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Decadal-scale regional variability in monitoring efforts significantly influences fish diversity trends in the Euphrates and Tigris catchments, Türkiye

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Abstract

1. This study investigates the temporal and spatial distribution of species richness in the Turkish portions of the Euphrates and Tigris catchments in Mesopotamia, aiming to identify areas lacking sufficient research and inform future conservation and management efforts.
2. Data from 153 fish assemblages in the Euphrates catchment and 100 in the Tigris catchment, spanning from 1941 to 2022, were analysed using a combination of analytical occurrence, spatial and space-for-time mixed effect models.
3. Results indicate an increase in reported species over time, attributed to heightened sampling efforts, and reveal significant differences in spatial species richness distribution influenced by uneven sampling and environmental suitability.
4. Identification of areas with insufficient research, potential undetected species and biodiversity losses highlights the need for improved assessments to prevent unnoticed biodiversity loss and ecosystem degradation.
5. Our results emphasize the importance of accurate biodiversity assessments for effective conservation and management interventions in these catchments.

KEYWORDS
anthropogenic impact, biodiversity hotspots, Euphrates catchment, fish biodiversity, Mesopotamia, spatial distribution, species richness

1 | INTRODUCTION

The region known as Mesopotamia has been inhabited by humans since ancient times, containing the remains of numerous early villages and cities (Jawad, 2021a). Although the local civilization had reached its peak size during the third millennium B.C., some of these settlements covered an area of up to 400 hectares and housed as many as 80,000 people (Morozova, 2005). Attracted by the need for fresh water, the civilization of this early period relied heavily on the flow of the Tigris and Euphrates catchments, providing all the essentials for survival and prosperity in the early Holocene (Jawad, 2021a).

Ever since, the region of the Tigris and Euphrates catchments has remained an important part of the Irano-Anatolian region and is recognized as one of the world's 34 biodiversity hotspots, in part due to the 92 known endemic fish species (Hanson et al., 2009). Of these, 20 fish species are endemic to the Euphrates and 51 to the Tigris catchment, underlining the distinctiveness and variability between these two closely tied catchments (Freyhof, Kaya, Abdullah, & Geiger, 2021; Freyhof, Kaya, & Ali, 2021; Freyhof et al., 2022; Turan et al., 2021; Jokar et al., 2023; Jouladeh-Roudbar et al., 2023). The entire Euphrates catchment hosts 55 native fish species, while the entire Tigris catchment supports 87 species (Freyhof, Kaya, & Ali, 2021), making these catchments important hotspots for fish biodiversity. One of the main reasons for the high number of endemic species in the Tigris catchment is attributed to the greater presence of mountains and headwater streams/springs (Freyhof, Kaya, & Ali, 2021). Additionally, downstream areas host various marine and estuarine fish species, and the catadromous fish fauna in the lower parts of the catchment (Freyhof, Kaya, & Ali, 2021) is crucial for fishing activities (especially in Satt-ul Arab), providing notable economic wealth to locals (Jawad & Qasim, 2021). The abundance and diversity of fish species in the catchments are vital for sustaining the livelihoods of approximately 8.7 million people in the surrounding areas (Jongerden et al., 2021). Yet, there has been limited research investigating both river catchments: Banister (1980) had discussed their fish fauna and published early checklists; Coad (1991, 1996) had listed many native freshwater fish species; and Freyhof, Kaya, & Ali (2021) published the most recent checklist for the Euphrates and Tigris catchments' fish community, showing the biogeographic similarities between both rivers.

Accompanying the anthropogenically driven overexploitation of fish stocks (Kennish, 2023), there are numerous intertwined drivers contributing to the decline of fish biodiversity world-wide (Reynolds & Peres, 2006), including erratic rainfall, temperature fluctuation and siltation (Sultana et al., 2022). According to Davidson (2014) and Reis et al. (2017), 75% of inland natural wetland habitats have been lost in the last century alone. While some drivers cannot be mitigated efficiently (Bastardie et al., 2021), management strategies and conservation studies also often fail to address many freshwater ecosystems adequately (van Rees et al., 2021). One reason for that is that the diversity of the inhabitant species, especially that of freshwater fishes, is still not exactly known (Balian et al., 2008). The Euphrates and Tigris catchments, for which the diversity of endemic species is still not completely known, are not exempt from such environmental challenges, facing high anthropogenic pressure (i.e. from recreational or provisional use) and substantial extinction risks to numerous native fish species inhabiting these river systems (Freyhof et al., 2014).

Moreover, there is only fragmented evidence of ecosystem-wide changes in both rivers' fish communities (Ünlü, 2021), caused by a lack of compiled information and data anecdotally analysed as isolated moments in time (Freyhof, Kaya, & Ali, 2021) as well as a lack of long-term biodiversity monitoring efforts (Jawad, 2021b). This is problematic, as a lack of information on biodiversity will ultimately result in the loss of numerous species and, with them, a loss of ecosystem functions and a plethora of important aspects for human well-being (Laureto et al., 2015). The lack of coherently and recurrently sampled sites spanning both catchments as well as interest in these two catchments' native biodiversity started to uptake only in recent years (Kaya et al., 2016; Kaya, Yoğurtçuoğlu, et al., 2024). As such, it is possible that certain species, and with them important biological or ecological traits and ecosystem functions, have been lost without notice (Freyhof et al., 2014). This neglect and lack of information is especially cumbersome in biodiverse regions like Mesopotamia, where the loss of species within complex ecosystems with numerous trophic links could have wide-reaching implications (Coad et al., 2019).

