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From wide distribution to localised persistence: Status and threats to the European eel in the eastern Adriatic Sea Basin, Croatia

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ABSTRACT

The European eel (*Anguilla anguilla*) has undergone a severe long-term decline worldwide, driven by multiple interacting pressures. Research on European eel in the eastern Adriatic Basin of Croatia has remained fragmented, with no systematic evaluation of population trends or documented stressors. This study reconstructs historical and recent distribution pattern of the European eel, identifies key anthropogenic pressures in the eastern Adriatic basin, and assesses the occurrence of the swim bladder parasite *Anguillicoloides crassus* using a case study from two short karst rivers. A comparison of data up to the 2000s with data obtained after the 2000s shows a shift from the historically widespread distribution to a fragmented pattern. Among the identified stressors, hydropower dams, river alterations, coastal development, and the planned expansion of the hydropower sector stand out as the main pressures along the Adriatic coastline. The prevalence of *A. crassus* in eel specimens collected from the Jadro and Žrnovnica Rivers ranged from 0% to 50% across sampling sites. Parasite infestation showed a size-dependent pattern, with infestation probability remaining low in individuals < 35 cm total length. The infestation probability increased with specimen size and exceeded 90% in individuals > 55 cm. Overall, the results reveal a substantial regional decline of European eel over the last several decades, highlight major threats, and confirm the presence of parasitic infection in coastal karst lotic ecosystems.

Keywords: *Anguilla anguilla*, population decline, freshwater ecosystems, multiple stressors, *Anguillicoloides crassus*

INTRODUCTION

The European eel, *Anguilla anguilla* (Linnaeus, 1758) has experienced a dramatic decline over the past decades, with current population levels representing only a small fraction of historical abundance (Aalto *et al*., 2016). Major threats to the species include extensive habitat loss, barriers to migration such overexploitation, dams and hydroelectric facilities, pollution, and changes in oceanic currents that as affect larval transport (Miller

et al., 2016; Piria & Tomljanović, 2025). Additionally, the impacts of climate change and the introduction of non-native species further contribute to the species' vulnerability (Mestav *et al*., 2004).

Habitat degradation, along with the loss of instream cover, may lead to a significant decline of the European eel and local extirpation (Piria & Tomljanović, 2025). Dams and hydroelectric facilities further disrupt the species' complex migratory pathways, causing direct mortality and preventing both upstream recruitment of juveniles and downstream migration of spawning adults (Feunteun, 2002; Calles *et al*., 2021). Overexploitation has significantly reduced the number of adult eels able to complete their life cycle, diminishing reproductive output and weakening already stressed populations (Drouineau *et al*., 2018). Pollution contributes additional physiological stress, impairing immune function and reducing overall fitness (Pujolar *et al*., 2012). Moreover, changes in oceanic currents, driven largely by climate change, can alter the transport of leptocephalus larvae from the Sargasso Sea to European coasts, resulting in reduced recruitment and long-term population instability (Miller *et al*., 2016).

Non-native species have had a notable impact on the European eel, further exacerbating its population decline (Batur *et al*., 2020). Invasive species can compete with eels for food resources, alter habitat structure, and introduce novel pathogens. One of the most significant examples is the introduction of the parasitic nematode *Anguillicoloides crassus* Kuwahara, Niimi, & Itagaki, 1974 originally native to East Asia, which has become widespread in European eel populations (Székely *et al*., 2009). The parasitic nematode colonises the swim bladder of eels, impairing its function and reducing the host's physiological performance, especially during long migrations (Myrenås *et al*., 2023). The most widespread species, *A. crassus*, is considered particularly pathogenic, causing inflammation, fibrosis, and increased mortality. The presence of this parasite is therefore regarded as a significant factor contributing to the overall decline of European eel populations (Székely *et al*., 2009).

