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Stepping Stone Wetlands, Last Sanctuaries for European Mudminnow: How Can the Human Impact, Climate Change, and Non-Native Species Drive a Fish to the Edge of Extinction?

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Abstract: Throughout their history humans "tamed" not only the Danube River basin land, but also the river and its associated wetlands, drastically influencing their characteristic habitats, associations, communities, and species. One of these flagship endemic fish species in this respect is the European mudminnow (*Umbra krameri* Walbaum, 1792), influenced by Danube Basin geography, history, politics, and ecology. A study about this European community concern species in the context of long term human impact on its specific habitats, with potential synergic negative effects of climate change, was treated as highly needed, in an international researchers group initiative to support the efforts to provide hope for preserving this fish species and its ecosystems, and brought it back from the brink of extinction. All the characteristic inventoried wetlands which were or some of them still are natural, semi-natural, or accidental anthropogenic habitats, reveal an accentuated diminishing trend of this species areal continuity; fragmentation being the force which skewed it drastically untill now, and inducing diminishing the specific habitats quantitative and qualitative characteristics in the Danube Basin where these fish fight for survival. The main categories of human activities which impacted the climate changes in the context of this species' habitats are: water regulation, pollution, dredging, draining, and introduction of non-native species. Overall, the diverse human impact in a climate changes in the context of this species' habitats, *Umbra krameri* wetlands, creates serious perspectives on negatively influencing this at a very high scale and level. All the inventoried wetlands where *Umbra krameri* still survive can be considered an ecologically managed as a refuge and stepping stone wetlands, especially in the increasing climate change trend situation. Supplementary inventory studies in the field should be done for the identification of some may be unknown *Umbra krameri* habitats and populations.

Keywords: drought; habitat degradation; refugees; endemic fish; isolation; risk management

1. Introduction and Background

Water is a key to understand the cosmos, controls the Earth environment [1,2], and drive among other elements the biodiversity [3–12]. In this context, the importance of wetlands for aquatic, semi-aquatic, and terrestrial biotopes is essential, mostly when are impacted by humans, such cases being in all the Danube Basin countries [13–30].

Climate change is one of the best known bad situations to face for wetlands, that Man has faced [31–36]. The planetary climate models reveals that the main element that caused this global event to happen are natural and induced by human activities; the conjunction of these factors can explain the last century and a half climate changes [36], influencing the water cycle and water supply [37] and the Earth ocean level rising [38].

The science agreed that among the determinants of the organisms' state, including the freshwater ones [39], the climate is on top because it influences everything [40]. Inland water is influenced by the weather and by the atmosphere temperature variations, consequently, the climate changes have effects on freshwater organisms [41].

The current IPCC Climate Report "Code Red for Humanity", reveals that warming has accelerated in the last decades; the planet is heating up, and supplementary warming is expected. Many changes inducing climate impact shocks will worsen [42]. Additionaly, the change of hydrologic cycles have repercussions on freshwater habitats organisms [42,43]. Increased climate modifications are predicted to impact the biodiversity of extensive regions [44]. The planetary heating up is putting at risk the Earth biodiversity, including fish [45–51], a main taxonomic group under high worldwide human-impact risks [52–63].

The air temperatures will increase in Europe too, due to anthropogenic effects on the atmosphere [64–66]. The forecasts reveal that the precipitation regime will be changed, with increasing drought events [67], and climatic crises anticipated [68]. Climate warming is due to a heating trend since the mid-20th century, tied to human activities [60–71].

Drought is an effect-dependent phenomenon [72], and human impact is partially responsible for the drought incidents [73] provoking a complex hydro-climatic risk influencing the ecosystems [74]. The heat waves' strength is forecasted to boost [75].

In the climate change context, the temperature raises all-around [76], even in surprising regions, like in a relative moderate climate of Danube Basin [77–90].

In the present heating up, freshwater ecosystems are strikingly sensitive, freshwater biodiversity has descended faster than marine or terrestrial [3–6].

The Danube Basin, due to the climate change effects together with other human activities' impact, present changes of temperature, precipitation, and hydrological regime [91–100] and of features of the associated aquatic communities. Overall, the climate change was identified as a new water management main issue in this basin [77–87].

Research in the Danube Basin reveal accentuated heat waves, droughts, evapotranspiration, and a runoff diminishing, disturbing the low flow seasons [43], and the associated organisms including fish are under humans' negative effects [101–107].

This study's main objective is to provide data related to the environmental relevance and risks of one of the imperiled fish of Europe [107] rather scarce and fragmented stepping stones and refuge habitats in the Danube Basin, in the context of human impact and climate change effects, the European mudminnow (*Umbra krameri*, Walbaum, 1792).

The Danube Basin extends up to 801,093 km^2, in 19 countries, from the Black Forest springs to the Black Sea, collecting nearly 827 km^3 of water every year [104].

Many historical records have voiced the importance of a high variety of fish species and fisheries in the Danube Basin [101–105], overlapping highly variable ecological and functional guilds [106], and covering a large variety of aquatic and semi-aquatic habitats.

There were and a high number of fish species of conservation importance, some of them having a high degree of specificity for the Danube Basin, one of them, is *Umbra krameri* which is one of the most endangered species of the original Danubian fish fauna and all the threats are directly and indirectly anthropogenic [107].

The European community's aim in the environment care is the protection, conservation, and improvement of the nature-related resources management characteristics and value, on the condition that these resources should be used wisely. Biodiversity protection and conservation is a more important aim of the European Union. The climate change background boosts the intricacy of this important issue [108].

The Umbridae family is present in some parts of the Northern Hemisphere in freshwater environments. It encompasses *Dallia*, *Novumbra*, and *Umbra* genera [109,110].

The genus *Umbra* is known since the Paleogene in the European continent [111]. The European representative of this genus *Umbra krameri* occur in south-eastern Europe, and has its terra typical in the Danube Basin, and have scattered small populations in the Danube and Nistru basins in Austria, Slovenia, Croatia, Serbia, Bosnia and Herzegovina, Slovakia, Hungary, Ukraine, Bulgaria, Moldova, and Romania [112–116]. This species was introduced recently in Poland, Germany, England, and Holland [114–116].

The genus term *Umbra* (shade) possibly invokes its aquatic habitat with often almost impenetrable vegetation associations, this tiny, quite enigmatic fish, an inhabitant of rather isolated and not easy accessible wetlands, has no direct economic value and is used by the fishermen only as living bait or sometimes as aquarium fish [110].

A concern must be always present, about the risks for these vegetation associations, that are given by an excessive (intense or/and frequent) anthropic pressure that can overwhelm the natural resilience, adaptability, and resistance that characterize these wetlands plant communities, and so changing the habitat. The greatest risks are for the more meso and oligotrophic plant species [117]. But even the communities that generally appear much more resistant to the anthropic pressure in certain situations can instead show a regression or disappearance phenomena, as especially happened for example, in several European wetlands [118] and as possible to observe in Danube Basin [119,120].

Umbra krameri is a short life span species, reaching its sexual maturity at one/two years. The reproduction is in the March–June, at a water temperature of 12–18 °C. For reproduction the females dig nests in the mud/sand, defend and oxygenate the spawn, and also the roes are laid on aquatic plants [110,112,121].

Even though this fish species is under the Bern Convention, CITES, IUCN Red List, etc. care [110,122], there are many causes that have induced its downturn, its spotty range along with its decreasing distribution area, and potential extinction risk, every one of the existing hazards can push to a major decline of this species [110,114,122,123].

Are the late climate changes a new synergic major risk for this already threatened European wetlands key and flagship indicator fish species? This paper’s main goal is to reveal the bio-geographical and ecological situation of the *Umbra krameri* specific habitats and populations and propose Danube Basin conservation strategy elements, measures, and actions, to conserve the still existing specific habitats and populations.

Climate studies go further than temperature tendency done in the past, and it was drawn up to the habitat and ecosystem approach when the first famous IPCC synthetic report was publicly released in 1990. Since that period, there was growing data about the effects of global warming overlapping depreciations by other human-induced impacts in scientific works, also in the whole area of the Danube Basin. Climate reaction for the Danube Basin is highlighted by four main elements: How to accurately determine the impact of climate change on freshwaters? What techniques are specific to revealing an ecosystem response to climate modifications? How to tackle which information suits an optimum way for climate study? What have we understood from climate research to better evaluate, monitor, and manage the ecosystems?

At the 21st century dawn, it was obvious that the human-nature interconnexions are unbalanced and had a serious complex negative impact on biodiversity, and the Danube Basin to which the studied area belongs is not an exception [13–30].

This study addressed some ecological aspects of frequent, extended, and intense drought periods of time and their long-term negative effects on the Danube Watershed *Umbra krameri* wetland habitats and populations, a fish species with a high indicative importance for the researched ecosystems’ ecological status trends under the constant significant negative human impact and climate change/drought seasons’ pressure.

The indirect and direct anthropogenic activities effects influence are the main elements of comprehension of the drought effects on the researched species habitats.

It is sure that the tendency of climate in this century in the Danube Basin will be very much like that of the end of the last past one, with rising values of extreme hotness and high-temperature waves and frequency [77–91]; this reaffirms the challenge for specific research based on field inventories of existent problems and update suggestions of proactively management plans including for key indicator species like *Umbra krameri*.

This study had the main aim to inventory and map the present wetland refuges and stepping stone habitats of *Umbra krameri*, and also to identify new potential areas where such wetlands should be rehabilitated or made, and repopulated with this species. Also, monitoring and management elements were suggested for these wetlands' natural processes recovery and improvement. It must be featured that no such specific study concerning the Danube Basin wetlands refugee and stepping stones habitats for *Umbra krameri* has formerly been done.

For the readers' navigation in the paper support, we highlight here the included chapters and subchapters: 1. Introduction and Background; 2. Materials and Methods; 3. Results and Discussion; 3.1.1. Wetlands in Austria; 3.1.2. Wetlands at the Austria-Slovakia-Hungary border; 3.2. Wetlands of the Danube River in Hungary; 3.3.–3.4. Lugomir and Kraljevac channel system in Danube drainage in Serbia; 3.5. Wetlands at the Serbia-Romania border; 3.6. Jiu River lower part in Romania; 3.7.–3.8. Olt-Vedea-Argeş rivers lower partin Romania; 3.9. Lower Danube River Basin-Danube River Delta in the Romania-Moldova-Ukraine border area; 3.10. Mura and Drava river system at the Slovenia-Croatia-Hungary border; 3.11. Zala River, Lake Balaton system in Hungary; 3.12. Upper Tisza system in Ukraine and Hungary; 3.13. Borsodi-mezőség plane, Tisza system in Hungary; 3.14. Bihar-plaine Tisza system in Hungary; 3.15. Wetlands at the Romania-Hungary border; 3.16. Lonja and Odra wetlands in Croatia; 3.17. Matura River system in Bosnia and Herzegovina; 3.18. Wetlands at the Serbia-Bosnia and Herzegovina border; 3.19. Timiș River system in Romania; 3.20. Prut River at the Moldova-Romania border; 3.21. Dniester River at Moldova-Ukraine border; 3.22. Danube Basin Umbra krameri populations state and potential trends under climate change impact; 3.23. Umbra krameri refuge and stepping stone habitats management elements proposals for the Danube Basin; 4. Conclusions.

2. Materials and Methods

This study was based on the synthesized available scientific studies results and on the biological samples obtained by the authors in the field from 2016 to 2021, in summer drought periods when this helpless fish were caught even by hand, simple fishing net-tools, electrofishing, or found in the fisherman captures in all the Danube Basin still proper areas (Figure 1). The major method limitation is field activities for checking the presence of this species were done over a six years period some of these populations can locally be extinct now.

The obtained data features the presence and refugee-stepping stone value of the analyzed sites.

The *Umbra krameri* fish species individuals were sampled with bare hands, simple fishing tools, electric fishery devices (Hans Grassl IG200b, Samus 725MP) or found in the fisherman captures alive, were released in the habitat of origin after a visual identification, specific research literature data was used too.

Different habitat characteristics data were registered and presented in the paper text.

This study suggests at the end in situ adapted management elements for the rehabilitation or reconstruction, at least in part, of the former ecologic status of these wetlands, and *Umbra krameri* populations.

