, *Oreochromis niloticus* and *Clarias gariepinus*, are known to occur in Sakarbaşı and Balıkdamı warm water springs (Emiroğlu 2011). However, they did not expand their non-native range to the lower regions of the basin during the cold season and were only recorded during months with suitable temperatures (Emiroğlu 2011; Keskin 2014). As water temperatures rise, tropical fish in outdoor aquaculture and aquatic gardens are likely to expand in some geographic areas with suitable temperatures. For example, optimal temperatures for aquaculture of catfish (*Ictalurus punctatus*) are estimated to move 240 km north in the southeastern United States for every 1°C increase in mean annual air temperature (Mccauley & Beitinger 1992; Rahel & Olden 2008). Breeding of tilapia (Cichlidae) may also expand into areas that are currently probably very cold for them (Lodge et al. 2000). Climate change may have a similar effect on the distribution of non-native fish species in the Sakarya Basin.

Cold water serves as a filter that prevents species adapted to warm water from establishing their populations (Rahel & Olden 2008; Emiroğlu 2011). With climate change, these natural barriers can expand. These expanding boundaries may allow non-native species to spread to larger areas. The range of 16 non-native hot water fish species in Europe is expected to expand, while the distribution range of 11 cold water species is expected to decline (Lehtonen 1996). Similarly, eight non-native species (*Clarias garipenius*, *Clarias batrachus*, *Pterygoplichthys disjinctivus*, *Pterygoplichthys pardalis*, *Oreochromis niloticus*, *Poecilia* cf. *reticulate*, *Xiphophorus* cf. *maculatus*, *Bujurguina vittata*) occur in a limited area in Sarısu (Emiroğlu 2011; Emiroğlu et al. 2016; Emiroğlu et al. 2020). Until 1950, northern pike (*Esox lucius*), wels catfish (*Silurus glanis*), rudd (*Scardinius erythrophthalmus*), freshwater bream (*Abramis brama*), chub (*Squalius pursakensis*), colchic khramulya (*Capoeta sieboldii*) and common carp (*Cyprinus carpio*) were common fish species in the Upper Sakarya Basin. In addition, two rare fish species, sterlet sturgeon (*Acipenser ruthenus*) and beluga (*Huso huso*), were also reported (Erençin 1978). However, *Clarias garipenius* and *Oreochromis niloticus*, which were introduced to the region for aquaculture in the 1980s, became invasive after they escaped into the river (Emiroğlu 2011). Today, *Esox lucius* and *Silurus glanis* are sporadically found in the region, whereas *Abramis brama*, *Acipenser ruthenus,* and *Huso huso* are absent. These invasive fishes have expanded their range to the Balıkdamı wetland where the water temperature is more suitable. Although the Sarıyar reservoir, where water temperature drops to 2°C in the cold season, was reported to have the highest population density of *Oreochromis niloticus* and *Clarias garipenius* (Keskin 2014), neither of these species was found there during any of our fish sampling campaigns over the past ten years. For this reason, non-native species in the Yenisofça and Sarısu hot springs in the Upper Sakarya Basin will be able to spread to the Porsuk and Sakarya rivers with the emergence of suitable environmental conditions as a result of climate change.

5. Conclusions

Our results clearly indicate that hot water resources could be suitable habitats, especially for tropical aquarium fish species once introduced into the wild. This is also relevant to sensitive areas (i.e. biodiversity hotspots in temperate climates) in light of projected climate change due to global warming. An increase in water temperature would cause a reduction in the amount of dissolved oxygen, which is considered a limiting factor for natural species but a contributing factor for non-native species. This could consequently lead to a rapid removal of native species from the environment and a faster establishment of non-native species in these abandoned niches. Another reason for the high rate of non-native species is that hot springs provide favorable environmental conditions, especially for aquarium and ornamental fish. Hot springs are located close to highly populated areas (i.e. some metropolitan cities such as Eskişehir, Sakarya), where aquarium trade is common and this situation increases the transportation of ornamental fish to these water sources.

For the ecological status of aquatic ecosystems to be sustainable, the existing balance must be kept stable. When non-native species enter a new aquatic system, they can cause changes in the existing ichthyofauna. This situation can lead to a series of negative consequences, causing significant damage to aquatic habitats and sustainable ecological services. To prevent these negative effects and ensure sustainable ecological services of aquatic ecosystems, non-native fish species should be continuously monitored and relevant management actions should be implemented.

Competing interests

The authors declare no competing interests.