For the eastern Adriatic basin, research on the European eel remains fragmented and spatially limited. Earlier studies primarily addressed basic biological traits, including length–weight relationships and body condition in karst waterbodies (Popović *et al*., 1984; Dulčić & Glamuzina, 2006; Piria *et al*., 2014; 2016; Milošević *et al*., 2022), heavy metal accumulation (Has-Schön *et al*., 2006), maximum recorded length (Tutman *et al*., 2007), and the status of eels in the Neretva River and the Hutovo Blato wetlands (Dulčić & Glamuzina, 2006; Glamuzina *et al*., 2008). More recently, several studies have broadened current knowledge on eel status along the eastern Adriatic coast, focusing on topics such as re-evaluation of catch per unit effort using traditional fishing gear (Glamuzina *et al*., 2022), age and growth (Hala *et al*., 2025), external morphology (Barić *et al*., 2023), otolith morphology and fingerprinting (Kanjuh *et al*., 2018; Milošević *et al*., 2021), and habitat use of eels in short karst rivers in Croatia (Piria & Tomljanović, 2025). The one recent study along the Croatian part of the Adriatic Sea mentions the presence of *A. crassus* in the swim bladder of European eels in the Neretva River (Glamuzina *et al*., 2022), and another in Lake Skadar in Albania (Kule & Hala, 2025). However, there is no information on the presence or prevalence of parasites from the short karst rivers in the area. Furthermore, comprehensive historical and contemporary population distribution are still lacking for the region. Although various threats to the European eel have been documented, they

remain dispersed across individual studies and have yet to be systematically evaluated.

Accordingly, the aims of this study are: (1) to assess historical and recent distribution trends of the European eel in the eastern Adriatic basin of Croatia, (2) to identify key threats, and (3) assess the presence of parasites in eels inhabiting short karst lotic rivers.

Given the species' complex life cycle, its long-term decline across Europe, and increasing pressures on Adriatic Sea Basin freshwater ecosystems, understanding regional patterns is important for effective conservation. The results of this study may support future planning conservation efforts, habitat restoration, and policy measures aimed at safeguarding the remaining European eel populations in the Croatian Adriatic Sea Basin.

MATERIAL AND METHODS

Distribution trend

Data on distribution trends were obtained from the Ministry of nature protection and green transition in Croatia. Records were categorized into two temporal groups: historical data (up to the 2000s) and recent data (from the 2000s onward). The dataset is based exclusively on field-collected records of live specimens and does not include data obtained through environmental DNA (eDNA) or other indirect detection methods that do not involve direct observation of individuals. The distribution maps were created using QGIS software.

Key anthropogenic pressures

To identify key threats and mitigation measures to the European eel in the eastern Adriatic Sea Basin, relevant information was compiled through a comprehensive review of scientific publications indexed in Google Scholar, as well as grey literature and other publicly available sources.

To assess the relative contribution of key anthropogenic pressures affecting the European eel within the Adriatic coastal basin, a semi-quantitative expert scoring method was applied. Each identified threat was assigned a strength value ranging from 1 to 5, based on its estimated ecological impact, spatial extent, and relevance in regional literature and management documentation (1 = negligible impact; 5 = dominant, population-level driver of decline).

The assigned scores were normalized to generate proportional percentages (P_i) for graphical representation using the formula (equation 1):

$$P_i = (S_i / \Sigma S) \times 100 \qquad (1)$$

where S_i is the threat score and ΣS the sum of scores across all threats. This approach allows multiple stressors to be compared despite incomplete quantitative population data, but it may introduce bias because the weighting relies on expert judgment rather than consistently measured quantitative data for each threat across the entire basin.

Eel sampling and assessment of parasite occurrence – case study

Sampling was conducted during daylight hours under consistent hydrological and climatic conditions. Fish were captured on 8 October 2015 in the Jadro (upper stretch 43.539008 N, 16.496244 E; lower stretch 43.541097 N, 16.516992 E) and Žrnovnica (upper stretch 43.513167 N, 16.538444 E; lower stretch 43.508903 N, 16.536506 E) Rivers using electric fishing gear. Continuous, single-pass electrofishing was performed along the riverbanks (Hans Grassl EL 63 II, 220/440 V, 17.8/8.9 A), covering a 100-meter section of shoreline with a width of

approximately 1 meter. To minimize between-operator bias, all electrofishing was carried out by the same sampling team (Bain & Finn, 1990; Zalewski, 1985).

Captured fish were measured for total length (*TL*, cm) to the nearest millimeter and for body weight (*W, g*) to the nearest gram. Sex and developmental stage of each individual were recorded. In the laboratory, the swim bladder of each specimen was carefully dissected and examined for the presence of *A. crassus* parasitic nematode. The presence of the *A. crassus* was assessed visually and scored as a binary infection variable: 0 = parasite absent, 1 = parasite present.

To assess the relationship between *A. crassus* infection and eel size, we fitted generalized linear models (GLMs) with a binomial error distribution and logit link function. Infection status was coded as a binary response variable (0 = uninfected, 1 = infected). In first model, we modelled infection probability as a function of *TL*. In a second model, *W* was used as the sole predictor. Finally, for full model we fitted a multivariate GLM including *TL* (continuous), developmental stage (yellow vs. silver) and river section (Žrnovnica upper, Žrnovnica lower, Jadro upper, Jadro lower) as categorical predictors. Categorical variables were dummy-coded. Models were fitted using maximum likelihood in a logistic regression framework (implemented in R, GLM, family = binomial), and statistical significance was evaluated at $p = 0.05$.