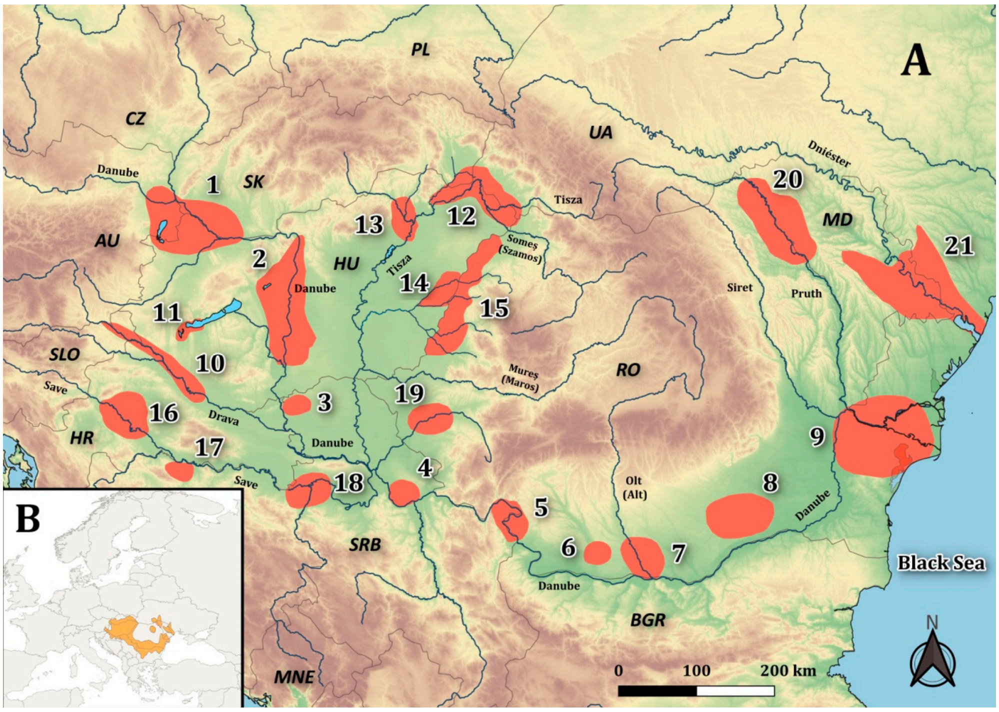

Figure 1. Recent (**A**) and historical (**B**) distribution of *Umbra krameri* in Europe. Biogeographical regions with numbers were designed by right of occurrence data adapted from this research's database and the following references: Kottelat & Freyhof, 2007 [124]; Sekulić et al. 1998 [125]; Takács et al., 2015 [126]; Marić et al., 2017; 2019 [126,127]; Covaciu-Markov et al., 2018 [128]. Recent regional distribution reports shown on the map include: (1) Wetlands in Austria and its borders with Slovakia and Hungary; (2) Wetlands of the Danube River in Hungary; (3) Lugomir channel system in Danube drainage in Serbia; (4) Kraljevac channel system in Danube drainage in Serbia; (5) Wetlands at the Serbia-Romania border; (6) Jiu River lower part in Romania; (7) Olt river lower part in Romania; (8) Vedea-Argeş rivers lower part in Romania; (9) Lower Danube River-Danube River Delta at the Romania-Moldova-Ukraine border; (10) Mura and Drava river system at the Slovenia-Croatia-Hungary border; (11) Zala River, Lake Balaton system in Hungary; (12) Upper Tisza system in Ukraine and Hungary; (13) Borsodi-mezőség plane, Tisza system in Hungary; (14) Bihar-plaine Tisza system in Hungary; (15) Wetlands at the Romania-Hungary border; (16) Lonja and Odra wetlands in Croatia; (17) Matura River system in Bosnia and Herzegovina; (18) Wetlands at the Serbia-Bosnia and Herzegovina border; (19) Timiș River system in Romania; (20) Prut River at the Moldova-Romania border; (21) Dniester River at Moldova-Ukraine border.

3. Results and Discussion

3.1. Wetlands in Austria and Its Borders with Slovakia and Hungary

- Wetlands in Austria

The *Umbra krameri* was described from the Danube floodplain by Marsili, the first record which comes from Austria was given by Kramer after whom the fish was named, later was considered extinct in Austria during the late 1970s and 1980s, however, has been rediscovered in 1992, exactly 30 years before present [129–132].

There were three historically known areas the fish could be found (before 1992): (1) The Danube floodplain between Vienna and Bratislava, (2) the lowlands southeast of Vienna along the rivers Leitha and Fischa, and (3) the Lake Neusiedl (Fertö).

After the rediscovery in 1992 in area 1, in the Danube old sidearm between the villages Orth and Eckartsau, the so called "Fadenbach" [129,130], the other areas were checked for remnant populations. In area 2 the result was positive and an extant population could be found near the Moosbrunn village. However, in area 3 the search was unsuccessful for Lake Neusiedl (Fertö). Two more areas were checked: The Austrian sides of the River

March (Morava) forming the border with Slovakia and of the River Mur (Mura) in the south of Austria, before it fully enters Slovenia. Potential occurrence in the latter area was hypothesized, because in Slovenia populations were found in the oxbows of the Mura river not far from the border with Austria. Nevertheless, no mudminnows could be found in those additional areas during the fishing campaigns in 1993–1996.

A metapopulation viability analysis was performed for the Fadenbach based on empirical demographic parameters obtained during the monitoring campaign of five years and additional experimental propagation [129]. A main finding was a probability of 50% of extinction of this metapopulation within 24 years, if trends in habitat reduction seen at that time persisted. This trend in the decline of habitat carrying capacity down to zero, i.e., complete disappearance or drying out of primarily groundwater-fed floodplain ponds, is based on the hydrological changes of the Danube river. Water regulation, which started in the 19th century, resulted in increased flow velocities causing the river to permanently cut a deeper main channel and concurrently sediment transport is blocked from upriver by a chain of hydropower plants. This lowers the groundwater level in the adjacent floodplain and transformed the former sidearm of the Danube into a chain of disconnected ponds unless high floods of the Danube reconnect the pools occasionally. All the ponds containing mudminnows are located outside of the main flood control dam, increasing the probability of desiccation, but also protecting mudminnows from occasional recolonization with other fish species.

Management actions to preserve the one and only remaining metapopulation of the Austrian Danube floodplain in the Fadenbach channel were conceptualized [133]. These authors suggested digging the channel of the Fadenbach deeper to slow down the trend of drying out of pools or becoming so shallow that drastic winter kills, caused by freezing of the water column, lead to population collapses. Furthermore, we suggested to locally deepening existing pools to sustain their role as refuge habitats during droughts. This was further developed by Spindler [134], in cooperation with the Austrian Danube National Park, established in 1996 (https://www.donauauen.at/en, accessed on 11 April 2022). Digging of the channel and of some pools carried out in winter 2000/2001 and a pronounced increase in metapopulation abundance was noted afterwards (Spindler 2006). Over one decade the mudminnow was found as the most abundant fish species in the Fadenbach channel [135]. There were confirmed habitat characteristics and associated fish community from the literature [116,136]. Then, the management of the mudminnow metapopulation in the Danube floodplain of Austria seemed to work since the management actions carried out in 2000/2001 in line with ecological goals defined for this channel [137]. The last survey, with good results, of that area was done in 2018 during a monitoring campaign fulfilling the Austrian obligations for the EU Habitats Directive [138].

For the second historic area of occurrence, in the Vienna basin southeast of the city, close to the Moosbrunn village, a viable population could be confirmed during 1993–1996. In the following few years a new monitoring campaign reconfirmed the recent existence of that population [139]. That population seems fairly stable and no specific management actions are imposed except the general protection of the area. The habitat is very different from the habitats in the Danube floodplain. It represents a groundwater fed spring followed by a rivulet running through a bog area. The cold-water stream is heavily overgrown and accompanying fish species consist of northern pike (*Esox lucius*) and bullhead (*Cottus gobio*) [133]. Similar habitat types are described from Hungary, for some streams entering Lake Balaton [139] and from Romania [128,140].

For the third historic area of occurrence, the Lake Neusiedl (Fertö) basin, no extant populations were found on the Austrian and the Hungarian side during early 1990s [130,141]. The reed belt of the lake was monitored in Austria, however, no mudminnows could be found [142]. In 2002–2005 a project for the re-introduction of this species was done [143,144], but not in the reed belt of the lake but in drainage ditches in the Hansag area east of the lake, very close to the Hungarian border. It was planned to get mudminnows from nearby Hungarian populations, however, as this proved difficult, reintroductions were performed with fish from the Danube floodplain (Fadenbach) metapopulation. A small remnant population was found in 2018 at the reintroduction site [139]. Close to the southern end of Lake Neusiedel (Fertö) mudminnows were detected in a drainage ditch on the Hungarian territory during a survey in 2017–2018 [145].

- Wetlands at the Austria-Slovakia-Hungary Border

In the past, *Umbra krameri* occurred in the Záhorie area only near Plavecký Štvrtok and Láb [146]. The historical area has been significantly reduced to only one locality near Plavecký Štvrtok [147], where the occurrence has now been confirmed. During the restitution of the species, the population coming from the Danubian Lowland was first stocked in the vicinity of Moravský Svätý Ján [148]. In 2007, the site was threatened with a complete drying out, so rescue catches and the transfer of European mudminnow to other sites were carried out. In 2008, we reaffirmed its occurrence in the channel system in the vicinity of Plavecký Štvrtok and Láb. Due to the occurrence of *Umbra krameri* in Záhorie, in the Morava's alluvium right-bank, it is highly probable that this species occurred in the territory of the Czech Republic in the left-bank alluvium of the Morava River in the past. In the seventies of the last century, old fishermen told us that they knew this species from the end of the First World War. Expanding occurrence within the original region would increase the stability of the population in Záhorie.

Within the Danube region, in the past, the richest localities of *Umbra krameri* were located on Žitný ostrov (Rye Island), especially in its SE part [149]. These were mainly drainage channels. To the east, the species extended beyond Komárno and to the north to Nové Zámky to the Nitra river basin, i.e., beyond the borders of Žitný ostrov (Rye Island). Valuable insights into the historical distribution and occurrence of the dark fern from the Danube region are summarized in the works of Kux [149], Mišík [150], Kopáčik [151], Balon [152], Brtek [153], and Hensel [154]. Recent data on the occurrence of mudminnow in the Danube region are in the works of Hajdú [155], Hajdú & Kováč [156], and Májsky & Hajdú [157]. Of the natural habitats, the occurrence of *Umbra krameri* on Žitný ostrov was confirmed practically only in the Čiližský stream. However, the occurrence of the species is mainly related to the system of drainage channels communicating with this former meandering arm of the Danube. Isolated populations on Žitný ostrov survive in the system of amelioration channels connected to the Jurová—Veľký Meder channel (Gabčíkovo, Vrakúň, Padáň) and in the lower section of the Čiližský brook. The most isolated and most vulnerable locality is the Ham Channel near Číčov.

The center of the *Umbra krameri* occurrence in the East Slovakian lowland was Medzibodrožie, in the southeast Slovakia bordered by the rivers Latorica and Bodrog. The only known locality north of this area was the old arm of Laborec, mentioned by Chyzer [158], Vladykov [159], and Záleský [160]. From Medzibodrožie there is more detailed research from the second half of the last century, mudminnow was found by Kux [149], Kirka et al. [161], Kokorák [162], and Weisz & Kux [163]. Evidence of its occurrence outside the river Bodrog basin—in the Slovakian part of river Tisza, was provided by Žitňan [164]. In the area of the Medzibodrožie, it is not currently a permanent occurrence, the population has symptoms of oscillation within the edge of the area. In recent years, we have confirmed *Umbra krameri* only at the channel near Streda/Bodrogom, connected through a network of other channels to the Tisza Old Arm—Krčava. Other sites are the old arm of Tisa-Tice near the village of Sv. Mária, the old arm of Bodrog and the channel near Somotor and also the Krčavský channel near the Dobrá village.