Assessing biodiversity, even when based on fragmented or incongruent data, serves as a crucial foundational step for understanding the dynamics of ecosystems. While time series data and congruent samples provide valuable insights into temporal trends and spatial patterns, assembling available information, even if not from systematically collected sources, offers a starting point for future assessments (Haase et al., 2023; Haubrock & Soto, 2023). This baseline knowledge helps establish a framework for tracking changes and identifying critical areas for conservation efforts (Niemelä, 2000). It allows us to glean insights into the historical state of ecosystems, providing context for current conditions and potential trajectories (Haubrock, Balzani, et al., 2023). Moreover, such a preliminary assessment may offer a vital benchmark against which future data can be compared, enabling us to gauge the effectiveness of conservation strategies and adaptive management practices to minimize anthropogenic stressors like non-native species (Soto et al., 2024; Tarkan et al., 2024). In the absence of such baseline assessments, we risk overlooking subtle yet critical shifts in biodiversity that may have significant implications for the health and functioning of ecosystems. To address this knowledge gap and to provide a sound basis for future assessments, we (1) compiled all available information on past and present fish communities of both Tigris and Euphrates catchments from fish collections and (2) investigated detection rates of species over space and time. With this information, we aim to (3) explore spatial differences and long-term changes in the freshwater fish composition of the Turkish parts of the Euphrates and Tigris catchments and to relate these to socio-cultural changes in the region. We hypothesize (i) a high similarity in fish community composition (i.e. number of species shared) between the Euphrates and Tigris catchments, (ii) an increase in detectable species richness with increasing sampling effort over space and time, underlining the importance of broad and comprehensive sampling for biodiversity assessments and (iii) that areas currently suffering from a lack of research effort may lead to unnoticed biodiversity loss.

2 | MATERIALS AND METHODS

2.1 | Data collection

All information on previously collected fish species (i.e. species richness) from the Turkish part of both the Euphrates and Tigris catchments was collected from two large fish collections (Recep Tayyip Erdoğan University Zoology Collection of the Faculty of Fisheries, Rize [FFR] and Ege University Faculty of Fisheries Collection [ESFM]), which were originally collected and preserved to display the diverse biogeographic history and significance of the regional ichthyofauna (Note S1). The collections entailed data from the period of 1941–2022, pertaining to only the identity of species, not their relative or marginal abundance. (Table S1). The collected information on both catchments' fish communities originated from 254 sampling sites (Figure 1), having been mostly collected using Samus pulsed DC electro-fishing equipment, rarely gill nets, cast nets and scoop nets. The collected specimens were fixed in 5% formalin. Although we only investigated the Turkish side of both catchments, we will continue referring to them as the Tigris and Euphrates catchments.

2.2 | Species detection and identification

2.2.1 | Empirical cumulative distribution function

To understand the temporal dynamics of the Euphrates and Tigris fish species identification over time (1941–2022), we identified the first record of species and consequently used the empirical cumulative distribution function (ECDF) to provide insight into the temporal