RESULTS

Distribution trend

A comparison of historical and contemporary records reveals a marked change in the spatial distribution of European eel occurrences across Croatia. The distributional data prior to the year 2000, indicates a broad and relatively continuous presence of the species throughout the country. Occurrence data are widely dispersed, with a high concentration along the Adriatic coastline. This pattern suggests that eel populations were historically widespread, occupying coastal freshwater habitats over a large geographic range (Fig. 1A).

In contrast, records from 2000 to the present reveal a decline in the number of localities where the species was observed. The distribution of European eel becomes more fragmented, with occurrences predominantly clustered along the Adriatic coast, accompanied by the disappearance of European eel from many isolated karst waterbodies in the Adriatic Sea basin. Furthermore, coastal and estuarine areas appear to be more spatially restricted for European eel compared to the historical dataset (Fig. 1B).

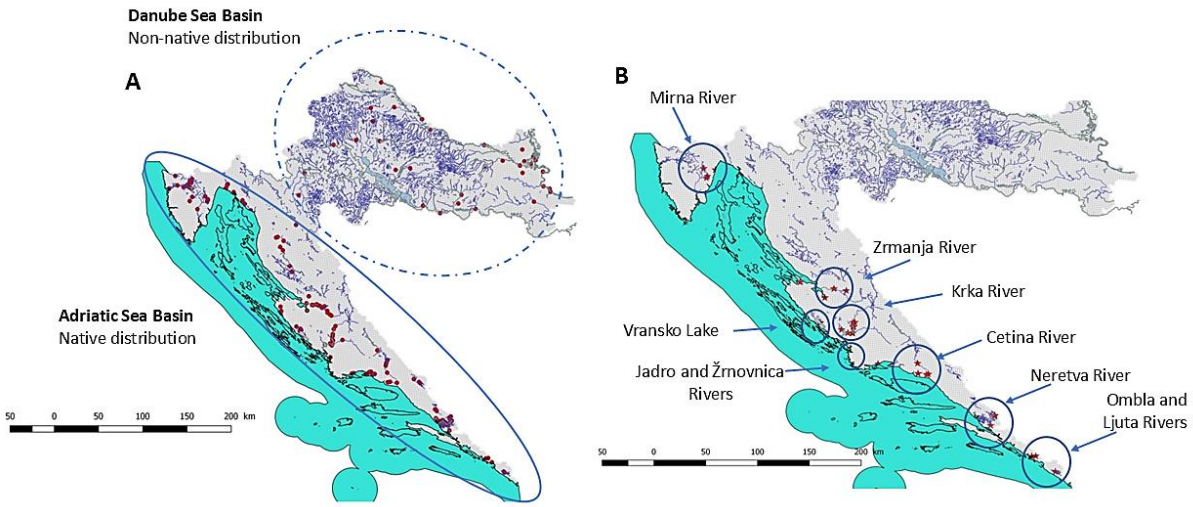


Figure 1. Distribution trend of the European eel (*Anguilla anguilla*) in Croatia, indicated by red dots. (A) Historical distribution up to the 2000s (note: the species is native only to the Adriatic basin - solid-line ellipse). (B) Recent distribution after the 2000s. Note: in the Ljuta River, the last recorded specimen was observed in 2014 (Piria &Tomljanović, 2025).

Threats

The comprehensive literature review identified major threats to the European eel in the eastern Adriatic Sea Basin. These include overfishing, existing hydropower dams, barriers and new hydropower developments, coastal urbanization and habitat loss, river modification in small rivers, the introduction of invasive species, parasitic nematode infection of swim bladder, marine intrusion into lakes and industrial pollution (toxins) (Tab. 1).

The weighted threat distribution demonstrates that hydropower dams, coastal urbanization, river alteration and future hydropower expansion represent the most dominant pressures on European eel populations, each accounting for approximately 14% of total impact. Overfishing, invasive species including parasitic nematode of swim bladder follow as secondary drivers (~11% each), while industrial pollution (~6%) and marine intrusion (~3%) represent lower, yet still significant, risk factors (Fig. 2; Suppl. Tab. S1).