Umbra krameri lives in overgrown slow-flowing or stagnant waters in space beyond or outside active inundation, out of the direct reach of flood waves. It also occupied man-made drainage channels or material pits. The main center of gravity is in the banks zone. The habitats inhabited by *Umbra krameri* are characterized mainly by shallow, clear, slow-flowing, or stagnant water and dense stands of aquatic vegetation. The bottom of these habitats is made up mostly of the fine substrate (clay, sapropel) and remnants of dead vegetation. [165] Among the aquatic plants, the dominant ones are *Lemna trisulca*, *Lemna minor*, *Spirodela polyrhiza*, *Stratiotes aloides*, *Ceratophyllum demersum*, *Hottonia palustris*, and

Hydrocharis morsus-ranae. The riparian stands are dominated by *Carex* spp., only rarely by the islets of *Phragmites australis*, *Typha latifolia*, and *Salix cinerea* [166].

Characteristic for these localities is the organic mud from accumulating plant residues. These are alkaline, medium to hard waters, characterized by large fluctuations in oxygen content, associated with dense growths of aquatic plants. This factor may be one of the limiting factors influencing the composition of ichthyocenosis in individual localities. *Umbra krameri* is adapted to living in overgrown waters, where it tolerates short-term oxygen deficits well. It is found in the largest numbers in small channels (the depth of the water is in the range of 40–150 cm) with dense macrophyte growth, in the preferred community with a low number of predominantly limnophilic fish species [166].

In terms of vegetation cover, mudminnow inhabits very diverse localities [166]. Localities with a dominant occurrence of *Umbra krameri* represent habitats in which the substrate is formed by fine-grained sediments—sapropel and clay. The depth of the water is in the range of 40–150 cm. These habitats are characterized by stagnant or only very low flowing water, they are often richly supplied with nutrients, with richly developed submerged vegetation and a thin layer and a continuous riparian edge of helophytes. The riverbeds tend to be continuously overgrown with submerged macrophytes, some of which have a well-developed layer, and all of them also have a continuous helophyte ridge, which in some cases overgrows to the center of the riverbed. In general, it can be stated that although these are mostly artificial channels, these also have the character of older grounded depressions in the advanced stage of succession in terms of vegetation cover. In some localities, only the native layer of macrophytes and the continuous riparian hemisphere, sometimes penetrating to the center of the riverbed, are well developed. The more massive development of macrophytes is probably hindered by shading by woody plants, which in the case of these channels from a more continuous riparian growth, especially *Salix cinerea*. *Umbra krameri* was most often recorded in habitats that are at an advanced stage of grounding in terms of succession, with a well-developed submerged layer of vegetation. These are often channels with a predominance of pleustofytes of the Lemnetea class, the dominant species being *Lemna trisulca* in the submerged layer and *Lemna minor* and *Hydrocharis morsus-ranae* in the natant layer.

In waters with a dense growth of aquatic macroflora, differences in the concentration of dissolved oxygen occur between day and night, also during the season. The intensity of putrefaction processes is associated with the consumption of oxygen and the production of toxic substances (methanogenic and hydrogen sulfide processes). Methane and hydrogen sulfide are released from sediments and become toxic to fish. Oxygen deficits determine the dominance of species with accessory respiration—*Umbra krameri* and *Misgurnus fossilis* [154]. Oxygen deficiency also occurs in the winter due to freezing of the level—1.52–12 mg/L. Significant oxygen deficits were also recorded in localities with the occurrence of the species in the winter during the freezing of the surface [154].

One main reason for the *Umbra krameri* decline is the hydrological regime change due to river regulation, flood reduction, gradual extinction, and the impossibility of the creation of new alluvial habitats suitable for this species. As a result of extensive hydromelioration modifications on Žitný ostrov (Rye Island) carried out after 1960, changes in hydrological conditions occurred in the system of the inland Danubian delta [153]. These changes induced the disappearance of *Umbra krameri* from much of the territory, mainly from the Čiližský brook basin. The formation of new dead branches and side branches is impossible due to the river regulations, and the old branches slowly ground, dry out, and disappear. Although *Umbra krameri* quite often occurs in channels (it tends to migrate mainly to newly dredged ones or deeper ones), they are unable to provide it with conditions for permanent existence they are not suitable habitats throughout the year due to their hydrological conditions. The main reason is their unnatural hydrological regime, but also the need to maintain them in a successive stage, as they are artificial ecosystems with a tendency to extinction. This relict fish species had long-term adaptations (especially reproductive ones) to the natural flood regime. The absence of a natural flooding regime is the most serious cause of the decline of this fish. The natural floods allowed the *Umbra krameri* populations to pulsate, to communicate with each other (between inundation populations and river populations—in the east—Bodrog, Tisa, in the west—Danube, Little Danube, Čiližský stream), which is important in terms of intraspecific diversity in terms of settlement of new localities after the extinction (succession) of old ones. Due to the floods, *Umbra krameri* had the opportunity to escape on its own from sites where the site was in danger of extinction due to succession. Another factor that may have caused its decline in the past was the appearance of non-native species, of which the brown bullhead (*Ameiurus nebulosus*) probably played the most negative role. Of the recently identified non-native fish species, black bullhead (*Ameiurus melas*) as a predator and food competitor and Amur sleeper (*Perccottus glenii*) as a food and habitat competitor poses greatest danger to European mudminnow [167].

We consider it important for the *Umbra krameri* population in Slovakia preservation to ensure the successful reproduction in localities in which it occurr, by appropriate management, especially of old river branches, which considered as being its refuges. The adjustments should concern the follow-up channel network and should aim at creating suitable habitat conditions for reproduction, rearing young, and the possibility of migrating back to the old branches. When maintaining channels (sediments cleaning) it is necessary to respect the ecological needs of this species. Details concerning the conservation management of the species' sites were elaborated in the European Mudminnow Rescue Program [157]. At selected localities on Žitný ostrov (Rye Island), measures were implemented in 2007 to restore the depth conditions of grounded sites, and to clarify the surface to support the development of macrophytes. This program thus became the starting point for the design and implementation of practical care and revitalization measures in specific localities. In order to evaluate the success of revitalization measures, *Umbra krameri* population development is monitored. In order to improve the condition of localities with the occurrence of *Umbra krameri* in the Záhorská lowland, the shading riparian vegetation of the melioration channel in the locality near Moravský Svätý Ján was experimentally removed. The purpose was to support the development of macrophytes, which are a necessary part of the habitat suitable for this species. In addition, the channel was deepened in selected sections. The deeper parts can serve as refuges during extremely low water conditions and the purpose of this measure is to prevent the extinction or excessive reduction of the population due to the desiccation that affected this site in the summer of 2007. We recommend setting up *Umbra krameri* breeding in Medzibodrožie, eastern Slovakia, most threatened with extinction [167].

3.2. Wetlands of the Danube River in Hungary

The Carpathian Basin, chiefly the Hungarian area of the Danube Basin, has suffered from large anthropogenic modifications in the middle of the 19th century. Antecedently, more than 21,000 km^2 areas were flooded periodically, providing a special type of habitat for many organisms [125]. The flooded fields were the main occurring places of swamp-like species, such as *Umbra krameri*, which were used in feeding domesticated animals due to its high abundance [168]. After the river regulations and hydro-technical modifications, 97% of fen habitats have been lost, which implied the declining and vanishing of a notable part of the *Umbra krameri* populations [169,170]. Remained populations have to adapt to the altered habitats and invade the newly constructed meliorate channels and remained oxbow lakes. Nowadays, recent occurring data have shown that habitats preferred by this fish are rare and isolated from each other [126,169].

The Danube Plain in the Middle Hungarian Danube basin area was rich in wetlands before the river regulation. With its wide and continuous floodplain, Danube Valley was appropriate for *Umbra krameri* [168]. After the regulations, the wideness of the Danube floodplain, for this reason, the living habitat of *Umbra krameri* had highly decreased. Presently, natron lakes, channels and oxbow lakes, and backwaters remained in the place [165]. Records about *Umbra krameri* have been found from the beginning of the 19th century till nowadays [111,157]. In the northern part of the Danube Valley still extend some relics of the olden swamps with small *Umbra krameri* populations, like Rákos creek and its marshland [109,125], the Turjánvidék in the Ócsa Protected Landscape Area [126,171,172]. In the middle of the Turjánvidék, one of the most important wetland habitats of Danube Plain have found, named Lake Kolon, which makes part of many international conventions. One of the densest *Umbra krameri* populations has lived here [126,173–175]. Different types of channels and streams contribute to living habitats for some remaining populations like Karasica-main-channel, Szőlőaljai-channel, and Adacsi-chanel in the southern part of the Valley [126,173,176]. Sallai and Vajda [177] have recently reviewed the status of *Umbra krameri* in the middle and the south part of the Danube Valley. They highlighted that the species have stable populations there, however, the decreasing water levels (and drying out) of wetlands is a serious problem in the region [177].

Along the Danube Valley, relatively many fen habitats, marshlands, melioration channels, backwaters, and natron lakes preferred by the *Umbra krameri* have remained.

In the case of Turjánvidék, a complex of shallow fen habitats and moorland forest are present. Although after regulations, the water supply of the area has been damaged, a major part of the habitat is still untouched. Fields are inundated permanently, and quite rich in organic matters. Several species of plants form suitable habitats for many species (e.g., *Cladium mariscus*, *Caricion davallianae*, *Stratiotes aloides*, *Iris pseudacorus*, *Hottonia palustris*, *Nuphar lutea*, *Lemna minor*). Lake Kolon, as a unique freshwater marshland habitat of the southern part of the Danube Valley, has salinating on the shallow parts. In the foreshadowing progress of succession, this fen has been loading. Submerse macrophytes like *Ceratophyllum demersum* and *Potamogeton natans* is considerable, but *Nymphaea alba* and *Lemna trisulca* are characteristic elements too [173,175,177].

The melioration channels and lowland streams function like potential secondary living habitats. Their average width varies between 1–5 m and the average water depth between 0.5–4 m. Because of the surrounding agricultural lands, these habitats are rich in nutrition, which can result in eutrophication. Generally, the conductivity varies between 500–1100 µS/cm, which can be explained by a high level of nutrition. Water flow in these channels is slow in general and the deposited layer could be almost 1 m depth. The level of dissolved oxygen does not exceed the 1 mg/L. Due to the increasing water use, and the climate change, their water levels have relevant fluctuations, and they show a decreasing trend. If their beds and banks have macrophytes they are generally the following: *Typha latifolia, Phragmites communis*, *Lemna minor*, *Lemna trisulca*, *Hydrocharis morsus-ranae*, *Nymphaea alba*, *Nuphar lutea*, *Utricularia vulgaris*, *Ceratophyllum demersum* [168,169,173].

River regulations have caused a large-scale degradation in the swamp-like habitats since the 19th century [126]. Aquatic organisms have low ability for dispersion, and habitats degradation could lead to genetic erosion [178,179]. Hungarian wetland habitats have been isolated from each other conducting genetic isolation of these populations too, there were proved the differences among the *Umbra krameri* populations. Based on the population genetic patterns among and within the observed areas, they justified that *Umbra krameri* populations can be related into two evolutionarily significant units, which measure up with the Danube and Tisza rivers basins [126].

Another type of hydro-technical modification is the treatment of the melioration channels newly colonized by the *Umbra krameri*. These narrow and shallow habitats have been used just periodically and reinforcements of the water are not appropriated. They can drought more times a year, even in the middle of the reproductive period of this fish species. As a short lifespan fish, whole populations can extinct without offspring recruitment. Poorly designed dredging of the river or stream beds can result in the decline or disappearance of the remained *Umbra krameri* population. This process could be harmful during winter dormancy or the spawning period [173,179,180].

Invading of alien species has become lately one of the main global issues likewise in the Carpathian Basin too [180]. Amur sleeper (*Perccottus glenii*) has been recorded in the Tisza River system (in Lake Tisza) in 1997, and its spreading is still happening [181]. Its ecology shows overlap with those of *Umbra krameri* [168,182] and as a generalist species, *Perccottus glenii* has an aggressive behavior against *Umbra krameri*, being a successful competitor [181]. *Perccottus glenii* was found at the Middle Danube Region in 2008 too [183,184]. The main parts of the wetlands of the Danube River are not penetrated by *Perccottus glenii*, but its further expansion can threat the *Umbra krameri* populations [183].

