

CURRENT RESEARCH IN THE FIELD OF AQUACULTURE

EDITOR

PROF. DR. EBRU İFAKAT ÖZCAN



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TABLE OF CONTENTS

DETERMINATION OF THE MORPHOMETRIC AND MERISTIC CHARACTERISTICS OF <i>CAPOETA DAMASCINA</i> (VALENCIENNES, 1842) IN THE PERTEK REGION OF KEBAN DAM LAKE	2
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Ebru İfakat Özcan, Sinan Özcan

ROTIFER FAUNA OF THE INLAND WATERS OF ELAZIĞ: A CURRENT ASSESSMENT	15
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Hilal Bulut

DETERMINATION OF OTOLITH BIOMETRY OF SIRAZ IN THE PERTEK REGION OF KEBAN DAM LAKE.....	34
---	-----------

Denizhan Doğan, Ebru İfakat Özcan

THE EVOLUTION OF UNDERWATER IMAGING TECHNOLOGIES	50
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Sinan Özcan

DETERMINATION OF THE MORPHOMETRIC AND MERISTIC CHARACTERISTICS OF *CAPOETA DAMASCINA* (VALENCIENNES, 1842) IN THE PERTEK REGION OF KEBAN DAM LAKE

Ebru İfakat Özcan*, Sinan Özcan**

INTRODUCTION

Turkey one of the richest freshwater fish faunas in Europe and the Middle East, owing to its diverse hydrographic structure, different climatic zones, and independent river basins. The geological history of the river systems in Anatolia, tectonic movements, and the processes of isolation among basins have facilitated the diversification of numerous fish species and the emergence of endemic species. Therefore, the freshwater fishes of Turkey have long constituted one of the important groups of interest to researchers in terms of taxonomy, systematics, biogeography, and population biology (Çiçek et al., 2015).

Cyprinidae, one of the largest families of freshwater fishes, is of considerable importance in terms of both species richness and geographic distribution. Species belonging to this family are widely distributed in lakes, rivers, streams, and reservoirs and can adapt to a variety of habitat conditions due to their high ecological tolerance.

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Capoeta damascina is one of the freshwater fish species widely distributed in Mesopotamia, Iran, and Turkey. Beyhan Reservoir is located on the Murat River, which is a tributary of the Euphrates River, and the fish species in this river system was previously known as *Capoeta umbla* (Heckel 1843) (Geldiay & Balık 2009; Kuru 1975). However, following the assessment conducted by Bayçelebi et al. (2024), this population, including those inhabiting the Euphrates River and its tributaries, was re-identified as *Capoeta damascina* (Valenciennes 1842). Like other *Capoeta* species, *Capoeta damascina* is a herbivorous benthic species. It feeds by scraping algae and periphyton from the substrate using the keratinized structure of its lower lips; it may also consume detritus and small invertebrates when available in the environment. This species has a broad ecological tolerance and inhabits various freshwater environments, including lakes, streams, and springs (Alwan 2010). Like other *Capoeta* species, *Capoeta damascina* exhibits upstream migratory behavior in river systems during the reproductive period for spawning (Mouludi-Saleh et al. 2024; Yüce et al. 2025).

The body is of medium size, slightly compressed laterally, and covered with relatively small cycloid scales. The head is pointed, the snout is slightly pointed, and the mouth is large, transversely slit-shaped, and ventrally positioned. The upper lip is well developed, whereas the lower lip is undeveloped and has sharp, keratinized margins. A pair of barbels is present around the mouth. The unbranched terminal bony ray of the dorsal fin is poorly developed and bears small denticles along its posterior margin (Kuru, 1975).

In fish systematics, morphometric and meristic characters have long been among the classical methods used for species identification and description. Morphometric characters include linear measurements such as total length, standard length, fork length, head length, head depth, eye diameter, caudal peduncle length, and body depth, whereas meristic characters consist of countable features such as the number of dorsal and anal fin rays, the number of lateral-line scales, pharyngeal tooth arrangement, and the number of gill rakers. These characters are widely used not only for species identification but also for comparing populations, determining phenotypic variation, and evaluating the effects of environmental factors on morphology. In particular, identifying morphological differences among populations inhabiting different drainage basins provides valuable information for stock discrimination and conservation biology (Dağlı & Erdemli, 2016).