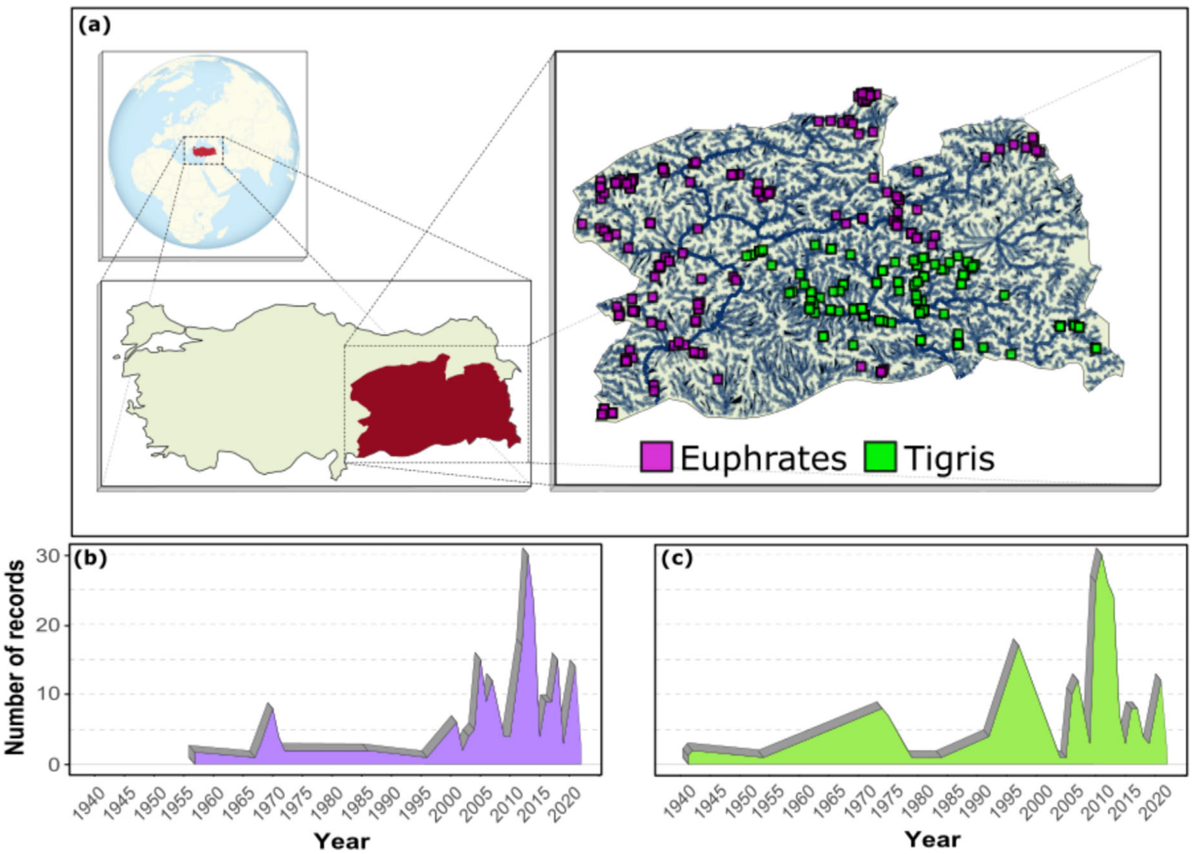

FIGURE 1 Locations of the 254 sampling sites in the Euphrates and Tigris catchments collated from fish collections records (a) and their respective sampling over time for the Euphrates (b) and Tigris catchment (c).

dynamics of both catchments (Henderson et al., 2014). We built ECDF plots using the function *geom_step* of the `ggplot2` R package (Wickham, 2011) to generate a visual representation of the cumulative proportion of a variable, which was, in our case, the first record of the native and non-native species over time.

2.2.2 | Species saturation curves

To determine whether sample size (i.e. the number of fish collection samples over time) was sufficient to describe the fish species richness of the Euphrates and Tigris catchments, the cumulative number of identified species from each catchment was plotted separately against the cumulative number of samples investigated per sample and year (Haubrock, Carneiro, et al., 2023). For this, we used the *specaccum* function of the `vegan` R package (Oksanen, 2013), randomizing each time series 10 times (Ferry et al., 1997; Ferry & Cailliet, 1996). Cumulative curves were considered to be asymptotic if 10 previous values of the total number of species were within ±0.5 of the range of the asymptotic number of species, indicating the minimum monitored time series years required to describe the diversity of non-native and native taxa (Huveneers et al., 2007).

2.3 | Temporal investigation of biodiversity

To analyse the richness (defined as the total number of different species present in a given area and year) and detection of new species within the Euphrates (from 1957 to 2022) and Tigris (from 1941 to 2022) catchments, we used a space-for-time approach (Haubrock et al., 2020). We utilized the base R (R Core Team, 2023) functions and packages such as `dplyr` (Wickham et al., 2019) and `tidyr` (Wickham, 2016) for the calculations of richness. We then modelled the annually detected species richness as well as the number of newly identified species from both catchments using generalized linear model (GLMs) as a function of time ('year') using the *glm* function of the `stats` R package implemented in base R. We selected (1) the sampling years to capture changes in community structure over time, (2) the number of records per year included as a proxy for sampling effort and (3) the sampling area as an additional proxy for sampling effort because larger sampling areas typically record higher species richness and abundance. We identified the negative binomial family as most appropriate after inspecting the model residuals to account for overdispersion in the count data.

2.4 | Spatial trends and projection of known species richness

We used the fish collection data as occurrence data. The maximum entropy model (MaxEnt), representing habitat projections through scenarios based on existing data, was used to determine the current and near-future habitat suitability areas of freshwater fish species distributed in the Euphrates and Tigris catchments (Aksu et al., 2020; Phillips & Dudík, 2008). These scenarios are designed to simulate various environmental and climatic layers, such as temperature, precipitation, evaporation and land use patterns. The modelling process incorporates these scenarios to capture a range of environmental and climatic factors that may affect species distributions. As a result, the potential distribution patterns of the species can be examined, and conservation and management strategies can be informed. Here, we examined bioclimatic models to determine the potential current and future distribution of the fish species in both catchments. The most recent available climate data (from 1981 to 2011) encompassed 23 bioclimatic variables (bio1–19 and gdd0, gdd5, gdd10, ngd0, ngd5 and ngd10, Table S2), which were downloaded from Chelsa-Climate version 2.1 at a high resolution at a monthly interval precipitation and temperature time series (Karger et al., 2017; Karger et al., 2021). For the future scenario (2011–2040), SSP1-RCP2.6 climate data, which is the optimistic scenario simulated by Global Climate Models (ssp126), was used.

To identify spatial hotspots for fish species in the study area, the kernel density method was used (Silverman, 1986). Based on a quadratic kernel function, kernel density mapping produces a circular area (kernel) around an indicator with a certain bandwidth (or search radius) (Brown, 2008). This count was then divided by the area of the neighbourhood, which extends to the distance between two raster cells as the crow flies (i.e. calculates from the centre point of the cell specified to the centre point of the target cell) to obtain the point density (low–high). These analyses were all conducted in ArcMap version 10.8.2.

3 | RESULTS

3.1 | Summary of the collected data

In the current study, a total of 74 fish species belonging to 32 genera was identified from the Turkish part of both river catchments. In the Euphrates catchment, we identified 45 species (19 endemic) from 24 genera and 9 families, whereas in the Tigris catchment, 50 species (17 endemic) from 30 genera and 13 families were identified. Another 19 species were reported for both catchments (Figure 2). The majority of species were reported after the 1990s, with some unique to the Tigris catchment. Species unique to the Euphrates catchment were reported in the 2000s, whereas the majority of species occurring in both catchments were identified in the 2010s (Table S3).