Towards to protect the remained European mudminnow populations, we should to work out conservation management plans, and avoid the destruction and artificial modification of their habitats. To reinvade the European mudminnow into its natural occurrence place, we have the opportunity to make up the offspring recruitment with artificial breeding techniques [126,169,173].

Degradation and alteration of fen habitats leading to the decline and vanishing of *Umbra krameri*. Many melioration channels are semistatic or astatic, so they can desiccate at least one time a year. During the drought, there is no chance to survive in these shallow habitats [174,177]. We recommend the aware use of irrigator water in the case of surviving any aquatic animals living in these places. In our opinion, keeping a 60 cm level of water would serve as a solution, permanently [168,169,173].

As an important part of watercourse management, dredging is a radical way to manage the load of the waterbed. Poorly planned management work can result in the destruction and alteration of the watercourses. Especially, in the winter period, *Umbra krameri* hide in the near of waterbed, therefore winter dredging can cause the death of many specimens. Hyidrotechnical modifications under the spawning season can disrupt the spawning of the fish or destroy its nest, resulting in the vanishing of recruitment. Therefore, we consider dredging out of the dormancy and spawning season, as well as the half part dredging of the waterbed [169,173].

The spreading of non-native species, especially the *Perccottus glenii* is a major issue. As a generalist competitor, this species can pose a serious threat to the extant *Umbra krameri* populations [182]. However, *Perccottus glenii* is not widespread in the Middle Danubian Region, but its further expansion can be expected in the near future [185].

3.3. Lugomir Channel System in Danube Drainage in Serbia

The Lugomir is part of the channel system which draining excess water from riverine land. It is situated close to the Serbia-Croatia-Hungary border, in the upper part of Danube drainage in Serbia, near Special Nature Reserve Gornje Podunavlje. The first record of *Umbra krameri* in Lugomir was in 2008. This species were frequently confirmed in this location [186,187].

This area represent extorted, artificial habitats formed due to the conversion of wetlands into agricultural land. These lowland channel biotopes characterize cold, clean water, muddy bottom, and dense macrophyte vegetation. The channels' widths are between 4–6 m, and deep up to 2 m. Large agricultural complexes surround the location.

This area is sensitive to changes in the hydrological regime. Additional human impacts are present through: pollution of habitats with pesticides and fertilizers, which lead to eutrophication and an overall decrease in habitat quality; introduction of non-native species, and their impact through competition and predation.

Prevention and restoration measures of human impacts on *Umbra krameri* habitats of Lugomir are the following: decrease of water usage for irrigation; reduction of using artificial fertilizers and pesticides near the watercourses; prohibition of the introduction of non-native species and reduction of the biological contamination level; dredging the channel network, to prevent their overgrowth and turn into terrestrial biotopes; since these are small localities, establishing aquaculture in ex situ conditions would enable an increase in the size of populations; raising awareness and active public involvement in the protection of this species and its habitats [188].

3.4. Kraljevac Channel System in Danube Drainage in Serbia

The Kraljevac belong to the channel system which draining water in excess from riverine area. Special Nature Reserve Kraljevac is located in the southern part of Banat region and belongs to the middle part of Danube drainage in Serbia, with 264 ha of protected area. The first record of *Umbra krameri* in Kraljevac was in 2014. This fish were frequently reconfirmed here [187].

This area is an extorted, human made habitats formed due to the transformation of wetland areas into agricultural land. These lowland channel biotopes characterize cold, clean water, muddy bottom, and dense macrophyte vegetation. The channels' widths are between 4–6 m, and deep up to 2 m. Big agricultural farms encircle this area.

This area is sensitive to modifications in the local hydrological regime. Supplementary human impacts are present: pollution, eutrophication, diminish of habitat quality; non-native species introduction, etc.

Mitigation and rehabilitation measures of human impacts on *Umbra krameri* ecosystems of Kraljevac are: decrease of using fertilizers and pesticides near the water bodies; diminish of water usage in agriculture; baning non-native species introduction; dredging the local channels; raising public consciousness regarding this species conservation.

3.5. Wetlands at the Serbia-Romania Border

Here, the Danube makes a huge meander, in few small riverine wetlands, *Umbra krameri* was found in the 19–21th centuries [189]. This species was rarely found in this area also in the last years by the authors on the Romanian side Danube bank area small wetlands. In the Serbian Danube River side no recent findings were registered [188,190–192].

The preferred habitats for the *Umbra krameri* in this area are small wetlands, with a muddy bottom and rich aquatic vegetation. This area's small wetlands are characterized by a high human activities impact, especially due to water pollution and favorable habitat destruction, on its fish fauna. The impacts of climate change on this area's fish species have not yet been studied. On the Serbian side, this site/population no longer exists because it was totally flooded by the construction of the Iron Gates/Ðerdap Reservoir.

Prevention, mitigation, and reconstruction work to compensate the human impacts on *Umbra krameri* habitats of this area are the followings: reductions in habitat fragmentation and loss; reductions of the current biocontamination level; stopping the impoverishment of aquatic habitats; restoration of floodplains and old-deserted irrigation channels; monitoring of water pollution and ichthyofauna habitats and populations; etc.

The following management elements for *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species habitat and populations; elaboration of management plans for specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; fighting pouchery, etc. [193].

3.6. Jiu River Lower Part in Romania

With a 339 km length and 10,080 km^2 of its basin, the Jiu River is formed in the Transylvanian Alps, it flows southward before flowing into the Danube [191,192]. In the 19th and 20th centuries *Umbra krameri* was not mentioned in the Lower Jiu River basin wetlands [112,193] but it was accidentally found in the present in some of these lower basin wetlands anthropogenic channels relatively close to the Danube [193]. This species was rarely found in this area also in the last years by the authors.

The preferred habitats for the Umbra krameri in this area are wetlands formed by old deserted small irrigation channels, with a muddy bottom and rich aquatic vegetation.

The Jiu River basin is characterized by a high human activities negative impact, especially due to water pollution and favorable habitat destruction on its fish fauna [193]. The impacts of climate change on this area's fish species have not yet been researched.

Prevention, mitigation, and restoration of this fish habitat affected by the human impacts in the study area are following: reductions in habitat fragmentation and loss;

stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; reductions of the current biocontamination level; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; etc.

The following management elements for these species populations are suggested: extension and creation of reserved areas for the conservation of this species habitat; dedicated management plans for the proper habitats; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands; etc. [193].

3.7. Olt River Lower Part in Romania

The 615 km long Olt River in central and southern Romania drains a catchment of 24,439 km^2 and enters the Danube. *Umbra krameri* was mentioned by Bănărescu [106] in some rather degraded wetlands. The preferred habitat for the *Umbra krameri* species in this area are wetlands with a muddy bottom and aquatic vegetation.

The Olt River basin is characterized by a high human activities and negative impact [100,191–195], especially due to water pollution and favorable habitat destruction. The impacts of climate change on this area's fish species have not been studied.

Degradation prevention, mitigation, and reconstruction of *Umbra krameri* habitats activities proposed for this area are: reductions of the current biocontamination level and habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution and ichthyocenosis; etc.

The following special management elements for these *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of management plans for specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; etc. [193].

3.8. Vedea and Argeş Rivers Lower Part in Romania

The 244 km long Vedea River confluence with the Danube River. The 327 km long Argeş River located also in southern Romania drains a catchment of 12,590 km^2 and enters the Danube [191,192]. *Umbra krameri* was mentioned by Bănărescu [106] in some degraded wetland areas. The favorite habitats there for this fish are wetlands with a muddy floor and thick aquatic vegetation.

These basins are influenced by accentuated human activities [100,195], in particular due to water pollution and habitat destruction. The influences of climate modification on this fish have not been studied in this area.

Habitats degradation avoidance and rehabilitation activities suggested for this area are: reductions of the existing biocontamination intensity and habitat breakup and loss; stopping the misery of aquatic ecosystems due to the extreme use of land for the agriculture; rehabilitation of floodplains and old channels; building and upgrading of wastewater treatment plants; water quality and biodiversity monitoring; etc.

The following management actions for these fish populations are recommended: creation of specific management plans for wetland areas of interest; ensuring sufficient water regime by omission the capture of springs and drainage of wetlands; expansion and establishment of reserved areas for the protection of this species and its ecosystems; etc. [193].

3.9. Lower Danube River Basin-Danube River Delta in the Romania-Moldova-Ukraine Border Area

The Danube Delta was created by a unique combination of integrated biotopes and biocoenosis related forces and counter-forces in time and space, is the second-largest (4152 km^2) and best-preserved river delta on Europe with its largest part in Romania, forms an extremely rich complex of ecosystems and "ichthyosystem" [91].

In the past *Umbra krameri* was mentioned as very common in all the Danube Delta. Since 1990, sporadic specimens have been reported in a small number of ponds and channels. Compared to the past, the number decreased due to the eutrophication phenomenon and consequently to the reduction of favorable habitats. [102,107,110,112,122,140,196–201] This fish was relatively rarely found in this area also in the last years.

Relatively numerous evidence of *Umbra krameri* presence in the Ukrainian section of the Danube Delta and adjacent water bodies were recorded by staff of the Danube Biosphere Reserve. The data of the collections catalog of the National Museum of Natural History at the National Academy of Sciences of Ukraine are the most reliable [202], the collection contains 158 specimens of mudminnow, collected nearby the town of Vilkovo over the years 1963–1974. Besides, the museum collection contains one specimen 57 mm long, taken on the Lung Lake, and four specimens, taken in the town of Vilkovo in 2007.

Indirect evidence regarding the occurrence of this species in many water bodies of the Danube Delta is contained in the paper [203] which states, that the *Triturus dobrogicus* and mudminnow inhabit the same water bodies outside the town of Vilkovo.

There is also evidence of the mudminnow occurrence in the Sasyk liman. After the liman desalinization by the Danube water, it was recorded in 1981 and by 2006 has become quite common [204]. The occurrence in the Danube lakes Yalpug, Kugurluy, and Katlabukh is confirmed [205]. The preferred habitat for the *Umbra krameri* in Danube Delta is formed by small ponds, with a muddy bottom and rich in vegetation [122,140].

The Danube Delta ecosystems exhibits, a significant level of flexibility, resilience, and adaptation over geological time, but have become much more sensitive to environmental perturbations due to the last century of human impact on the Danube Basin (e.g., geomorphological and hydrological changes, aquatic and semiaquatic riverine habitat fragmentation and/or loss, aquatic and semiaquatic vegetation diminishing/disparition, pollution and/or eutrophication, fish pouching and/or overexploitation, alien species introduction, and trophic resources diminishing/disparition, etc.) [91].

Prevention, mitigation, and restoration of human impacts on *Umbra krameri* habitats are the following: dam management in a way in which the hydrological, morphological, and hydraulic effects will be controlled in terms of sediment balance up and downstream at a basin-wide scale; reductions in riverbank covering and reinforcement; introduction of non-native species; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of hydropower; recreational and professional poaching control; restoration of floodplains to fulfill the targets of European Union Water Framework Directives; acceleration of construction and improvement of wastewater treatment plants; monitoring of organic pollutants, heavy metals, and any other hazardous substances in the fish meat; etc. [91].

The following special management elements for these *Umbra krameri* populations are suggested: rehabilitation of old destroyed wetland areas; extension of new reserved areas for the conservation of this species and its habitat; elaboration of management plans for wetland areas of specific interest; ensuring adequate water regime by prohibiting the drainage of wetland habitats to obtain new agricultural land; etc. [193].

3.10. Mura and Drava River System at the Slovenia-Croatia-Hungary Border

The Drava River is a right, fourth longest tributary of the Danube, with 725 km length it crosses five countries, and is of European Union fish fauna conservation interest. The largest tributary of the Drava is Mura River which flows through four countries and after more than 400 km near Legrad town inflows into the Drava [206–209].