The majority of studies on *C. damascina* have focused on its biological characteristics (Şen et al., 2001; Aydın & Şen, 2002; Yüksel et al., 2014; Gündüz et al., 2015; Eroğlu et al., 2018; Kara et al., 2023; Yüce et al., 2025; Özcan & Serdar, 2025). In contrast, studies focusing on morphometric and meristic characters are relatively limited compared with biological studies (Birecikligil & Çiçek, 2011; Dağlı & Erdemli, 2016; Çoban et al., 2013; Yıldırım et al., 2015; Koyun et al., 2018; Özcan & Serdar, 2024). This study is important for the detailed determination of the morphometric and meristic characteristics of *C. damascina* in the Pertek region of Keban Dam Lake, for supporting the taxonomy of the species, and for providing baseline data for future management studies.

MATERIALS AND METHODS

The Keban Dam was constructed between 1965 and 1975 on the Euphrates River in Elazığ to generate electricity. At its normal water level, the dam has a volume of 31,000.00 hm³ and an area of 675.00 km². The Keban Dam is one of the largest dams in the world and in Türkiye. In addition to electricity generation, fish farming is also carried out at the Keban Dam (Bulut & Saler, 2019; Bulut & Saler, 2024). The study area, the Pertek Region of the Keban Dam Lake, is a region with a ferry terminal between Elazığ and Tunceli, where fishing is intensively practiced (Figure 1).

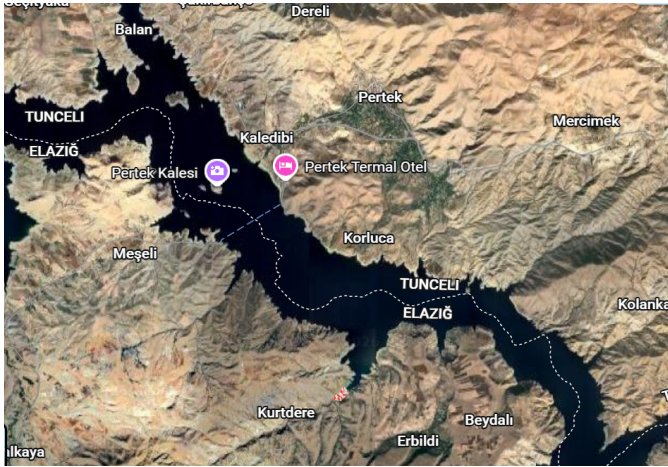


Figure 1. Pertek Region of Keban Dam Lake, where fish samples were taken.

In this study, 58 *C. damascina* fish were obtained from the Pertek region of Keban Dam Lake in June-July 2025. Species identification of the fish brought to the laboratory was performed using the identification keys given by Geldiay & Balık (2007). Morphometric feature measurements and meristic feature counts were

performed. Metric measurements were taken using calipers with 0.01 mm accuracy and rulers with 1 centimeter accuracy, and weights were determined using an electronic precision balance with 0.01 g accuracy.

The following morphometric characteristics were determined: body weight, total length, fork length, standard length, snout length, predorsal length, postdorsal length, eye diameter, postorbital length, head length, head width, head height, body width, body height, interorbital distance, caudal peduncle length, mouth width, distance between pelvic fin and anal fin, distance between pelvic fin and pectoral fin, standard length/snout length, standard length/predorsal length, standard length/postdorsal length, standard length/eye diameter, standard length/postorbital length, standard length/head length, standard length/head width, standard length/head height, standard length/body width, standard length/body height, standard length/interorbital distance, standard length/caudal peduncle length, standard length/mouth width, standard length/distance between pelvic fin and anal fin, standard length/distance between pelvic fin and pectoral fin.

Meristic characters were counted under a magnifying glass and a binocular microscope. The following meristic characters were identified: number of simple rays of the dorsal fin, number of soft rays of the dorsal fin, number of simple rays of the pectoral fin, number of soft rays of the pectoral fin, number of simple rays of the ventral fin, number of soft rays of the ventral fin, number of simple rays of the anal fin, number of soft rays of the anal fin, number of lateral line scales, number of transversal line scales, and pharyngeal teeth.

The minimum and maximum values (Min-Max), mean, standard deviation (SD), standard error (SE), and coefficients of variation (%) of morphometric and meristic values were calculated and presented in tables. The coefficient of variation was calculated using the formula $\%CF=(SD/Mean) \times 100$ (Avşar, 1998). The relationship between standard height and morphometric characteristics was determined using a regression model $y=a+bx$. R^2 values (regression coefficients) were calculated.