In the period 2001–2022, the collected data from 253 sites identified the native *Alburnus sellal* as the most dominant species in the Euphrates catchments, being identified at ∼8% of all sampled sites (Table S4, Figure S1). For the Tigris catchment between 2004 and 2022, *A. sellal* was found to be the most common species, identified at ∼7% of sampled sites. The second species in the Euphrates catchment was the native species *Capoeta damascina* (∼7%), and the native *Capoeta umbla* for the Tigris catchment (∼6%) (Table 1, Figure S2). Five non-native species were identified in the collection materials, namely, *Carassius gibelio*, *Cyprinus carpio*,

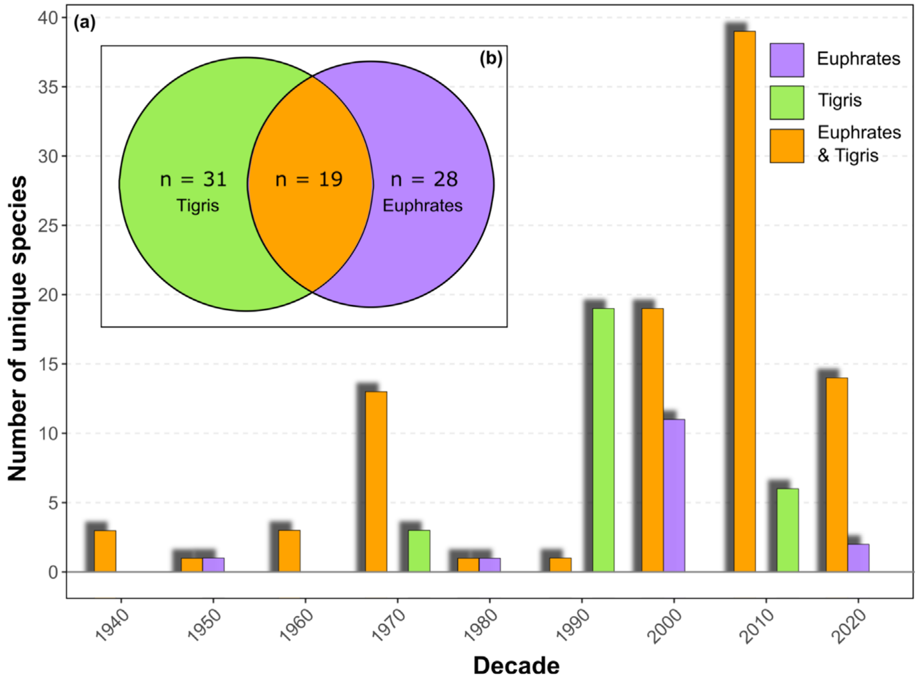

FIGURE 2 The distinct and overlapping richness of the species in the Euphrates and Tigris catchments examined in this study.

TABLE 1 The most common species and percent of occurrence (in parenthesis) collected in both catchments.

Euphrates	Tigris
Ac sellal (∼8%)	*Alburnus sellal* (∼7%)
Capoeta damascina (∼7%)	*Capoeta umbla* (∼6%)
Barbus lacerta (∼5%)	*Barbus lacerta* (∼5%)
Garra rufa (∼4%)	*Garra rufa* (∼5%)
Oxynoemacheilus bergianus (∼4%)	*Cyprinion macrostomum* (∼3%)

Gambusia holbrooki and *Heteropneustes fossilis*. All of them were listed in the Tigris catchment, while only *C. carpio* was identified for the Euphrates catchment (Figure S3).

3.2 | Species detection and identification

Although first samples date back as far as the 1940s for the Tigris and 1957 for the Euphrates, continuous or large-scale sampling only started in the early 1990s (Tigris) and 2000s (Euphrates), reaching their respective peak in 2013 for both catchments with 30 samples per year (Figure 3; Table S4).

Saturation in the detection of species was the same in both catchments but occurred in the Euphrates sampling after 11.0 years, and the asymptote was reached after 32.3 years (Figure 4a). For the Tigris catchment, this was the case after 16.4 and 33.5 years, respectively (Figure 4b).

The analyses of known species richness (i.e. known biodiversity) generated with a generalized linear model detected differences between the catchments over time (Figure 5a). Both catchments showed comparable responses over time, but the response of the Euphrates remained below the Tigris due to a generally lower known species richness, with known species richness increasing over time in congruence with a higher number of records (i.e. effort) per year (both $p < 0.05$). In the case of new species detections over time, we found that for both Euphrates and Tigris, the number of records per year was statistically significant (both $p < 0.05$), indicating that sampling effort drives the number of newly identified species. Although not significant, the number of new species found in the Euphrates declined over time, whereas it was increasing in the Tigris ($p > 0.05$). The sampling area was not statistically significant in both generalized linear models (Tables S5 and S6).

3.3 | Spatial trends and projection of known species richness

The spatial analysis revealed a potential spatial bias in the conducted sampling efforts (see Figure 6a,b). This discrepancy was particularly evident in the central north of the Euphrates catchment and the southeast of the Tigris basin. Moreover, when we projected our data into the future, we found that certain areas with high habitat suitability for species (refer to Figure 6c) showed an increased suitability in the southern regions of both the Euphrates and Tigris catchment areas (as shown in Figure 6d). This trend coincided with the lower-lying areas within the region (see Figure 6e). This was also evident when compared with the most abundant species analyses (Figures S4 and S5).