Table 1. Multiple interacting threats affecting European eel populations in the Adriatic basin, including impact mechanisms, documented examples at specific locations, and possible mitigation measures

Threat	Impact mechanism	Documented example(s)	Location(s)	Mitigation measures	References
Overfishing	Depletion of spawning biomass; reduced silver eel escapement	Historical harvest up to 70,000 kg/year; 10–15% of migrating stock fished	Neretva River	Fishing quotas, seasonal closure during migration, effort control	Glamuzina, 2024
Hydropower dams & barriers	Blocked upstream/downstream migration → recruitment collapse	HE plants **Neretva**: Jablanica, Grabovica, Salakovac, Mostar; **Cetina**: Kraljevec, Peruča, Zakučac, Đale, Orlovac; **Zrmanja**: Velebit → post-1960s stock decline	Neretva, Cetina, Zrmanja Rivers	Fish ladders, eel passes, bypass channels, minimum ecological flow	Piria & Tomljanović, 2025
Coastal urbanization & habitat loss	Reduction of estuaries & migration corridors	Loss of coastal wetlands and river mouths	Eastern Adriatic region	Estuary restoration, creation of brackish protected zones	Piria & Tomljanović, 2025
River modification (small rivers)	Loss of connectivity with sea → local extinction of glass eel influx	Severe eel decline in Žrnovnica, Jadro, Ljuta	Dalmatian coastal rivers	Barrier removal, micro-passages, flow management	Piria & Tomljanović, 2025
Invasive species	Competition & predation → trophic displacement	*Cyprinus carpio*, *Carassius gibelio*, *Silurus glanis* dominance; *Onchorhynchus mykiss*	Vransko Lake Small rivers (e.g. Žrnovnica, Jadro, Ljuta)	Removal programs, monitoring, non-native ban enforcement	Piria & Tomljanović, 2025
Parasitic nematode infection of swim bladder	Swim bladder damage → reduced swimming, impaired physiology & spawning success	*Anguillicoloides crassus* infection documented across Europe and eastern Adriatic Sea coastline	Neretva Rivar	Monitoring and early detection of infection hotspots, targeted management to reduce stressors (e.g., pollution, low-flow conditions)	Glamuzina *et al*., 2020
Marine intrusion into lakes	Euryhaline fish invasion → collapse of eel biomass	Drop from 28% → 1–2% biomass	Vransko Lake	Salinity control, canal regulation, population monitoring	Piria & Tomljanović, 2025
New hydropower developments	Future fragmentation & range reduction	New dams proposed for coastal catchments	Adriatic Basin	Strict EIAs, legal requirement for passage systems	Piria & Tomljanović, 2025
Industrial pollution (toxins)	Toxic bioaccumulation → impaired growth, mortality, recruitment failure	Industrial discharge events recorded in protected eel habitat	Krka River (National Park)	Pollutant control, effluent treatment, rapid response protocols, protected-area enforcement	Cukrov *et al*., 2024