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Supplementary material

Endemic, native, and non-native species in the Sakarya Basin

Family	Species	Status	Literature &S
Petromyzontidae	**Lampetra lanceolata*	E	Özuluğ et al. 2007; Çiçek et al. 2020
Acipenseridae	**Acipenser stellatus*	N	Memiş et al. 2019
	**Acipenser gueldenstaedtii*	N	Memiş et al. 2019
	**Acipenser ruthenus*	N	Erençin 1978
	**Acipenser sturio*	N	Memiş 2014
	**Acipenser nudivenris*	N	Memiş 2014; Memiş et al. 2019
	**Huso huso*	N	Memiş et al. 2019
Anguillidae	**Anguilla anguilla*	N	Özuluğ et al. 2007
Clupeidae	**Alosa maeotica*	E	Özuluğ et al. 2007
	**Clupeonella muhlisi*	E	Özuluğ et al. 2007
Cobitidae	***Cobitis simplicispina*	E	S
	**Cobitis emrei*	E	Freyhof et al. 2018
Nemacheilidae	***Oxynoemacheilus angorae*	E	S
	****Oxynoemacheilus* cf. *samanticus*	E	Aksu et al. 2018 & S
	****Oxynoemacheilus* cf.*kosswigi*	E	Aksu et al. 2018 & S
	****Seminemacheilus lendlii*	E	Yoğurtçuoğlu et al (2020) & S
Cyprinidae	****Barbus escherichii*	E	S
	**Barbus tauricus*	E	Turan et al. 2018
	***Capoeta baliki*	E	S
	***Capoeta sieboldii*	N	Erençin, 1978&S
	***Capoeta tinca*	E	Bektaş et al.2017; Kaya, 2020
	***Carassius auratus*	I/A	S
	**Carassius carassius*	I/A	Emiroğlu et al. 2012; Duman & Helli, 2019
	***Carassius gibelio*	I/A	Duman & Helli, 2019 & S
	***Cyprinus carpio*	N	Erençin, 1978; Memiş et al. 2019 & S
Tincidae	***Tinca tinca*	N	Memiş et al. 2019 & S
Acheilognathidae	***Rhodeus amarus*	N	S
Gobionidae	***Gobio sakaryaensis*	E	Turan et al. 2012 & S
	***Pseudorasbora parva*	I/A	S
Leuciscidae	**Abramis brama*	N	Özuluğ et al. 2007
	***Alburnoides kosswigi*	E	Turan et al. 2017 & S
	**Alburnus derjugini*	E	Bektaş et al. 2020
	***Alburnus escherichii*	E	S
	**Leuciscus aspius*	N	Özuluğ et al. 2007
	**Blicca bjoerkna*	N	Duman&Helli, 2019 & S
	***Chondrostoma angorense*	E	S
	**Petroleuciscus borysthenicus*	N	Özuluğ et al. 2007 & S
	***Rutilus rutilus*	N	Duman & Helli 2019 & S
	***Scardinius erythrophthalmus*	N	Memiş et al. 2019 & S
	**Squalius cephalus*	E	Özuluğ et al. 2007 & S
	***Squalius pursakensis*	E	S
	***Vimba vimba*	N	Özuluğ et al. 2007 & S
Serrasalmidae	**Pygocentrus nattereri*	I/A	Tarkan 2006
Loricariidae	****Pterygoplichthys disjunctivus*	I/A	S
	****Pterygoplichthys pardalis*	I/A	S
Pangasiidae	****Pangasius sanitwongsei*	I/A	Yoğurtçuoğlu & Ekmekçi, 2018
Siluridae	***Silurus glanis*	N	Erençin, 1978; Özuluğ et al. 2007; MEMİŞ et al. 2019 & & S
Claridae	****Clarias batrachus*	I/A	S
	****Clarias gariepinus*	I/A	S
Esocidae	***Esox lucius*	N	Erençin, 1978; Özuluğ et al. 2007 & S
Salmonidae	****Oncorhynchus mykiss*	I/A	Özuluğ et al. 2007 & S
	**Salmo* cf. *coruhensis*	E	Özuluğ et al. 2007
	**Salmo* cf. *rizeensis*	E	Özuluğ et al. 2007
Syngnathidae	**Syngnathus abaster*	N	Özuluğ et al. 2007
	**Syngnathus tenuirostris*	N	Özuluğ et al. 2007
	**Syngnathus tenuirostris*	N	Özuluğ et al. 2007
	**Syngnathus nigrolineatus*	N	Özuluğ et al. 2007
Gobiidae	**Babka gymnotrachelus*	N	Duman & Helli 2019
	**Knipowitschia caucasica*	N	Özuluğ et al. 2007
	***Neogobius fluviatilis*	N	Özuluğ et al. 2007 & S
	**Neogobius melanostomus*	N	Özuluğ et al. 2007 & S
	**Ponticola syrman*	N	Özuluğ et al. 2007
	**Proterorhinus marmoratus*	N	Duman & Helli 2019
Cichlidae	****Bujurquina vittata*	I/A	S
	****Oreochromis niloticus*	I/A	S
Atherinidae	**Atherina boyeri*	N	Özuluğ et al. 2007
	**Atherina pontica*	N	Geiger et al. 2014
Aphaniidae	****Anatolichthys villwocki*	E	S
Poeciliidae	***Gambusia holbrooki*	I/A	Kurtul & Sari, 2019 & S
	****Poecilia* cf. *reticulata*	I/A	S
	****Xiphophorus* cf. *maculatus*	I/A	S
Mugilidae	**Mugil cephalus*	N	Bozcaartmutlu et al. 2015
	**Planiliza haematocheilus*	N	Bozcaartmutlu et al. 2009
Centrarchidae	**Lepomis gibbosus*	I/A	Duman & Helli 2019 & S
Percidae	**Perca fluviatilis*	N	Duman & Helli 2019 & S

E – Endemic; N – Native; I/A – Invasive/Alien; S – Sampling; * distributed only in the Lower Sakarya Basin; ** distributed throughout the Sakarya Basin; *** distributed only in the Upper Sakarya Basin

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