CONCLUSION AND RECOMMENDATIONS

The total length of *C. damascina* was found 220-460 mm, the fork length 201-430 mm and the standard length 184-400 mm in the Pertek Region of Keban Dam Lake. The minimum and maximum values (Min-Max), mean (Mean), standard deviation (SD), standard error (SH) and coefficient of variation (CV) of the morphometric characters of the samples are given in Table 1. In the morphometric characteristics of *C. damascina*, the lowest variation was found in the eye diameter 8.6%, and the highest variation was in the mouth width with 26.7%. It was determined that the coefficient of variation of the morphometric characters of the *C. damascina* was generally high in the Pertek Region of Keban Dam Lake.

Table 1. Morphometric measurements of *C. damascina* in the Pertek Region of Keban Dam Lake

Morphometric features	Min-Max	Mean	SD	SE	CV (%)
Body weight	182.3-892	412.9	150.2	32.0	36.4
Total length	220-460	354.0	42.5	9.1	12.0
Fork length	201-430	319.9	40.0	8.5	12.5
Standard length	184-400	297.5	38.6	8.2	12.9
Nose Length	13-22	15.5	1.8	0.4	11.9

Predorsal Length	9.6-20	14.0	2.0	0.4	14.5
Postdorsal length	11-24	14.8	3.0	0.6	20.6
Eye Diameter	7-11	9.2	0.8	0.2	8.6
Postorbital Length	23-44	29.7	5.3	1.1	17.8
Head Length	45-80	57.2	7.2	1.5	12.6
Head Width	23-59	38.9	8.8	1.8	22.7
Head Height	26-58	42.7	6.6	1.4	15.5
Body Width	30-84	49.4	10.3	2.1	20.8
Body Height	48-107	65.2	12.6	2.7	19.4
Interorbital Distance	20-42	28.1	4.9	1.0	17.5
Caudal Peduncle Length	40-79	54.3	8.9	1.9	16.5
Mouth Width	13-32	18.4	4.9	1.0	26.7
Pelvic Fin-Anal Fin Distance	55-94	77.5	11.1	2.3	14.3
Pelvic Fin-Pectoral Fin Distance	60-133	86.3	15.6	3.3	18.1

The ratio of standard length to morphometric characters of *C. damascina* is given in Table 2. The lowest variation was found standard length/predorsal length with 6.2% and the highest variation was found standard length/interorbital distance with 18.3%. In their study conducted in Şiro Stream (Malatya), Dağlı & Erdemli (2016) reported the average standard length/head length as 23.71; standard length/body height as 23.15; standard length/predorsal length as 47.46; and standard length/tail peduncle length as 14.20. Çoban et al. (2013) in their study in Uzunçayır Dam Lake, reported the average standard length as 243.129 mm, standard length/body height as 4.58; standard length/head length as 5.23; standard length/head height as 6.85; standard length/nose length as 13.4; standard length/predorsal length as 2.10; standard

length/tail peduncle length as 3.42; head length/head height as 1.31; head length/nose length as 2.57; and head length/eye diameter as 6.07. They reported a tail peduncle length/tail peduncle height ratio of 2.96.

Table 2. Ratios of morphometric characters of *C. damascina* in the Pertek Region of Keban Dam Lake

Ratios of morphometric characters	Min-Max	Mean	SD	SE	CV (%)
Standard length/Nose Length	14.1-22.35	19.1	1.5	0.3	7.9
Standard length/Predorsal Length	18.6-23.8	21.1	1.3	0.2	6.2
Standard length/Postdorsal length	13.8-25.4	20.3	3.0	0.6	14.9
Standard length/Eye Diameter	26.3-42.2	32.2	3.6	0.7	11.3
Standard length/Postorbital Length	8.0-11.22	10.0	0.8	0.1	8.4
Standard length/Head Length	4.1-6.8	5.1	0.3	0.2	6.7
Standard length/Head Width	6.3-9.6	7.8	1.0	0.2	12.8
Standard length/Head Height	5.9-9.7	7.0	1.0	0.2	14.1
Standard length/Body Width	4.8-7.5	6.1	0.5	0.1	8.8
Standard length/Body Height	3.7-6.6	4.6	0.5	0.1	12.3
Standard length/Interorbital Distance	20.0-42.0	28.0	5.1	1.0	18.3
Standard length/Caudal Peduncle Length	4.3-6.6	5.5	0.5	0.1	10.6
Standard length/Mouth Width	12.0-19.5	16.6	2.3	0.4	14.0
Standard length/Pelvic Fin-Anal Fin Distance	3.1-4.8	3.8	0.4	0.1	12.4
Standard length/Pelvic Fin-Pectoral Fin Distance	3.0-4.4	3.5	0.3	0.1	8.7

Regression models and relationships of standard length-morphometric features of *C. damascina* in the

Pertek Region of Keban Dam Lake are given in Table 3. The highest regression relationship was found between standard length and predorsal length ($R^2=0.85$), while the lowest relationship was found between standard length and head height ($R^2=0.65$).