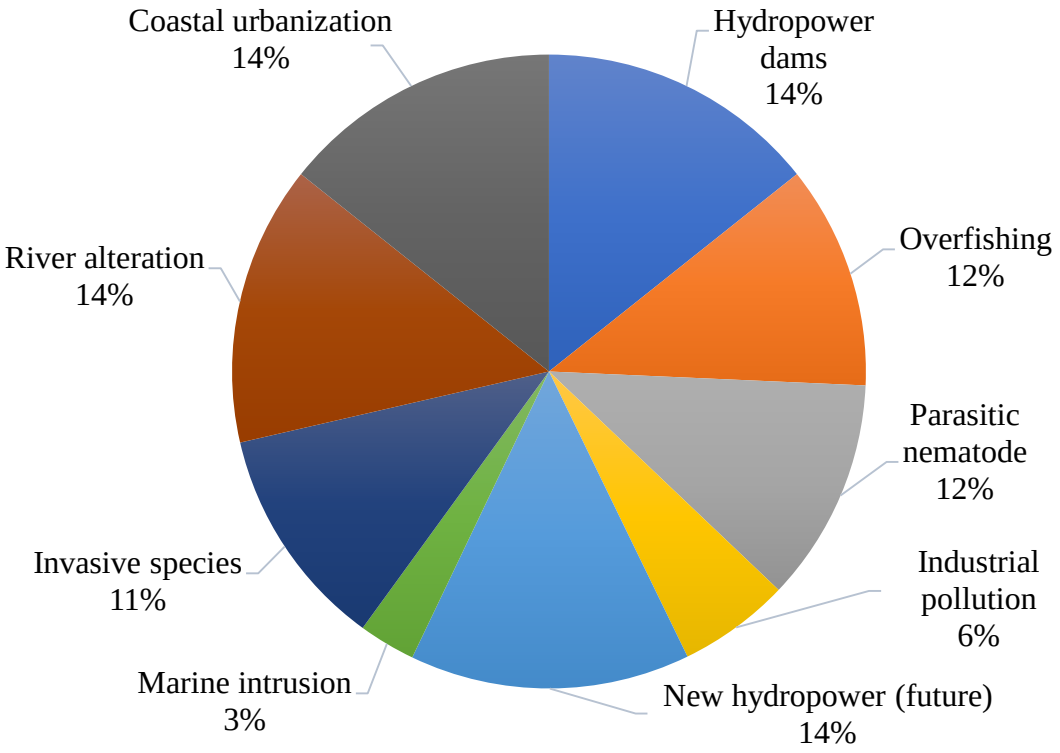


Figure 2. Weighted threat share (%) based on semi-quantitative scoring of pressures on European eel (*Anguilla anguilla*) in the Adriatic Basin

Swim bladder parasite case study

A total of 26 European eel specimens were examined for swim bladder infection by *A. crassus* across two rivers and two river sections in each river (Žrnovnica upper, Žrnovnica lower, Jadro upper, Jadro lower). Infection prevalence varied substantially between sites, with the highest prevalence recorded in the Jadro estuary (50%), followed by similar values in upper and lower Žrnovnica (42.9% and 40.0%, respectively), while no infected individuals were detected at the Jadro spring (Tab. 2; Suppl. Tab. S2).

Table 2. Summary of European eel (*Anguilla anguilla*) infection by *Anguillicoloides crassus*, including total sample size (N), prevalence in yellow and silver stages, and overall infection prevalence per river section.

River section	Total (N)	Yellow eels (N)	Yellow infected (N)	Yellow prevalence (%)	Silver eels (N)	Silver infected (N)	Silver prevalence (%)	Overall prevalence (%)
Žrnovnica – upper	7	7	3	42.9	0	–	–	42.9
Žrnovnica – lower	10	7	3	42.9	3	1	33.3	40
Jadro – upper	1	1	0	0	0	–	–	0
Jadro – lower	8	6	3	50	2	1	50	50

Eels infected with *A. crassus* were predominantly larger individuals. Logistic regression revealed a significant positive relationship between total length and infection probability (GLM binomial, $\beta = 0.245 \pm 0.101$, $z = 2.422$, $p = 0.015$). The probability of infection was near zero in individuals < 35 cm *TL*, increasing sharply between 40–50 cm and exceeding 90% in fish > 55 cm (Fig. 3).

A similar pattern emerged when body weight was used as a predictor ($\beta = 0.060 \pm 0.030$, $p = 0.042$), indicating that heavier individuals carried proportionally higher infection risk. The weight-only model explained 54% of deviance, slightly outperforming the *TL*-only model (35%), (Suppl. Tab. S3). A multivariate GLM including *TL*, developmental stage and river section showed that *TL* remained the strongest predictor of infection and the only factor approaching statistical significance ($\beta = 0.836 \pm 0.426$, $p = 0.050$) (Suppl. Tab. S2). Developmental stage and river location did not significantly influence infection probability ($p > 0.05$), likely due to small sample size and uneven distribution of infected individuals across river segments. Nevertheless, the combined model achieved the highest explanatory power (Pseudo $R^2 = 0.66$), supporting the conclusion that *A. crassus* infection risk increases primarily with eel body size, reflecting cumulative exposure time and movement dynamics.

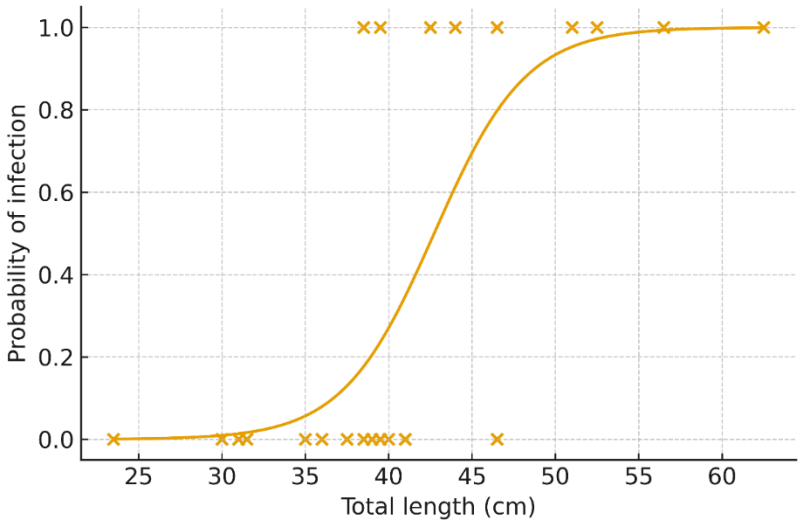


Figure 3. Logistic regression model of the probability of *Anguillicoloides crassus* infection in European eel (*Anguilla anguilla*) as a function of total length (TL). Points represent individual eels (0 = uninfected, 1 = infected), and the line indicates the fitted binomial GLM with logit link. The model shows a steep increase in infection probability in individuals larger than approximately 40 cm TL.