4 | DISCUSSION

Understanding the complex network of biodiversity is paramount to accurately assess shifts within ecosystems, which underlines the pivotal role of comprehensive biodiversity knowledge in evaluating

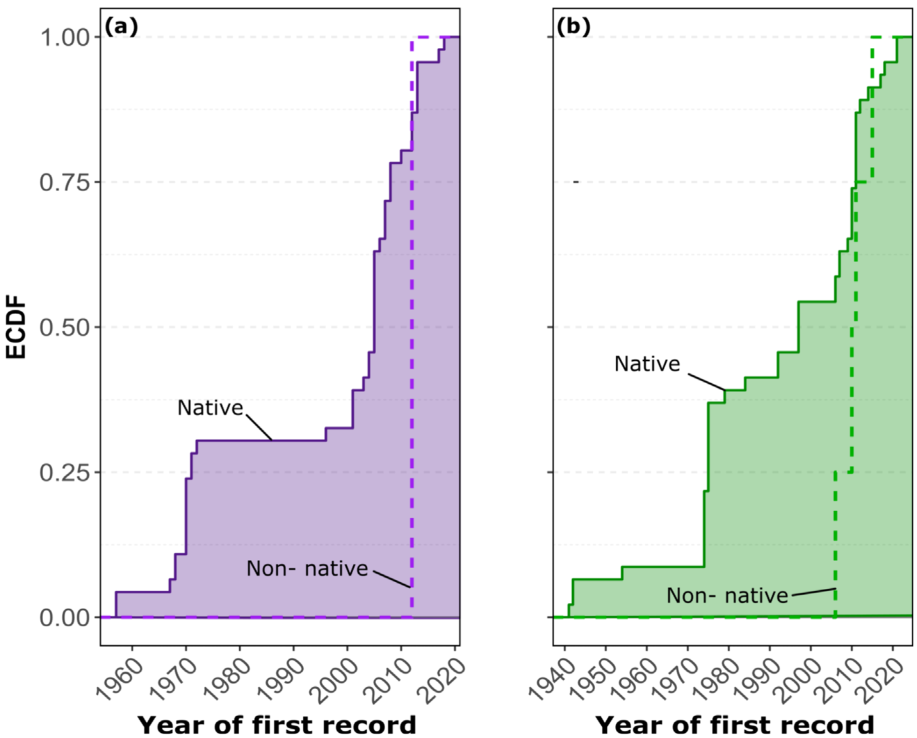

FIGURE 3 Empirical cumulative distribution function (ECDF) for the detection of native and non-native species within the Euphrates (a) and Tigris (b) catchments.

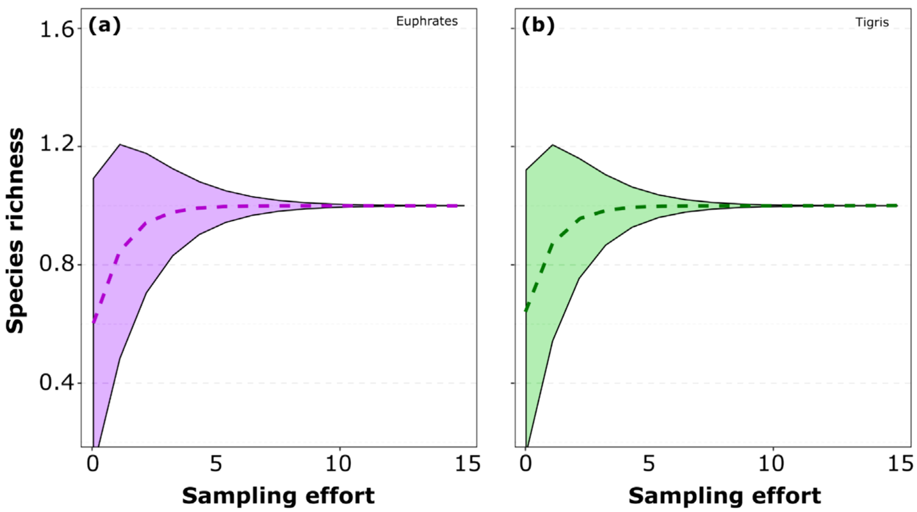

FIGURE 4 Species saturation curve showing the averaged identified species richness (in %) with deviation from the mean as a function of increasing sampling effort (sampled sites per year).

and responding to environmental changes. The Euphrates and Tigris catchments are known for their rich biodiversity, particularly in terms of endemic freshwater fish. With regard to our first hypothesis, we identified substantial similarities but also differences between the fish community compositions—and the description of species—of the Euphrates and Tigris catchments over time. These were, in accordance with our second hypothesis, driven by differing research efforts across space and time, underlining the importance of congruent biodiversity monitoring and the concurrent lack of urgently needed information on both catchments and their respective fish biodiversity. The current information, obtained from fish collection material, already highlights increasing trends in the detection of species, underlining how increased effort can enhance our knowledge of biodiversity, revealing so far unknown species.

4.1 | Species detection and identification

With 74 species, the fish diversity of the upper part of the Euphrates and Tigris catchments reflected a large part of the total known fish diversity (∼400) of Türkiye. Interestingly, both catchments were found to host considerably unique species, with only 19 species occurring in both catchments. While the species belonging to the family Cyprinidae were the most common (18 species), Nemacheilidae (18 species) and Leuciscidae (17 species) also played significant roles. The considerable share of the ichthyofauna of the Upper Euphrates and Tigris catchments had been identified after the 2000s, especially with the acceleration of genetically supported taxonomic studies. In fact, following the increased attention given to both catchments in the past two decades, 25 species have been described (Table S3) and