Table 3. Regression models and relationships of standard length-morphometric features of *C. damascina* in the Pertek Region of Keban Dam Lake

Morphometric Characters	Regression Models	R^2
Standard Length/Nose Length	$y=1.578x+1.829$	0.80
Standard Length/Predorsal Length	$y=1.721x+3.964$	0.85
Standard Length/Postdorsal length	$y=1.968x+1.910$	0.60
Standard Length/Eye Diameter	$y=3.471x-2.025$	0.63
Standard Length/Postorbital Length	$y=4.505x+7.815$	0.79
Standard Length/Head Length	$y=5.499x-1.383$	0.84
Standard Length/Head Width	$y=0.381x+1.920$	0.82
Standard Length/Head Height	$y=1.083x+1.940$	0.65
Standard Length/Body Width	$y=3.866x+10.39$	0.88
Standard Length/Body Height	$y=2.669x+12.35$	0.77
Standard Length/Interorbital Distance	$y=3.894x+7.832$	0.80
Standard Length/Caudal Peduncle Length	$y=4.118x+7.888$	0.68
Standard Length/Mouth Width	$y=5.614x+1.420$	0.69
Standard Length/Pelvic Fin-Anal Fin Distance	$y=2.472x+1.980$	0.72
Standard Length/Pelvic Fin-Pectoral Fin Distance	$y=2.512x+8.713$	0.80

The number of scales in the lateral linea was found to be 87-99 by Karaman (1969), 73-92 by Kuru (1975), 90-96 by Çolak (1981), 73-99 by Gediay & Balık (1988), 74-85 by Erdemli & Kalkan (1996), 76-88 by Örün & Erdemli (2000), 70-82 by Temizer (2001), 72-93 by Dağlı & Erdemli (2016) (80.8 ± 3.93), and 78-91 by Çoban et al. (2013). In this study, it was determined to be 78-90.

Table 4. Meristic characters of *C. damascina* in the Pertek Region of Keban Dam Lake

Meristic characters	
Number of linea lateral scales	78-90
Number of linea transversal scales	14-20/11-18
Number of dorsal fin rays	III-IV/9-10
Number of pectoral fin rays	I-II/12-18
Number of ventral fin rays	I-II/7-9
Number of anal fin rays	II-III/5-6
Pharynx teeth	2.3.4-4.3.2

In this study, the morphometric and meristic characteristics of *C. damascina* were determined in the Pertek Region of Keban Dam Lake, and it can said that habitat differences are effective in the change of morphometric and meristic characteristics. In conclusion; It is thought that this study may contribute to future studies on *C. damascina*, to determine the morphological changes that may occur in the population and to better protect the species. In this respect, the study will serve as an example both for the development of regional fisheries policies and for future studies in similar inland water ecosystems.

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ROTIFER FAUNA OF THE INLAND WATERS OF ELAZIĞ: A CURRENT ASSESSMENT

Hilal Bulut*

INTRODUCTION

Rotifers (Rotifera) are microscopic invertebrates commonly found in freshwater and other inland-water habitats, where they represent an important component of zooplankton communities. They occur in a wide variety of aquatic environments, ranging from large permanent lakes and small temporary water bodies to littoral and interstitial habitats. Together with Cladocera and Copepoda, rotifers are among the major zooplankton groups considered in limnological studies because of their wide distribution and ability to reach high abundances under suitable environmental conditions. Many rotifer species also feed on algae and bacteria, and therefore contribute to the transfer of matter and energy through aquatic food webs (Segers, 2008).