DISCUSSION

The temporal comparison of distribution trend of the European eel in the Adriatic Sea basin indicates a transition from a historically widespread distribution to a more limited, discontinuous, and coastal-dominated pattern in recent decades. Records from the Danube River system in the dataset prior to the 2000s represent the non-native distribution of the

European eel and may be a consequence of escapes from fish farms or various modes of intentional translocation (Apostolou *et al*., 2013). After the 2000s, such observations are non-existent, despite increased field survey efforts and continuous fish monitoring studies since 2003 (Treer *et al*., 2003; Piria *et al*., 2024). The distribution of the European eel in the Adriatic Sea basin represents the species native range (Vucić *et al*., 2023). However, the dataset in our study is based on field observations, which may represent a limitation because field surveys likely did not cover all water bodies within the Adriatic Sea basin. Nevertheless, this spatial restriction, particularly after 2000s, is consistent with the well-documented decline of European eel populations across Europe (Aalto *et al*., 2016). The precipitous decline of European eel populations observed throughout Europe and the Adriatic Sea basin during past decades has been attributed to multiple, often interacting, stressors (Pike *et al*., 2023). Among these, habitat fragmentation caused by hydropower dams, over-exploitation, environmental degradation including pollution, and biological stressors such as parasites and invasive species stand out as principal drivers (Jacoby *et al*., 2015) which is supported by results of this study.

The European eel has long held ecological, cultural, and economic significance in the eastern Adriatic basin of Croatia, particularly in the Neretva River, where traditional eel fishing practices date back to ancient times (Glamuzina, 2024). Historical accounts describe the Neretva as a centre of eel exploitation; by 1834 the species had already been recognised as commercially important, and an eel-processing factory had been established (Erco, 1919). Throughout the late 19th and early 20th century, eels were harvested using specialised selective nets ("tratun"), longlines, and harpoons designed for extracting eels from the river's muddy substrates (Basioli, 1957). Although eel fishing was important throughout the year, most fishing was done at the time of mass migration to the sea (Fijan, 1948). By 1909, eels from the Neretva region were exported to both domestic and international markets (Erco, 1919).

Commercial fisheries flourished during the early to mid-20th century. In the period 1931–1940, annual catches of reached 68,850 kg, and in 1953–1956 they exceeded 70,000 kg (Morović, 1948; Basioli, 1957). During these decades, eels together with mullet (*Mugil* spp.) accounted for approximately 80% of the total fishery yield. Fishing pressure was particularly intense during the peak downstream eel migration, when 10–15% of the entire migrating stock was reportedly harvested (Morović, 1961). However, the construction of a cascade of hydropower plants along the Neretva [Jablanica (1955), Grabovica (1982), Salakovac (1981), and Mostar (1987)] coincided with a pronounced decline in eel abundance from the mid-1960s onward, largely due to the obstruction of essential migratory routes (Morović, 1966; Glamuzina, 2008). Since the 1990s, commercial eel fishing in Croatia has persisted only in the lower Neretva, accompanied by repeated public reports of diminishing annual catches (Glamuzina, 2024).

Urbanization and the loss of natural habitats have significantly affected European eel populations along the eastern Adriatic coastline (Piria & Tomljanović, 2025). As coastal areas have become increasingly developed, river mouths and estuaries (critical environments for eel feeding, growth, and migration) have been reduced, fragmented, or heavily modified (Glamuzina & Glamuzina, 2001; Cukrov *et al*., 2008; Glamuzina, 2024).