The first data about the *Umbra krameri* presence in Drava-Mura river system comes from the end of the 19th century [210] with mentions in the reeds at the confluence of the Drava and the Danube (Kopački rit). Several later authors mention this species as part of the Yugoslavian ichthyofauna and write that it lives in this part of the Danube basin, but do not specify the exact range or specific localities [211–214]. This fish was recorded again in the Drava-Mura river system, in the early 1980s in oxbows along the Mura River near the settlement Petišovci in Slovenia [215–219]. This species was found also in oxbows south of the Mura River, in the area of Međimurje in Croatia [220]. These first findings were followed by more sites along the Mura River in Slovenia and Croatia [221–223]. It was recorded also in several localities in the middle part of the Drava in Slovenia [224] and Croatia [221,225]. In the lower reaches of the Drava River the species has been found at a large number of localities in the Virovitičko-podravska County in Croatia [226–228].

Umbra krameri along the Mura River in Slovenia and Croatia, mostly lives in small swamps and ponds (dead arms, backwaters, marshes, oxbows) [217,221,223]. These are smaller water bodies of very complex habitats, with muddy bottoms, large amounts of organic material, dense aquatic vegetation, and filled with fallen trees. In Međimurje in Croatia, inhabits also smaller flowing waters such as streams and channels with the constant or occasional flow and well-developed aquatic vegetation. Along the Drava River, the species is much more often recorded in streams and irrigation channels that form an amelioration network connected to the main river [221,226–228]. For most of the year, the water in streams and channels stagnates or flows slowly, they are overgrown with dense riparian and aquatic vegetation, and their surface is often covered with duckweeds Taler [211] and Pavletić [212] among the first mentions that the biggest threats for this fish in Yugoslavia are land management and stream regulations. Other negative impacts on *Umbra krameri* populations in the Mura-Drava River system are habitat degradation and destruction due to regulation and channelization of watercourses, drainage of wetlands, and embankment construction, river damming, and introduction of the alien (exotic) fish species [218,219,221,223,226–228]. Various forms of water pollution, such as agricultural, industrial, and municipal wastewater, also have an impact. Natural burying, overgrowing, and disappearing ponds and wetlands are also a problem in some places.

In order to protect and manage the populations of the *Umbra krameri* in the area of the Mura-Drava River system, it is necessary primarily to protect and preserve the habitats where the species was recorded. Mura and Drava with their wetland habitats are protected as a UNESCO 5-country Biosphere Reserve Mura-Drava-Danube. It is the largest protected river area in Europe, called the European Amazon. In addition, Croatia protected most of the river system as the Regional Park Mura-Drava which stretches from the Slovenian border to the confluence of the Drava and the Danube. Within the park, natural wetland habitats are protected (e.g., floodplain forests, dead backwaters, abandoned river beds) as well as the species that inhabit them. In Slovenia and Croatia, the *Umbra krameri* is one of the target species in 10 special areas of conservation of the EU ecological network NATURA 2000. Within the Interreg Danube Transnational Program, in Virovitičko-podravska County, an expert report for the implementation of the Management Action Plan for *Umbra krameri* was prepared [227]. Specific measures that would contribute to the protection of species in the Mura and Drava river system are protection, rehabilitation and revitalization of wetlands (i.e., dredging oxbows), preservation of small irrigation channels and improving water quality and ecological conditions.

3.11. Zala River, Lake Balaton System in Hungary

Before the 19th century hydro-technical works, drainage of the Lake Balaton had one of the biggest marshland and fen habitats in the Transdanubian area. Due to the human impact (e.g., construction of railway network, agricultural cultivation, etc.) which resulted in the large-scale degradation of fen habitats, several animal species, as well as the population of the European mudminnow, have started to decrease considerably. Nowadays, the Kis-Balaton reservoir system, as the result of the restoration of fen habitats, forms a prominent wetland of the Lake Balaton catchment [229,230]. Based on the regular ecological assessment by the fish fauna, the European mudminnow has a dense and stable stock in the Kis-Balaton reservoir system and its channels [173,176,231–235].

The first records about the European mudminnow originated from the middle of the 19th century, before the draining of the region [236]. After the hydro-technical modifications and habitat degradation, a decrease in the mudminnow population has been recorded. In our days, the constructed reservoir system and the connected channels are protected by nature conservation, therefore the mudminnow stocks are stable now, based on regular surveys of the fish fauna [173,237–239].

Within the reconstructed reservoir system, we can distinguish several types of natural habitats. The lakes of the reservoir (Lake Hídvégi and Lake Fenéki) with dense aquatic macrovegetation represent the standing water environment. Dense reeds (*Phragmites communis*, *Glyceria maxima*, *Schoenoplectus lacustris*, and *Typha angustifolia*) and other aquatic and hydrophilic plants (*Iris pseudacorus*, *Ceratophyllum* spp., *Utricularia* spp., *Lemna* spp., and *Stratiotes aloides*) serve not just like a perfect filtering system prevent the nutrition overload of Lake Balaton but provide a much appropriate living and spawning habitat for fish. As the connection between the lakes of the system, River Zala serves a heterogenous, riverine ecosystem for the fish species. Artificially created irrigation or melioration channels forms a transition between the lotic and lentic environment [173,240,241].

Since the middle of the 19th century, the Lake Balaton catchment and the Zala River had changed. Due to the construction of the railway along the southern part of the Balaton, drainage of the marshlands and fen habitats and regulation of the Zala River has been started. After this, agricultural cultivation and peat extraction led to further habitat degradation [241,242]. Nowadays, many reconstructions work has resulted in this unique natural habitat which is a prominent spot for plants and animals, being part of many international conveniences and being protected by nature conservation. Currently, insufficient treatment of wastewater and the spreading of nonnative species constitute a threat to the wildlife and the remained mudminnow stocks. In many cases, the Zala River is the recipient of mainly treated wastewater, antibiotics, endocrine disruptors, and pharmaceutical residues that can harm the environment [242–245]. The appearance of the Amur sleeper in the late 2000s is a serious concern, as well as the tropical aquarium fish, which originated from the field of aquaria [165,176,177,234,235,245,246].

In the light of faunistic surveys and human impacts, the Kis-Balaton reservoir and Zala River Basin still have stable mudminnow populations, although, we cannot ignore all of the obvious menace factors. Monitoring of the populations of the European mudminnow and nonnative species like Amur sleeper is necessary. In consideration of the impact of Amur sleeper on other mudminnow populations, we have to prepare a conservation management plan for saving mudminnow stocks and their specific genetical background too in the case of a strong population decrease [173].

3.12. Upper Tisza System in Ukraine and Hungary

In the Ukrainian part of the Tisza basin, *Umbra krameri* was distributed quite widely [247]. Particularly, it was found nearby the town of Beregovo in the leftovers of the drained wetland massif "The Black Mochar," in the flood-land water bodies of the Tisza, Latoritsa, and Borzhava rivers. The maximal number of the relatively recent records of the *Umbra krameri* is known from the flood-land over-wetted slow-flowing water bodies in the area of the modern location of the Beregovo polder system.

Reliable data on records of the *Umbra krameri* in the Ukrainian part of the Tisza Basin are absent. The collections' catalog of the National Museum of Natural History at the National Academy of Sciences of Ukraine contains information on specimens, taken in July 1986 in the Latoriza river side arms (35 specimens 24–87 mm long) [203].

Kurtiak et al. [248,249] mention this species in the species lists, however, without any specification of the sampling site or size of the taken specimens.

Over fish studies in Transcarpathia in 2008–2014 [165,250,251], this species was not found, though investigation covered the water bodies in the flood-lands, where habitat conditions to the maximal degree correspond to the *Umbra krameri* biological features.

Our only actual record of the species occurred in August 2015, two years after ichthyomeliorative activities, mechanical cleaning of a small area and stocking with herbivorous fish were carried out, in the dead arm Charonda/Csaronda, which previously was thoroughly surveyed and *Umbra krameri* was not found [252,253]. Two specimens 42 and 64 mm long were found in the forgotten poachers' fishing pot (48°26′13.74″ N, 22°15′59.24″ E). The net catches of the closest biotopes gave no results. Probably, it was brought along with the fish stocking, taken in the Transcarpathian fish farms.

The Upper Tisza Region in Hungary involves three typical biogeographical plains areas where *Umbra krameri* have existed: Bodrogköz, Szatmár, and Bereg [126,173,254].

Before the regulations of the Tisza River system in the 19th century, the Bodrogköz was characterized as a large floodplain of Tisza and Bodrog Rivers. This area was rich in wetlands, where limnophilic species such as *Umbra krameri* was widely distributed. After the regulations and draining of these wetlands, the stocks of this species have started to decline. The remained populations survived in the artificial channels e.g., Ricsei, Bélyi, Tiszakarádi, Szenna-lápi [126,173]. Due to the expansion of the Amur sleeper and the regular desiccation of these channels, the species is surely extinct from Bodrogköz, the last occurrence data is from 2012 in this rergion [126].

The Bereg plain was also rich in wetland habitats before the 19th century. The largest in the area was the Szernye marsh, where the *Umbra krameri* was extremely abundant, and it was used to feed domestic animals (e.g., pigs and ducks). After the regulation of the Tisza River, the populations of *Umbra krameri* also decreased significantly and were established sporadically in artificial channels (e.g., Csaronda/Charonda, Szipa main channel), and in the unique peat bog habitats of the Bereg plain (e.g., Bábtava) [173]. Tatár et al. [170] assumed the extinction of *Umbra krameri* from the Bereg plain in the early years of the 2010s. Due to the dynamic expansion of Amur sleeper in this area, and the regular drying out of habitats, the extinction was also confirmed in 2019. At the same time, Polyák et al. [253] described a new population of *Umbra krameri* from the peat bog called Lake Zsid in 2020, which is the last known population in the Bereg plain.

One of the most famous wetlands was the Ecsedi marsh in the Szatmár plain before the 19th century, where limnophilic species were abundant. After the water regulations, the *Umbra krameri* was known only in two watercourses: Gőgő-Szenke and Öreg-Túr. In the early years of the 2010s, due to the expansion of Amur sleeper and regular water pollution, the population of *Umbra krameri* critically decreased in the Gőgő-Szenke [170]. Tatár et al. [170] rescued fish from the polluted watercourse and reintroduced the captive-produced offspring to their original habitat. But despite all these factors, the habitats of *Umbra krameri* in Gőgő-Szenke dried out more than once in the second part of the 2010s, and the population extinct. Sevcsik and Tóth recorded a huge population from Öreg-Túr in 2010 [255], but thereafter, only five specimens were caught in the last 11 years, in 2021 and 2022 [256], which indicated the critically decrease of this population especially due to the Amur sleeper's appearance.

In the Ukrainean dead arm, "Charonda", is a sinuate lake system of the Charonda River, which once was a tributary of the Latoritsa River (Tisza's basin). Owing to the water flow redistribution after the construction of the channels "Charonda-Tisa" and "Charonda–Latoritsa", the river section from the Demychi village to the mouth was transformed into the dead arm of the same name. Its width somewhere reaches 57 m, depth from 1 m near the bank to 1.5–1.8 and even 3.4 m. The water flow is absent owing to the embankment. At the distance of 6.5 km from the dead arm upper, there is a pumping station N12.

The bottom substrate consists mainly of the silt deposition up to 1.5 m thick, plant residues, and filamentous algae. In summer the water area is overgrown by 70–90%, mainly by the Stratiotes aloides. Among the invertebrates, the Chironomidae larvae are the most diverse (25 species) and abundant, both on the bottom and in aquatic plants. Other groups comprised 1 to 5 species.

When *Umbra krameri* was widely distributed in the Hungarian Upper Tisza Region, the increasing agricultural cultivation, the not well-treated wastewater influents, and the decreasing water levels were the most threatening factors of the habitats. From the second part of the 2010s, the annual drying out by artificial flow regulation and climate change is the most serious problem. Due to these changes, the original habitats of *Umbra krameri* became astatic, and the rate of decrease of populations is higher than 95% [253].