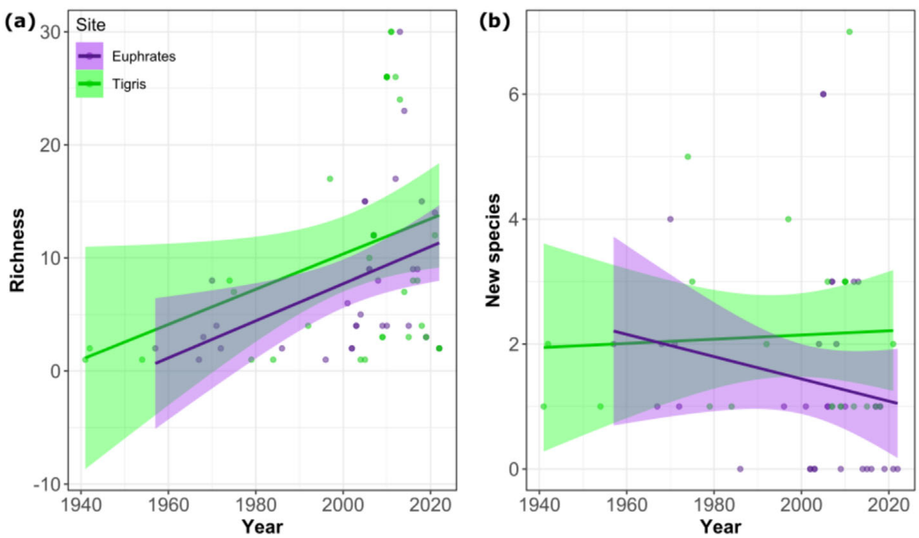

FIGURE 5 Known species richness for the Euphrates and Tigris catchments (a) and the reporting of new species over time (b).

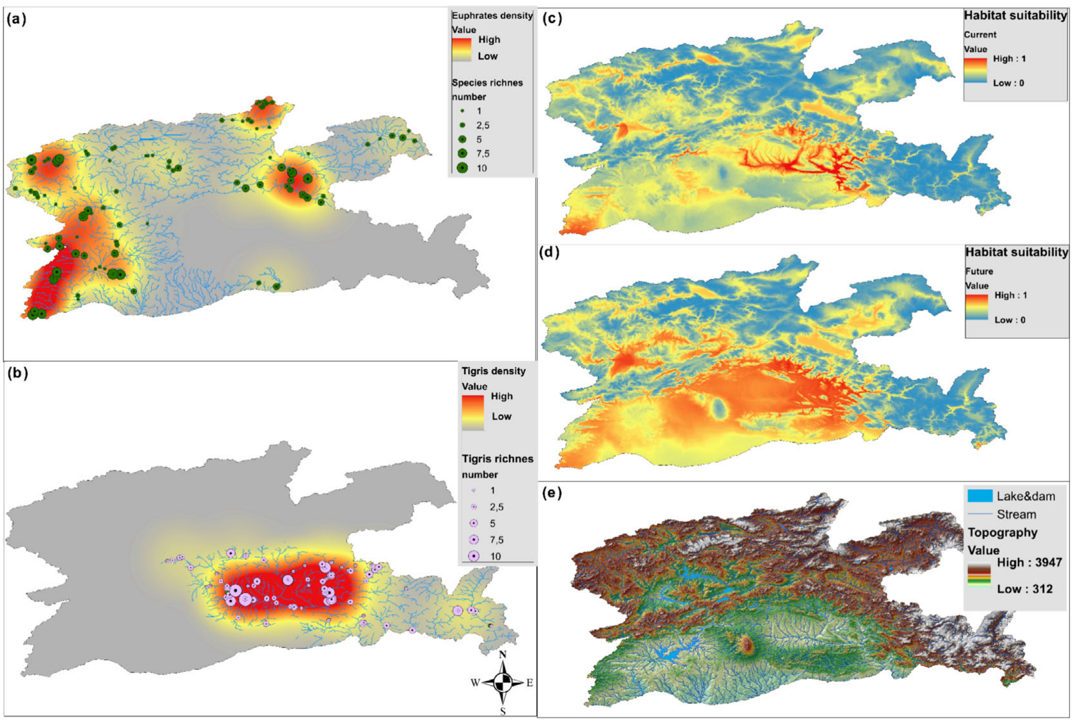

FIGURE 6 Spatial distribution of the conducted sampling for the Euphrates (a) and Tigris catchment (b), respectively, displayed as heatmaps, indicating the identified species richness per site, the current (c) and future habitat suitability (d), as well as a topographic representation of the region (e). Maps were created with ArcMap version 10.8.2.

21 of these (*Alburnoides diclensis*, *Alburnoides velioglui*, *Garra rezai*, *Glyptothorax daemon*, *Oxynoemacheilus arsaniasus*, *Oxynoemacheilus hazarensis*, *Oxynoemacheilus kentritensis*, *Oxynoemacheilus marunensis*, *Oxynoemacheilus muefiti*, *Paracobitis salihae*, *Paracobitis zabgawraensis*, *Salmo baliki*, *Salmo euphrataeus*, *Salmo fahrettini*, *Salmo munzuricus*, *Salmo okumusi*, *Squalius semae*, *Squalius seyhanensis*, *Squalius verepi*, *Turcinoemacheilus ekmekciae*, *Turcinoemacheilus minimus*) have even been described in the last 10 years alone (Turan et al., 2021; Turan et al., 2016; Turan et al., 2020; Freyhof et al., 2017; Freyhof, Kaya, & Ali, 2021; Mousavi-Sabet et al., 2022; Kaya, Imre, & Kurtul, 2024; Kaya, Yoğurtçuoğlu, et al., 2024). However, the identification of new species differed between both catchments. This indicates an—albeit not significant—decline in the Euphrates and an increase in the Tigris catchments, which were modulated by the sampling effort. This suggests that more currently unknown species in both catchments have not yet been identified.