Besides the Neretva River, several other large coastal rivers in Croatia have undergone substantial fragmentation over the past

century. Notable examples include the Cetina and Zrmanja Rivers, where the upper sections have been isolated by multiple hydropower dams lacking fish passage systems (Bonacci & Roje-Bonacci, 2003; Schwarz, 2025). Consequently, European eel is absent from upstream reaches of these rivers (Piria & Tomljanović, 2025). Several smaller coastal rivers, such as the Žrnovnica, Jadro, and Ljuta, have also experienced extensive hydromorphological alteration, including reduced connectivity with the sea (the Ljuta River), which has led to severe declines or complete local extinction of eel populations (Piria & Tomljanović, 2025). In addition to the extensive habitat degradation already evident across many watercourses along the eastern Adriatic Sea coast, numerous new hydropower dams are currently proposed (Schwarz, 2025). The construction of these dams would intensify habitat fragmentation and further restrict the spatial range available to the European eel, negatively affecting its long-term conservation status.

A clear example of population decline linked to habitat disruption is Vransko Lake, historically a landlocked system where European eel was once one of the two most abundant fish species (Morović, 1962). Following the construction of a canal connecting the lake to the Adriatic Sea, several marine euryhaline fish species entered the system (Mrakovčić, 2004). In addition, during the 1940s several non-native freshwater species from the Danube River basin were intentionally introduced (Morović, 1970; Pofuk *et al*., 2017), including common carp (*Cyprinus carpio*), gibel carp (*Carassius gibelio*), rudd (*Scardinius erythrophthalmus*), and European catfish (*Silurus glanis*), which subsequently became dominant (Treer *et al*., 2010; Piria & Tomljanović, 2025). Despite these ecological shifts, in the 1970s the European eel still comprised approximately 28% of the total catch biomass (Popović *et al*., 1984). However, a study conducted in the early 2000s reported a dramatic decline, with eel biomass reduced to just 1–2% of the total fish assemblage in Vransko Lake (Mrakovčić, 2004).

Synergistically with hydromorphological modifications, incidental water pollution further contributes to habitat degradation. There have been repeated pollution events in the upstream section of the Krka River, despite the area belonging to a protected National Park in Croatia. Within this system, the European eel is a strictly protected species under national legislation (Piria & Tomljanović, 2025). Nevertheless, pollution incidents have been recorded, for example, in April 2019 industrial wastewater from a lagoon adjacent to a screw-factory near Knin entered the tributary Orašnica and subsequently reached the Krka River, triggering an official water-quality alert (Hina, 2019). Such pollution is ecologically relevant for species dependent on estuarine gradients, including the European eel, whose early life stages and upstream-migrating glass eels are highly sensitive to toxic contaminants (Gravato *et al*., 2010; Geeraerts & Belpaire, 2010). Early work by Cukrov *et al*. (2008) revealed substantial trace-metal accumulation in estuarine sediments, indicating that the Krka system had already undergone significant anthropogenic alteration. More recently, Cukrov *et al*. (2024) confirmed persistently elevated concentrations of Mn, Pb, Zn, Cd, Cu and As in surface sediments, particularly near former industrial sites, port and marina areas, implying long-term remobilisation potential and continued exposure risk. Such legacy contamination, combined with recent pollution incidents, likely reduces habitat quality and may further erode the suitability of the Krka estuary as feeding and transitional habitat for eel.

The European eel is listed as Critically Endangered (CR) on the IUCN Red List (Pike *et al*., 2023) and is included in Appendix II of both CITES and the Convention on Migratory Species (CMS). In Croatia, the species is nationally recognized, yet freshwater populations are formally protected only within Vransko Lake Nature Park and the upper Krka River National Park (Official Gazette, 2013; 2016). However, despite their protected status in Vransko Lake and the Krka River, legal designation alone is insufficient, as historical pressures, including the introduction of non-native species, pollution, and other legacy impacts, continue to influence the system. Moreover, the presence of active pollution sources near protected zones further undermines the effectiveness of current conservation measures.

The introduction and spread of the non-native parasitic nematode *A. crassus* have had significant physiological impacts on eels. Infection degrades swim bladder function reducing buoyancy, impairing osmoregulation and oxygen uptake, thereby diminishing swimming performance, increasing energy cost of migration, weakening immune responses, and ultimately lowering likelihood of successful spawning migration (Dezfuli *et al*., 2021). Our study demonstrates clear spatial and size-related patterns in *A. crassus* occurrence in European eel populations inhabiting freshwater area of small coastal rivers of the eastern Adriatic. Parasite prevalence was highest in the lower section of the Jadro River (50%) and moderate in both upper and lower Žrnovnica River (43% and 40%, respectively), while no infected individuals were detected at the Jadro spring. The absence of infection upstream suggests either limited upstream dispersal of infected eels or reduced availability of intermediate hosts in spring zones, which are typically colder, faster flowing, and less productive. Similarly, in the freshwater section of the Neretva River, *A. crassus* infestation was detected in 41% of examined eels, while only around 7% of specimens closer to the estuary were affected (Glamuzina *et al*., 2022), but this aspect was not addressed in our study.