In the Hungarian Upper Tisza Region generally, *Umbra krameri* exists only in Zsid lake and Öreg-Túr. In the northeastern part of the Great Hungarian Plain, peat bog lakes were formed from old oxbow lakes of Tisza River from the last glacial period, providing now a unique living habitat for the *Umbra krameri*. As the southernmost peat bogs of Europe, they have a special microclimate, flora, and fauna. The water chemistry of peat bog lakes is so specific, the only source of nutrition recruitment originates from precipitation, and therefore these habitats are oligotrophic. In terms of acidity, they have an acidic pH environment (<6 pH), however, Hungarian peat bog lakes need a special way of water reinforcements, therefore the acidity can change between a wider range. From a vegetation point of view, the following relatively rare plants occur: *Sphagnum magellanicum*, *Dryopteris cristata*, *Typha latifolia*, *Hammarbya paludosa*, *Eriophorum vaginatum*, and *Lemna minor* [257]. The most relevant peat bogs are the Bábtava and the Lake Zsid in the Bereg plain. To avoid the desiccation of these peat bogs, they have had an artificial groundwater supply since the 1980s [257].

The Öreg-Túr is the original lower part of the regulated Túr River. Nowadays it is the only habitat of *Umbra krameri* in the Upper Tisza Region which is not endangered by the drastically changing water level and drying out. The average width of the lower section of Öreg-Túr changes between 5–10 m and the average water depth changes between 1–2 m. *Sparganium erectum* are very specific for the Öreg-Túr, they make a floating vegetation cover on the surface of the sides of the river [258].

In the territory of the Ukrainian Transcarpathia, the lacustrine-wetland ecosystems experienced the most drastic modifications owing to amelioration and flood-protective measures. Only in the Transcarpathian lowland their area reduced almost by 90%. For instance, the wetland massif "The Black Mochar", which once was the biggest and covered about 15 ha, or about 1/5 of the Transcarpathian lowland area, was totally ameliorated as early as to the first half of the 19th century [259]. Further, the large-scale construction of the polder and ameliorative systems, like Beregovo and Tur-Botar, almost destroyed the natural water bodies—the Umbra krameri habitats. At the turn of the 20th century, agricultural activity decreased, vast areas of agrocenoses are not developed and ameliorative systems in many regions are out of operation. The biogeocenosis started renaturalization, and ameliorative channels were not cleared and became excessively overgrown by diverse submerged and emerged aquatic plants.

The priority tasks regarding the *Umbra krameri* protection and conservation in this Ukrainian area should include protection and rehabilitation of its habitats. This can be reached by creation of the botanical and hydrological reserves. The protection measures should cover all remaining wetlands, natural water bodies (dead and side arms, flood-land oxbow lakes), flood-land complexes and forests, independently of their origin. This work in Ukraine was started by the organization of the Regional Landscape Park "Prytysianskiy". For the groundwater level elevation and hydrological regime improvement, this park should include all forest massifs, which surround "The Black Mochar" wetland. The most depressing sites of the former bog should be considered as zones of the landscapes' renaturalization. The system of the ameliorative channels in the lower sections of the Tisa River and its tributaries, particularly Latoritsa, should be rearranged in order to partially rehabilitate the hydrological regime of the naturally over-wetted territories.

Due to the huge habitat loss and the rapid expansion of Amur sleeper, definitively there are no viable habitats for *Umbra krameri* in the Hungarian Upper Tisza Region. The Hungarian "European Mudminnow Conservation Pilot Programme" has solved the rescuing and artificial breeding process of *Umbra krameri*, and they captured 15 specimens from Gőgő-Szenke in 2010, and 30 specimens from the Lake Zsid peat bog in 2021 [169,170,260]. For the successful restocking of *Umbra krameri*, rehabilitation and creation of habitats without the presence of non-native species and stable water levels is essential.

3.13. Borsodi-Mezőség Plane, Tisza System in Hungary

Borsodi-Mezőség plane is a small biogeographical region of the Tisza River Basin. Before human alterations, the northern part of the plane was characterized by alluvial fens, streams, and channels from Bükk Mountains. The southern part was abounding in watercourses, fen habitats, and marshlands which were flooded by the Tisza River periodically. After hydro-technical activities the southern part of the plane has lost most of these habitats, drained fields had been used for agricultural cultivation. However, the northern region still has many streams, channels, oxbow lakes, and fen habitats [261].

Ichthyological records of the region have remained from the beginning of the last century [261]. The watercourses in the northern part of the region originate from the Bükk Mountain and are regulated (e.g., Hejő-main-channel, Álom-Zugi-channel, Matola-channel, Rigós, Takta). Due to the hydrogeological modifications, the lower sections of these channels are suitable for stagnofil fish species, as well as the European mudminnow [173]. Several oxbow lakes of Takta and Tisza River have remained from the river regulation and serve as a potential lentic ecosystem. Residual fens and oxbow lakes, as well as the lowland channels, are surrounded and covered by emerse and submerse macrophytes (*Phragmites communis*, *Typha latifolia*, *Stratoides aloides*, *Hydrocharis morses-range*, and *Ceratophyllum demersum*) and have a thick deposit layer [262].

After the great river regulation and canalization of the 19th century, the degradation and disappearance of fens and marshland have been started. Today, agriculture is the main economic sector of the region, which result in the nutrition overload and eutrophication of the remaining and created waterbodies [173,263]. Poorly planned hydro-technical modifications, like dredging of stream and river bed can be harmful in the winter dormancy and breeding season either. Furthermore, these waterbodies are quite shallow and usually desiccate [173]. At the beginning of this century, the non-native Amur sleeper appeared in the region. Due to its rapid spread, the Amur sleeper is one of the most dominant species in some of the region's waterbodies [173,181,244,264,265].

Because of the large-scale destruction of the biotope and rapid expansion of Amur sleeper, the development of a suitable conservation management plan is needed [169,170]. Due to these threats, artificial breeding is necessary to keep populations stable in the future [170]. To avoid desiccation and the accompanying extinction of mudminnow stocks, we suggest controlling the water level and supplementing water bodies [126].

3.14. Bihar-Plaine Tisza System in Hungary

As an alluvial fan of the Berettyó and Sebes-Körös River, the Bihar plain is a unique region of the Tisza Basin. Before the Bihar plane became part of the agricultural sector of Hungary, it was rich in marshlands and fens. Due to the draining of these wetlands and the creation of irrigation channels, nearly all wetlands disappeared, causing the alteration of wildlife [173,259,262,266–268]. Nowadays, the irrigation channels as a secondary habitat serve as a sanctuary for fish. Stable and dense mudminnow stocks have been recorded here in the last decades (e.g., Kutas-main-channel, Kis-Körös, Barát-ér, Ölyvös-ér) [126,173,266]. Only a few isolated natural salt marsh habitats have remained after the hydro-technical modifications. The most significant is the Pocsaj swamp, which has a stable European mudminnow population [126,173]. The irrigation channels are temporary watercourses, their water supplements are organized artificially, which is usually not synchronized with the life history (spawning period, diapause) of aquatic animals. Because of the poorly planned artificial recharge of water, these water bodies desiccate regularly, therefore, the aquatic macrovegetation cover is quite poor in the channel's bed, presence of reeds is sporadically. Beyond anthropogenic activity, pollution originates from agricultural cultivation and desiccation, and the spreading of alien species, especially the non-native Amur sleeper is threatening the remained European mudminnow population. The first occurrence of the species had been recorded from the Berettyó River and its northern tributaries in 2011 and appeared in southern watercourses too less than a decade [269]. In order to prevent further disappearance of the European mudminnow, we should moderate human impact like water pollution, nutrition overload, organizing the artificial recharge of the water bodies and develop a suitable management plan for alien species.

3.15. Wetlands at the Romania-Hungary Border

The Someş River has a 15,015 km^2 and a length of 435 km; Ier River has in Romania a 100 km length and a basin of 1392 km^2; Crişul Alb has a 235.7 km; Crişul Negru has a length of 168 km and Crişul Repede a length of 209 km [269].

In all of this west-northwest of the Romanian border with Hungary low courses associated wetlands *Umbra krameri* populations were constantly found in the 19–21th centuries. In the present these were still found in the Ier basin area [270].

In this area Hungarian side of the border most of the watercourses are originated from Romania and belong biogeographically to the Hungarian Bihar plain [260]. The species still have stable stocks in many streams e.g., Kis-Körös [266].

The preferred habitat for the *Umbra krameri* species in the Romanian side wetlands is formed in old river branches, with a muddy bottom and rich aquatic vegetation.

In the Hungarian side channels usually shallows, with the average width between 0.5–6 m, and the average depth changes between 0.3–3 m, with stream banks covered with aquatic and hydrophilic vegetation densely (e.g., *Typha latifolia*, *Phragmites communis*, *Lemna minor*, *Lemna trisulca*, *Hydrocharis morsus-ranae*, *Nymphaea alba*, *Nuphar lutea*, *Utricularia vulgaris*, and *Ceratophyllum demersum*). Conductivity is usually higher and the level of dissolved oxygen is lower, the water temperature is high in summer. Extant fen habitats are usually covered by macrovegetation (e.g., *Phragmites communis*, *Typha latifolia*, and *Stratiotes aloides*), and have quite high conductivity, and water temperature in summer too [169,269]. The studied Romanian area wetlands are characterized by a high human activities negative impact, especially due to water pollution, hydro technical works, water accumulations, settlement works and construction of dikes and banks defense, agricultural and industrial development, and urbanization, inducing finally favorable habitat destruction of its fish fauna [196]. The impacts of climate change on this area's fish species have not yet been studied.

On the Hungarian side, artificially constructed melioration channels are endangered by erosion, and desiccation, and their water supplement are not appropriate. The regulation of the water flow and water level is poorly planned, channels are usually desiccating by the end of summer causing the strong decline of the *Umbra krameri* population year by year. The region has been consisting of agricultural cultivation, therefore the extravasate of nutrition into the surface waters from the fields is considerable [266].

Basically, the same management elements should be enforced on both Romanian and Hungarian sides of the border.

Prevention, mitigation, and especially reconstruction and restoration of negative human impacts on *Umbra krameri* habitats of this area wetlands are the followings: reductions of the current biocontamination level; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; reconnection of the old river courses branches with the neighboring wetlands, channels, and river sectors, etc.

The following special management elements for these *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of specific management plans for the wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land and to redirect too much water in different basins; etc.

Desiccation of the habitats is not sustainable for the living organisms in the biotopes of the studied area, therefore, we suggest keeping a permanent water level in each season. As a competitor species, the spreading of Amur sleeper can result in the destruction of *Umbra* *krameri* populations in the near at hand. Because of its rapid proliferation, we have to keep the species under constant monitoring by fishery surveys.

The main problem is the artificial damming and water retention, due to this fact not enough or no water arrives from upper sectors in lower sectors. In order to avoid further habitat loss and a decrease of populations of *Umbra krameri*, a transborder agreement about the guarantee ecological water demand in the lower areas would be essential.

Overall, *Umbra krameri* stocks have been living in the studied area, however, some menace factors can result in the rapid decline of these populations like desiccation, habitat degradation, and the spreading of Amur sleeper.

3.16. Lonja and Odra Wetlands in Croatia

The Sava River is the largest Danube tributary in terms of discharge and the second largest (after the Tisza) in terms of length and catchment area, which is under human impact [271–275]. Lonja and Odra are rivers in Croatia that belong to the Sava River Basin. Their floodplains are part of the former wider floodplain of the middle part of the Sava River, which extends downstream from Zagreb after which the Sava begins to flow more slowly and becomes a typical lowland river with characteristic meanders. Furthermore, the Sava River downstream from Zagreb is affected by several larger tributaries such as Lonja, Ilova, and Orljava on the left, as well as Kupa and Una on the right, which influenced the formation of the biggest floodplain and wetland area of the Sava river basin—Lonjsko polje/field. Something smaller but equally interesting floodplain is the Odransko field, which is located somewhat more upstream along the river Odra between the Sava and the Kupa rivers [276].