On the other hand, two species that were believed to have been lost (*Alburnus kurui* and *Paraschistura chrysicristinae*) have recently been rediscovered (Freyhof et al., 2018; Shoal, 2024). Moreover, the saturation curve indicated that, based on the currently sampled sites, a saturation in species detection had been reached after ∼39 years. This result, however, should be interpreted with caution, given that a substantial portion of the sampling was conducted in the last two decades, highlighting the importance of proportionate long-term monitoring efforts. Given the importance of both catchments as biodiversity hotspots (Yousefi et al., 2022) and, thus, for the conservation of fish biodiversity in the catchments (Freyhof, Kaya, & Ali, 2021), this result nonetheless raises certain concerns given the lack of information on species diversity due to anecdotal reporting and sampling in the studied period. Specifically, species might have gone extinct without ever being recorded because of substantial anthropogenic activities in that area (Kaya et al., 2020).

Compounding this issue, the invasion of non-native species poses another major threat to the native fish fauna due to competitive advantages (Haubrock et al., 2021). Thus, non-native species often outcompete native species for resources (Top Karakuş et al., 2021), but they may also alter local ecosystems, sometimes irreversibly (Bernery et al., 2023). According to recent studies, the number of non-native species in the Euphrates and Tigris catchments has surpassed 30 established non-native species (Esmaeili, 2021), continuing to increase with new introductions (Kırankaya & Ekmekçi, 2021). Since the 1950s, reservoirs across Iran have been invaded by the grass carp (*Ctenopharyngodon idella*), one of the large carps native to China (Armantrout, 1980). Similarly, the Asian stinging catfish (*H. fossilis*) was introduced to the Tigris catchment for the first time within the second half of the 1950s in southern Iraq (Zakaria, 1964) and recorded for the first time in Türkiye in 2011 (Ünlü et al., 2011). Considering that the Eastern mosquitofish (*G. holbrooki*) was also identified in the Euphrates catchment, it is likely that it will or already has spread substantially (Kurtul et al., 2022). The Eastern mosquitofish is recognized for its harmful effects on indigenous fish populations (Pyke, 2008; Kurtul et al., 2024), which introduces a critical spatial and temporal aspect to the significance of including non-native species in biodiversity evaluations, particularly in biodiversity-rich regions such as Mesopotamia. However, the data underlying the analysis only considered species distributed in the upper reaches of both catchments that were preserved in the two major freshwater collections of Türkiye (FFR and ESFM). Because primarily native species were targeted by the underlying surveys, the distribution of non-native species (especially in the Euphrates catchment) remained anecdotally described. For example, *C. carpio*, *Carassius carassius*, *C. gibelio* and *Oncorhynchus mykiss* were recorded in the Atatürk Reservoir located in the Euphrates River (Bayhan, 2021), *Xiphophorus hellerii* and *Poecilia reticulata* are known for the upper Euphrates catchment (Kırankaya & Ekmekçi, 2021), *H. fossilis* is known to occur in the Tigris catchment (Kaya et al., 2016), and *Atherina boyeri* was described from the Devegeçidi Reservoir (Ünlü et al., 2017). However, these species did not occur in the collection material analysed, emphasizing the prevailing threat presented by lacking or anecdotal information on community compositions.

4.2 | Spatial trends and projection of known species richness

The mountainous rivers in the Turkish part of the Euphrates and Tigris create diverse ecosystems, providing habitat for numerous fish species (Freyhof, Kaya, & Ali, 2021). In Syria and Iraq, the downstream sections of both river catchments exhibit lower species richness compared with their upstream counterparts, with Syria hosting 39 native species and Iraq hosting 52 (Freyhof, Kaya, & Ali, 2021). This pattern arises from the fact that a majority of rare species are predominantly found in the upper regions, particularly in Türkiye, while the main rivers and lower reaches tend to be inhabited by more common species such as *A. sellal*, *C. damascina*, *Paracapoeta trutta*, *Barbus lacerta*, *Cyprinion macrostomum*, *Garra rufa*, and *Carasobarbus luteus* (Freyhof, Kaya, & Ali, 2021; Kaya et al., 2016).

The fact that the majority of native and non-native species within the Turkish part of both catchments was identified after the year 2000 underlines the significance of increased sampling efforts affecting the detection of species. Moreover, the sampling locations in both catchments clustered in specific areas (such as Botan, Batman and Yanarsu rivers in Tigris; Göksu, Karasu and Murat rivers in Euphrates), leaving several areas without notable sampling effort. This might lead to a misinterpretation of identified species information as the connection between sites in complex river networks (Freyhof, Kaya, & Ali, 2021). Moreover, it creates the possibility that some parts of the fish fauna may remain unknown due to, for example, regions that remain limited due to security reasons (Freyhof et al., 2018) or persisting anthropogenic pressures in insular streams (Karimi & Jones, 2020). This in turn suggests that the species diversity reported from both catchments is likely a conservative estimate, with possibly more unidentified species.

The climate has impacted the Euphrates–Tigris catchments, with future projections indicating substantial changes in both catchments (Kibaroglu & Maden, 2014; Özdoğan, 2011). It has been emphasized that significant alterations in the Euphrates–Tigris hydroclimate may lead to further impacts on the physical and biological components of the ecosystems along these rivers. Additionally, increase the challenges associated with reservoirs and hydropower plants in the basin (Bozkurt & Sen, 2013). Considering the predicted increase in climatic suitability for high species richness in the region, the often occurring downstream and upstream expansion of species (Haghighi et al., 2020) could have far-reaching implications for the ecological and economic dynamics of the catchments. As species find suitable habitats further downstream or upstream, a potential shift in the balance of the aquatic ecosystem is anticipated (Ben-Hasan et al., 2018; Mustafa, 2017). This could lead to increased competition between native and non-native species for resources and habitats (Mohamed & Abood, 2021). For example, climatic models suggest that *G. holbrooki* can inhabit with a wide average annual temperature, indicating temperature is not a limiting factor for its invasion (Kurtul et al., 2024), consequently, invasive *G. holbrooki* populations may proliferate through the Euphrates and Tigris catchments. Such scenarios could lead to changes in food webs, potentially giving rise to new predator–prey relationships (Esmaeili, 2021), thereby impacting overall biodiversity and trophic structure (Haubrock et al., 2021).