Body size emerged as the strongest predictor of infection by *A. crassus* in our study. Larger eels (> 40 cm TL) exhibited a steep rise in infection probability, reaching > 90% above 55 cm. Similar trends have been reported throughout Europe, where *A. crassus* prevalence correlates positively with length, age, and downstream residency (Simon *et al*., 2023; Hein *et al*., 2016). Such size-linked infection patterns are consistent with parasite accumulation through time, as yellow eels may be repeatedly exposed during foraging, while silver eels experience increased migration-driven contact with parasite reservoirs. Several authors have reported size-dependent increases in infection prevalence or intensity in both European and American eels, with larger, older individuals showing higher parasite burdens (Kangur *et al*., 2002; Denny *et al*., 2013; Simon *et al*., 2023; Hein *et al*., 2016). Similarly, spatial gradients in infection along river–estuary continua, with higher prevalences in downstream or brackish habitats, have been described for European eels in northern Europe and for American eels in North American systems (Zimmerman & Welsh, 2012; Hein *et al*., 2014; Glamuzina *et al*., 2022). Although the combined GLM (*TL* + stage + river section) explained the most variation overall, developmental stage and habitat location were not statistically significant independent predictors after accounting for body size. This likely reflects limited sample size, uneven representation of silver eel stages, and quasi-separation within categorical levels. Nonetheless, the full model reinforces the central conclusion that size structure is the primary driver of infection risk,

and that spatial variability across short karstic rivers is secondary to age-related exposure.

In conclusion, given the multiplicity and interaction of threats, European eel conservation cannot rely on a single measure. Instead, an integrated management framework is required; combining habitat restoration (including estuary reconnection and wetland rehabilitation), effective fish-passage solutions, strict fishery regulation, pollution control, and comprehensive health monitoring (parasites and contaminants) (see Tab. 1). This approach aligns with recommendations under the current regulatory frameworks (such as the Council Regulation (EC) No 1100/2007) and international conservation assessments (Euopean Union, 2007; Pike *et al*., 2023; Glamuzina, 2024).

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Supplementary material

The supplementary material for this article can be found at: https://studiamarina.ucg.ac.me/archive.

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Od široke distribucije do lokalnog opstanka: status i ugroženost evropske jegulje u istočnom Jadranu, Hrvatska

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SAŽETAK

Evropska jegulja je pretrpjela ozbiljan dugoročni pad populacije širom svijeta, uzrokovan djelovanjem više međusobno povezanih pritisaka. Istraživanja evropske jegulje u istočnom jadranskom slivu u Hrvatskoj ostala su fragmentisana, bez sistematske procene trendova populacije ili dokumentovanih stresora. Ova studija rekonstruiše istorijski i noviji obrazac rasprostranjenosti evropske jegulje, identifikuje ključne antropogene pritiske u istočnom jadranskom slivu i procenjuje prisustvo parazita plivaćeg mjehura *Anguillicoloides crassus* kroz studiju slučaja na dvije kraške rijeke. Poređenje podataka do 2000-ih sa podacima prikupljenim nakon 2000-ih pokazuje pomjeranje sa istorijski široke rasprostranjenosti ka fragmentisanom obrascu. Među identifikovanim stresorima izdvajaju se hidroelektrane, izmjene riječnih tokova, razvoj obale i planirana ekspanzija hidroenergetskog sektora, kao glavni pritisci duž jadranske obale. Učestalost *A. crassus* kod jedinki jegulje prikupljenih iz rijeka Jadro i Žrnovnica kretala se od 0% do 50% u zavisnosti od lokaliteta uzorkovanja. Infestacija parazitom pokazala je zavisnost od veličine jedinki, pri čemu je vjerovatnoća infestacije ostajala niska kod jedinki ukupne dužine manje od 35 cm. Vjerovatnoća infestacije rasla je sa veličinom jedinki i prelazila 90% kod jedinki dužih od 55 cm. Ukupno posmatrano, rezultati ukazuju na značajan regionalni pad populacije evropske jegulje tokom poslednjih nekoliko decenija, ističu glavne prijetnje i potvrđuju prisustvo parazitske infekcije u priobalnim kraškim lotičkim ekosistemima.

Ključne riječi: *Anguilla anguilla*, pad populacije, slatkovodni ekosistemi, višestruki stresori, *Anguillicoloides crassus*