The first data on the presence of the Umbra krameri in this area are from the end of the 19th century from wetland habitats in the Lonja river basin near settlement Lupoglav, about 20 km east of Zagreb [276]. Today, the species probably does not inhabit this area because the area is ameliorated, drained, and the Lonja River is channelized and enclosed with embankments. After that, there were no findings of *Umbra krameri* in Croatia, only the presence of species was mentioned, but without actual data on specific water bodies or localities [204,205,277]. The next *Umbra krameri* finding in this area was recorded a hundred years later, 20 km to the south in the Žutica forest near Ivanić Grad [278]. Žutica forest is located on the northwestern border of the Lonjsko polje/field and it is an old flooded (swamp) forest in which the remains of the old course of the river Lonja and its tributary Lonjica are partially preserved. The species was found at several sites in the oxbows and the old course of the river. In the rest of the Lonjsko polje/field, *Umbra krameri* was never found, despite many years of intensive research [274,278] A few years ago, Umbra krameri was surprisingly recorded at a new site in the very source part of the Odra River [274,278], which is the westernmost finding of the species in the Sava River Basin. Despite further research, it has not been recorded in the surrounding wetland habitats and tributaries of the Odra River.

Umbra krameri in the Lonja River basin uses mostly typical wetland habitats. Žutica is a floodplain forest that occupies an area of 60 km^2, and it is located at the Northwestern edge of the Lonjsko polje/field. *Umbra krameri* occurs in the marshes, oxbows, and dead arms of the Lonja and Lonjica rivers [278]. These are mostly smaller water bodies with very complex habitats, muddy bottoms, large amounts of organic material, and dense aquatic vegetation and they are full of old tree trunks [278].

In the Odra Basin, *Umbra krameri* is recorded in the source area of the river but only in the smaller section of the river, which in that part is about 5 m wide and 1 m deep. It is a small lowland river that flows slowly, but the water is clear and transparent. The bottom is composed of silt, sand, and gravel and it is well-developed underwater and floating aquatic vegetation along the banks as well as riparian vegetation.

The Žutica forest, located on the very edge of Lonjsko polje/field serves as a semi-natural retention area into which the high floodwaters of the Sava River are released in order to mitigate the flood wave and protect downstream areas, especially the city of Sisak [278].

As the surrounding watercourses are channelized and enclosed by embankments and the inflow of water depends on the floodgate on the Sava River, the hydrological regime is not natural, and lately it also depends on the water inflow from hydropower plants on the Sava River in Slovenia. Žutica has been serving as an oil field exploitation area for 60 years, i.e., the so-called satellite reservoir of the Sava Depression [279]. There are more than 150 different oil wells in the forest area, which changed the appearance of the forest and affected the whole area due to road, paths, and pipeline construction. In the waters of the floodplain of Žutica forest, an increase in the number of alien species has been recorded, where they are becoming dominant in the population and negatively affecting the number of *Umbra krameri* due to competition and predation pressure [280]. Most wetland habitats in the Žutica forest are smaller water bodies (oxbows and ponds) that makes an additional negative influence on the Umbra krameri populations because of sedimentation and disappearance of water bodies.

The *Umbra krameri* population in the upper reaches of the Odra River is isolated and it was recently discovered [280,281]. The whole area is not sufficiently investigated and there is lack of data on the size and status of the *Umbra krameri* population. The upper course of the Odra River flows between several settlements and is surrounded by agricultural land, which leads to different types of pollution. Thus, they were measured during the field research lower oxygen concentration, as well as quite high values of BOD5, nitrite, and nitrate [276]. Based on genetic research, low values of genetic diversity and a very small effective population size have been recorded [278].

Umbra krameri is protected by the Convention on the conservation of European wildlife and natural habitats (Bern convention) as a strictly protected fauna species (Annex II). It is protected by Council Directive 92/43/EEC 1992 on the conservation of natural habitats and of wild fauna and flora (EU Habitats Directive) as one of the animal species of community interest whose conservation requires the designation of special areas of conservation (Annex II). It is also listed on the Croatian red list of endangered species in the category of vulnerable species (VU) and protected by national legislation as a strictly protected species [278].

The Žutica forest is one of the areas of the NATURA 2000 ecological network (HR2000465), and the *Umbra krameri* is designated as one of the target species. In terms of conservation and management of the *Umbra krameri* population in the floodplain of the Žutica forest, the remaining microhabitats and water bodies in which the *Umbra krameri* has been recorded need to be protected and preserved. Specific conservation measures would include habitat restoration and revitalization in terms of dredging small water bodies like oxbows and pools. In case the *Umbra krameri* disappears from some previously known water bodies, translocation from the closest existing micropopulation should be considered. More detailed research is also needed in the whole forest with the aim of discovering new potential locations inhabited by the *Umbra krameri*.

3.17. Matura River System in Bosnia and Herzegovina

The Matura River belongs to the middle Sava River in Bosnia and Herzegovina (Republic of Srpska). In the Matura River system, *Umbra krameri* was discovered for the first time in 2016 [127]. The species was detected in the Matura River, including the tributaries Kraljica, Karavida, Glibača, and Adžaba, as well numerous springs in this area. Umbra krameri was frequently found in this area, which covers the surface of 35 km^2.

The preferred habitats of *Umbra krameri* in the Matura River system are lowland rivers and springs, with a muddy or gravel bottom and rich in submersed vegetation.

The Matura River system is very sensitive to environmental perturbations due to intensive human impacts that include: regulation of watercourses and changes in the hydrological regime; pollution and loading of habitats with communal waste, which lead to eutrophication, and the overall deterioration of habitat quality; intensive agricultural activities reflected in meliorations and the usage of artificial fertilizers and pesticides;

introduction of non-native species and their impact through competition and predation; the impacts of climate change on this area.

Proposals for the prevention, mitigation, and restoration of negative human impacts on *Umbra krameri* habitats of the Matura River system are following: preserving habitats by enabling optimal water regime especially during the summer season; construction of wastewater treatment plants; prohibition of the introduction of non-native species and reduction of the current biological contamination level; stopping the desiccation of aquatic habitats due to their excessive use for agricultural activities; reductions of using artificial fertilizers and pesticides in the immediate vicinity of watercourses; placing the area under state protection; raising awareness and active public participation in the protection of species and habitats.

3.18. Wetlands at the Serbia-Bosnia and Herzegovina Border

Transboundary wetlands include Special Nature Reserve Zasavica in Serbia and Special Nature Reserve Gromiželj marsh in Bosnia and Herzegovina (Republic of Srpska). Both areas belong to the lower Sava River system. The Special Nature Reserve Zasavica is situated east of the Drina River and south of the Sava River, with 1825 ha of the protected area. The Special Nature Reserve Gromiželj marsh is situated west of the Drina River and south of the Sava River, with an area of protected asset of 831 ha. The first record of *Umbra krameri* in Zasavica was in 1998, while in Gromiželj marsh, it was in 2008. After the first registrations, the presence of this species was frequently confirmed in microspecific locations in both areas [109,125,127,186,281,282].

The preferred habitat for the *Umbra krameri* in Zasavica is lowland reverie and creek biotopes with a muddy or gravel bottom and dense macrophyte vegetation. In Gromiželj marsh species dominantly inhabits a small, deep pond (0.14 ha) with a muddy bottom and dense macrophyte vegetation. This pond is the only water body in the Gromiželj area that never dries out. Thus, both areas are characterized by the mosaic of aquatic and wetland ecosystems with fragments of flooded forests [186,280].

These two close areas are very sensitive to environmental perturbations due to climate changes (dry year, formation of arid surfaces) and changes in the hydrological regime (reduction of groundwater levels, absence of floods, and human regulations of watercourses including habitat fragmentation). Also, additional human impacts are present through: pollution of habitats with communal wastewaters, leachate from landfills, pesticides, and fertilizers from arable land, which overall lead to eutrophication and deterioration of habitat quality; conversion of wetlands into the agricultural surfaces and forestry plantations of monocultures; introduction of non-native species and their impact through competition and predation [186,188].

Prevention, mitigation, and restoration measures of negative human impacts on *Umbra krameri* habitats of Zasavica and Gromiželj are the following: dam and water management, which will enable control and maintenance of optimal water regime; reductions of habitat fragmentation and using artificial fertilizers and pesticides in the immediate vicinity of watercourses; construction of wastewater treatment plants and remediation of illegal landfills; stopping desiccation of aquatic habitats due to intensive use for agricultural and forestry activities; prohibition of the introduction of non-native species and reduction of the current biological contamination level; raising awareness and active public participation in the protection of species and habitats [186,188].

3.19. Timiș River System in Romania

With a 359 km length and 10,280 km^2 of its basin, the Timiş River is formed in the Semenic Mountains, it flows into the Tisza River [193]. In the 19–20th centuries *Umbra krameri* was not mentioned in the Timiş River basin wetlands [102,111] but it was accidentally found in the present in some of these lower basin old river courses dead branches [193]. This fish was rarely found in this area also in the last years by the authors.

The preferred habitat for the *Umbra krameri* species in the Lower Timiş River basin wetlands consist of old river branches, with a muddy bottom and rich aquatic vegetation.

The Lower Timiş Basin wetlands are defined by a high human activities impact, mainly due to pollution, hydro-technical works, water accumulations, settlement works and construction of dikes and banks defense, agricultural and industrial development, and urbanization, inducing favorable habitat destruction of its fish fauna [283–285]. The impacts of climate change on this area's fish species have not yet been studied.

Prevention, mitigation and reconstruction and restoration of the human impacted habitats of *Umbra krameri* of the Lower Timiş Basin are the followings: reductions of the biocontamination level; reductions in habitat fragmentation and loss; stopping the impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; reconnection of the old Timiş River branches with the neighboring wetlands, channels, and river sectors, etc.

The following management elements for *Umbra krameri* populations are suggested: extension and creation of reserved areas for the conservation of this species and its habitat; elaboration of specific management plans for the wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land and to redirect too much water in different basins; etc.

3.20. Prut River at the Moldova-Romania Border

With a 953 km length and 28,396 km^2 of its basin, the Prut River flows southward for the big majority of its length between Romania and Moldavia into the Danube [286]. In the 20th century *Umbra krameri* was mentioned in this area by Bănărescu et al. [111]. This species was rarely found in this area also in the last years by the authors.

The preferred habitat for the *Umbra krameri* species in the Prut River basin is the wetland habitat, with a muddy bottom and rich aquatic vegetation.

The Prut River basin wetlands are characterized by a high human activities negative impact, especially due to water pollution and favorable habitat destruction on its fish fauna. The impacts of climate change on this area's fish species have not yet been studied.

Prevention, mitigation, and especially reconstruction and restoration of negative human impacts on *Umbra krameri* habitats of the Prut Basin are: reductions of the biocontamination level; habitat fragmentation and loss; impoverishment of aquatic habitats due to the excessive use of land for the so-called extensive agriculture; restoration of floodplains and old-deserted irrigation channels; acceleration of construction and improvement of wastewater treatment plants; monitoring of water pollution; etc.

The following management elements for *Umbra krameri* are proposed and creation of reserved areas for the conservation of this species and its habitat; elaboration of management plans specific wetlands of interest; ensuring adequate water regime by prohibiting the capture of springs and drainage of wetlands to obtain new agricultural land; etc.

3.21. Dniester River at Moldova-Ukraine Border

In the relative proximity of the Danube basin is also the Dniester basin, with together have a good potential refuge and stepping stone habitats role for *Umbra krameri*.

The Dniester River's source is located in the northern slopes of the Ukrainian Carpathians (the Chentiyivka Mountain, of 932 m altitude), runs through different geographical zones and falls into the Dniester liman. Total river length amounts to 1362 km, of them 662 km in the territory of Ukraine, 225 km—along the Ukrainian-Moldavian boundary, and 475—in the territory of Moldova. The total basin area is of 72.1 km^2, of which 52.7 km^2—in the territory of Ukraine. In the view of the peculiarities of the geographical location, hydrological and hydrochemical regime the Dniester basin is traditionally divided into three parts: Carpathian—upper section, Podillia—middle section, and southern—lower section. The average river discharge in the lower section amounts to 310 m^3/sec, the annual river discharge is estimated as equal to 10 km^3 [287].

The basin comprises both quite undisturbed and densely populated and urbanized territories. Significant elongation of the basin from the north-west to the south-east (about 700 km) induces notable difference of the climatic characteristics. It is also essential that the upper river part is located in the Carpathian region' mountainous and piedmont, which explains significant differences in conditions of the river flow forming in the upper and lower sections of the basin [287].