4.3 | The relevance of socio-economic drivers

The freshwater fish communities in the Euphrates and Tigris catchments of upper Mesopotamia have been influenced by a complex interplay of socio-economic drivers in the past. The region is characterized by major cities such as Malatya, Erzurum, Van, Elazığ, Erzincan, Gaziantep, Diyarbakır and Şanlıurfa, which have fostered diverse industrial activities including textile, food, metal and machinery production, as well as agriculture and animal husbandry (Karan & Basbag, 2022; Muratoğlu, 2020; Ögel & Avcı, 2023). Notably, the implementation of the Southeastern Anatolia Project (GAP) has introduced dams, hydroelectric power plants and irrigation facilities along the Euphrates and Tigris, accompanied by substantial investments across various sectors and work that is ongoing in this area (Bilgen et al., 2021; Saysel et al., 2002). Population growth in the region, fuelled by high birth rates and inadequate education and health services, has been a significant factor. The absence of robust population planning measures has concomitantly led to a continual rise in localized populations, consequently increasing pressures on the diverse ecosystems and, in particular, both catchments (Başıbüyük, 2011). Water abstraction, the removal of vast quantities of water for human use, is altering the natural hydrological regime of both catchments, thereby impacting their ecological dynamics (Ünlü, 2021). In addition, overfishing is leading to a drastic reduction in fish populations, skewing the balance of aquatic ecosystems and compromising their resilience (Freyhof et al., 2014). Moreover, the potential for tourism in this area is anticipated to flourish, particularly as security concerns are addressed, further amplifying the impact of human activities on the environment (İskenderoğlu, 2013).

Although there is no land-use data available for the region with sufficient spatio-temporal resolution that could be used to infer the impact of land use on fish biodiversity change, the anthropogenic presence in the region likely affected both rivers and their native fish communities while facilitating the introduction of non-native species. Recent developments, however, show signs of abatement: The region boasts several conservation areas, including Munzur Valley National Park, Botan Valley National Park, Hakkari Cilo and Sat Mountains National Park and, among others, Hazar Lake Nature Park (Şahbaz & Altınay, 2015), which could play a crucial role in safeguarding biodiversity. In recent years, there has also been a notable shift in the region's industrial development trajectory, with political stability contributing to an acceleration in industrial activities. This trend is expected to persist, signifying a trajectory of continued change and development in the near future (İskenderoğlu, 2013).

4.4 | Implications for management and conservation

The health and ecological stability of the Euphrates and Tigris catchments have been affected by a variety of detrimental forces. Species such as *Acanthobrama marmid*, *A. sellal*, *C. damascina*, *C. umbla*, *Chondrostoma regium*, *Luciobarbus barbulus*, *Luciobarbus xanthopterus*, *Luciobarbus esocinus* and *P. trutta* are migratory. Ensuring migration could be instrumental in preserving their current populations. However, especially current irrigation practices and dry season droughts, they significantly impact the resources of both rivers and hinder migrations. Authorities should design new management strategies that involve regular monitoring of fish distribution, diversity and abundance in the upper, middle and downstream sections of both river catchments to provide a deeper understanding of their ecological dynamics.

A key finding remains that, although an increased sampling effort over time led to an increase in detected species in both catchments, the spatially fluctuating nature of the sampling hinders effective and clear inferences of biodiversity trends and shifts in space and time. This could be compensated in the future with a homogenous net of sampling stations with an elaborate as well as continuous sampling effort over time, similar to that of the Water Framework Directive (Haase et al., 2004), to proactively monitor native species and possibly manage the upstream expansion of non-native species. Such a sampling scheme could be easily set up (see eLTER, Integrated European Long-Term Ecosystem, Critical Zone and Socio-ecological Research; Mirtl, 2018) for future studies, providing valuable information for future generations. Implementing adaptive management strategies that consider the changing dynamics of the catchments will be crucial. This could involve regular assessments of fish populations, habitat conditions and ecosystem health, coupled with flexible management plans that can be adjusted in response to emerging trends. Additionally, engaging with stakeholders, including local communities, resource managers and policymakers, will be essential in crafting effective strategies that balance ecological conservation with sustainable economic activities (Tarkan et al., 2024).

AUTHOR CONTRIBUTIONS

Esra Bayçelebi: Conceptualization; writing—original draft; data curation. **Cüneyt Kaya**: Writing—review and editing; data curation. **Irmak Kurtul**: Writing—review and editing; data curation. **Davut Turan**: Investigation; data curation. **Phillip J. Haubrock**: Conceptualization; methodology; visualization; writing—review and editing. **Ismael Soto**: Methodology; visualization; writing—review and editing. **Sadi Aksu**: Methodology; visualization. **Ali Serhan Tarkan**: Conceptualization; writing—review and editing; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data have been provided as supplementary material in accordance with the data management policy of Aquatic Conservation: Marine and Freshwater Ecosystems.

ETHICS APPROVAL STATEMENT

The collection materials have been used in this study, and as the samples belong to enclosed projects, there is no need for an ethical statement.

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SUPPORTING INFORMATION

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