The Carpathian part amounts to 9% of the total basin area, however, it is covered by the well-developed and dense river net (1.0–1.5 km/km^2), and the main river discharge is formed just here, mainly owing to the floods. The upper, properly mountainous section, is located upstream of the Stryi River mouth and is the main for the discharge forming. The mountainous tributaries produce 50% of the river discharge. The rivers of the upper basin section run within the Carpathians, Pre-Carpathian upland, and Volyn-Podillia plateau. Thus, the riverbeds within these regions are different in terms of the discharge regime, including the geology, relief peculiarities, and climatic conditions [287].

The Dniester River, along with Danube, Dnieper, and South Bug rivers belong to the big rivers, which fall to the north-western section of the Black Sea. The Dniester River basin district is located in the territories of three states—Poland, Ukraine, and Moldova. Though the portion of Polish territory in the Dniester basin is only 0.6%, it belongs to the European Union transboundary river basins [287].

Actual data on *Umbra krameri* numbers in the Lower Dniester basin in the territory of Ukraine are practically absent. Relatively actual data (2006–2010) are given in a report [287]. The obtained data regarding distribution, abundance and size-weight characteristics of *Umbra krameri* in the water bodies of the Lower Dniester basin were analyzed. On the basis of analysis of the dependence of the ichthyofauna diversity on the annual water yield and pollution degree it was stated, that the flow regulation and pollution are the main reasons of the *Umbra krameri* and other fish species' abundance decrease.

The relatively good status of the species in the Ukrainian part of the Lower Dniester basin is confirmed by the Official application of the Lower-Dniester National natural park on 10.03.21 N 132/05 to the National Commission on the Red Data Book of Ukraine regarding issuing Permission to catch *Umbra krameri*, which indicated, that according to data of the research catches, carried out by the park staff in 2020, in the channel in the 51st km of the automobile road Odesa—Reni (the section between the villages of Mayaki and Palanka, Biliayivkka district of the Odesa oblast) the local population of *Umbra krameri* occurs, not less than 2000 specimens.

The Dniester River is the biggest river in Moldova and third biggest river in Ukraine, serving with its tributaries for water extraction for some big cities. In this basin, are also pollutant oil extraction and refinery enterprises, as well as other numerous industries.

3.22. Danube Basin Umbra krameri Populations State and Potential Trends under Climate Change Impact

Major geographical obstacles (e.g., the Carpathian and Alps mountains and the Black Sea), significant different geographical areas with significantly different climate and zoo-geographical influences (i.e., Alpine, Pannonian, Continental, Mediterranean, and Steppic), major/significant river and lake water catchments with more or less dense and permanent or not hydrographical nets basins where the *Umbra krameri* populations were identified (i.e., Danube, Morava, Bodrog, Ipoly, Jiu, Olt, Vedea, Argeş, Mura, Drava, Kis-Balaton area, Tisza, Sava, Crişuri, Timiş, Lonja, Odra, Matura, Suceava, Prut, Dnister) and highly dynamic ichthyological zone like the Danube Basin is, are the main natural driving forces which clustered along with history the wetlands fish fauna. The relatively recent human impacts (dams, pollution, siltation, dredging, draining, desiccation, habitat imperiling, fragmentation and destruction, introduction of non-native fish, pouching, etc.) as well as unproper fish fauna management hazards including chaotic stockings created changed separate geographical clusters of wetlands as habitats for *Umbra krameri*.

The ichthyofauna had full geological extent of time over which had to evolve and acclimate together with their habitats characteristic changes, and this included wetlands which played the role of refuge habitats and stepping stones in the distribution Danube basin area. All these refuge and stepping stone wetlands were and still are of extremely high importance in the circumstances of the zoogeographical and ecological importance of a needed hydro-biological Danube trans-basin functional ecologic macro-continuum.

The present and estimated and expected climate warming and the becoming more intense and extensive of droughts, as well as the human impacts nevertheless will form a synergic significant complex of pressures that will endanger the optimum *Umbra krameri* characteristic wetlands and this fish species itself.

Climate change-induced impacts, were not studied on the whole Danube basin scale till now regarding *Umbra krameri*, in spite of the fact that is to be expected that them induced and will induce potential breaks-in the existing stepping stones Danubian hydrographical net qvasi-continuum of wetland habitats.

Moreover, climate change effects will also substantially disturb the *Umbra krameri* and other fish species which depend by wetland habitats. Therefore, there is a need for the Danube basin management plan of action relying on lasting and even improving suitable climate and microclimate typical features, wetlands connectivity, their quantitative and qualitative attributes safety, the fish genetic diversity backing, and survival potential for *Umbra krameri* populations and species.

3.23. Umbra krameri Refuge and Stepping Stone Habitats Management Elements Proposals for the Danube Basin

Climate modifications impact the biotopes and biocoenosis and activate hidden risks concerning the natural products and services; humans should forecast and adjust to such global challenges situations and conditions. The management actions which should be implemented to diminish/ward off the climate modifications' unfavorable effects on the researched wetland habitats should be made at the watershed level, for integrated rationality in actions and best outcomes. Among these actions we propose: the design and development of a long-lasting intricate integrated monitoring system for the wetland habitats, their water bodies connections, and fish, controlling poaching, water use rationalization, forestation/reforestation of the wetland ecosystems riverine basins to stimulate the local and regional water cycles water recirculation, imposing taxes for ecosystem services including for the natural water and riverine wood resources, discriminatory fishing of non-native and not economically or conservation important species, reducing/preventing fragmentation of the hydrographical nets which connect permanently or seasonally the wetland habitats, reducing/avoiding pollution, etc.

The Danube Basin was revealed as being one of the major hot spots in terms of fish fauna status major threats, pressures, and risks, this time in a potential climatic change (heating-drought-water depth decreasing) scenario.

As a result of climate change, it is likely the wetlands will suffer disturbance through the worsening water quality and quantity, some spawning habitats will be lost, there will be habitat and species loss, increased suspended sediment and nutrient levels in water and eutrophication, diminishing and/or loss of hydrological connectivity, alteration of fish communities structure, and an increase in eurytopic fish species occurrence.

The climate change impact on the studied wetlands can be: isolation of wetlands by the surrounding hydrographical networks, either for safety reasons or to reclaim land should to be forbidden in a future drought scenario; these wetlands should be considered as international importance and needed stepping stone for *Umbra krameri* fish species; avoiding the complex human impact effects on already unbalanced from the point of view of the fish communities and the most sensible to any other supplementary stress, including the climate changes type too.

The Danube Basin hot spot area identified potential ecological changes trends that can be used also as a pre-alert information area, for the potential arrival of similar changes for other surrounding major European and West Asian hydrographic systems like (i.e., Évros, Po, Rhine, Elbe, Oder, Vistula, Dnestr, Bug, Dnepr, etc.).

It is more than questionable that a species like *Umbra krameri* will be able to shift to more appropriate habitats/climate conditions, the relatively unnaturally fast likely changes will strongly affect the ecological equilibrium of wetlands locally and regionally, diminish their populations, and break down the natural continuity of the specific wetlands net as habitats for this species, along the entire Danube Basin.

Opportune and convenient water resource management actions for *Umbra krameri* wetland habitats can safeguard fish populations' climate modification-related effects and alike threats. The disaster-case scenario should be to guarantee an optimum frequency and density of potential refuge wetland habitats as abundant as possible, or it will not be possible then knots of convergence and divergence of an ecologic functional hydrographic Danubian Basin network, in which climate modifications alert conservation managers to can be capable of performing the optimization and conservation of economic objectives by recognition, focusing, and connecting all these wetlands as potential *Umbra krameri* refuge/areas of a functional convergence-divergence Danube basin net.

The climate changes trend in the Danube Basin will affect the studied wetland areas' ecological state and associated *Umbra krameri* populations, increasing the threats and risks upon this endemic protected fish species; mitigating measures are urgently needed. The future diminishing of these habitats areas, the quality of the habitat lowering and the fragmentation and isolation of these habitats increasing by the surrounding hydrographical nets, for so-called safety reasons of human communities or to convert inland areas should be fought against.

The conservation measures should target the characteristic wetlands preservation in their original state; the avoidance the changes which might affect the water regime and alter the vegetation. The partial rehabilitation and restoration of its native distribution area and its reintroduction should be also strongly recommended for this species quantitatively aspects and stability increase. Due to its relatively complex behavior of breeding and wintering, in its reproduction and winter periods, the human impact on its habitats should decrease to a minimum.

From the scientific point of view, population studies and monitoring are needed in respect of highlighting the trend of this species at all these as well as other sites.

On a yearly basis, the hydrologic regime and water temperature are conspicuous elements that stimulate or restrict the life cycles of this fish, so the climate changes unmanaged effects can be significant.

Exceptional parameters of genetic polymorphism of the species impose mandatory genetic characterization of individuals during the implementation plans for future protection, conservation, and sustainable management of this species.

4. Conclusions

Small-bodied freshwater fish species like *Umbra krameri* with a high conservation value but with no commercial value can be considered as excellent environmental indicators, being antropofuge species. These species possess special requirements (specialized habitat, ichthyocenosis, and/or diet), a small population size, a short lifespan, a reduced dispersal capability, and a low fecundity rate. Thereby *Umbra krameri* are often living in fragmented residual habitats that could be much distanced and geographically and hydrographicaly isolated. Fragmentation and habitat degradation and loss are causes of the formation of small isolated subpopulations with possible little to no gene flow, consequently further under risk of inbreeding and associated bottleneck negative effects. Population fragmentation, due to specific habitat requirements, has existed partially in the past too but at a much lower level, but gene flow among these fragmented habitats has been ensured by regular floods with subpopulation mixing. Today, the situation is negatively changed from this perspective, for those populations, random genetic drift leading to loss of genetic diversity and inbreeding may reduce the species' adaptative and evolutionary potential, pushing it toward local extinction risk.

Comparing recent occurrence data with old literature records we established a strong population decline in the *Umbra krameri* populations along the Danube and Dniester river basins. This short lifespan, metaphytic species is extremely sensitive to the disturbances in their natural habitat. Intensifying anthropogenic effects (e.g., hydro-technical modifications, dredging) and the change of our climate induces the large-scale degradation of fen habitats and the decline and dispersion of its stocks. Furthermore, the widely isolated populations are threatened by not just the loss of genetic diversity, but the dynamic spreading of adventives species is an additional major risk.

Hence, for the conservation of *Umbra krameri* species, protecting the specific habitats is of immense importance and may contribute largely to its preservation. Also, appropriate artificial breeding techniques and the outplacing of the offspring to its natural or restoration habitats are as important as the management of adventives elements to prevent the further population decline of the species.

For these reasons, *Umbra krameri* can be used as indicators of environmental quality and excessive human impact. As an endemic species of the Danube Basin with a high conservation value, the expansion of integrated conservation management plans is essential. In consequence, we should think about the human impact reduction/primary habitat restoration together with the conservation of natural spaces where vegetation is allowed to evolve according to natural processes and dynamics. The non-channeled water bodies with natural vegetation in natural dynamics/non-managed by man, it is very important to be protected and conserved.

Umbra krameri has become a rarity in its native endemic area, disappearing from many zones due mainly to the human-induced deterioration of favorable habitats to which the pressure of climate change was added. This fish is given increased concern for protection at the European level and only well-oriented efforts including obtaining genuine biological and ecological knowledge and management know-how and best practices will succeed to avoid not only postpone a final death blow strike and extinction. It is possible that these paper authors' generations may be one of the last ones to have direct memory of this species in perilous decline in the last remaining watersheds as habitats for European mudminnow before it will vanish? The authors of this study still hope that will not be the case, in spite of the fact that this species has been significantly winking out in the course of our life!

General permanent ichthyological monitoring is necessary for the characteristic wetland habitats and also emphasized for the adventive species, which can be the competitors and predators of native elements.

With the present-day obvious climate changes, the *Umbra krameri* situation needs to make the scientific community, wetlands stakeholders, and managers, keep monitoring this species population and stay on track with new extended innovative measures in all the Danube Basin.

Based on all of the above it would be recommended to develop specific in-situ tailored locally adapted action plans for the management of *Umbra krameri* in each identified stepping stone area, all of them being only finally put together in a general master plan for the whole area of the Danube basin.

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