The ecological success of rotifers is largely related to a combination of biological features, including their small size, flexible feeding strategies, effective dispersal, and reproductive characteristics. Most rotifers are about 50–2,000 µm in size and are distinguished by structures such as the ciliated corona and the mastax, which contains the trophi. Their ability to persist during unfavorable periods is another important advantage. Monogonont rotifers can produce resistant resting eggs, while bdelloids are able to survive adverse conditions by entering an anhydrobiotic

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state. These adaptations not only increase their chances of survival but may also support dispersal between aquatic habitats. In addition, parthenogenetic reproduction allows rotifer populations to establish and increase rapidly once environmental conditions become suitable again (Segers, 2008).

Monogononta and Bdelloidea are the two most diverse rotifer groups found in freshwater environments. Segers (2008) reported 1,570 recognized species-level taxa of Monogononta and 461 species of Bdelloidea worldwide. Of the monogonont taxa, 1,488 were free-living forms occurring in freshwater or other inland-water habitats. Even so, the actual diversity of rotifers is likely to be higher than current estimates suggest, mainly because some taxonomic groups remain insufficiently studied and cryptic species may be difficult to distinguish on the basis of morphology alone. Species richness also differs considerably among aquatic habitats. Littoral areas of standing waters, for example, often contain particularly diverse rotifer communities, and the occurrence of certain taxa may be closely related to local environmental conditions. Many benthic and littoral forms are typically associated with oligotrophic or mesotrophic waters that are slightly acidic and relatively soft, whereas several species of *Brachionus* are more frequently found in alkaline and eutrophic waters (Segers, 2008). This variation among habitats shows the value of regional taxonomic and faunistic studies for documenting rotifer diversity and examining how species distributions are related to environmental conditions.

Rotifer communities often respond to changes in the physical and chemical conditions of aquatic environments,

which makes them useful in biological assessments of water quality. Different species vary in their tolerance to factors such as organic enrichment, saprobic conditions, and trophic state, so changes in community composition can provide valuable information about environmental conditions. Sládeček (1983) evaluated the indicator value of rotifers by examining the occurrence and ecological characteristics of numerous species under different water-quality conditions. The findings indicated that rotifer assemblages can be interpreted more effectively by considering the ecological preferences and tolerance ranges of individual species rather than simply recording whether a particular taxon is present or absent.

Rotifer assemblages can also provide useful information about the trophic status of freshwater ecosystems. Ejsmont-Karabin (2012) examined rotifer abundance and community composition in both dimictic and polymictic lakes and found significant relationships between several rotifer-based parameters and commonly used indicators of lake trophic state, particularly chlorophyll-a concentration and Secchi disk transparency. Based on these relationships, the Rotifer Trophic State Index was proposed using a number of community characteristics, including total rotifer abundance and biomass, the proportion of bacterivorous taxa, biomass-to-abundance relationships, and the contribution of taxa associated with more eutrophic conditions. Its application in both deep stratified lakes and shallow polymictic systems indicates that rotifer assemblages can serve as a useful complementary tool for evaluating eutrophication and changes in freshwater ecosystem productivity (Ejsmont-Karabin, 2012). The main ecological characteristics and indicator roles of rotifers are

summarized in Figure 1. This chapter brings together the available literature on the inland waters of Elazığ Province to provide an updated overview of the Rotifera fauna recorded in the region. It also compares rotifer diversity among different aquatic habitats and examines general patterns in their distribution and ecological occurrence based on previously published records.

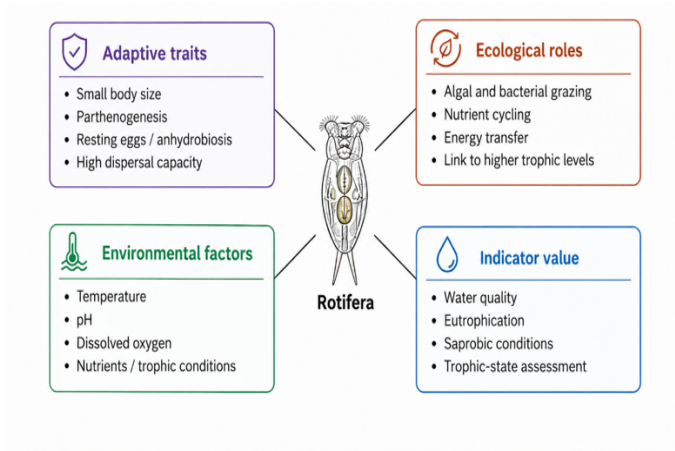


Figure 1. Adaptive traits, ecological roles, environmental factors, and indicator value of rotifers in freshwater ecosystems.

LITERATURE REVIEW

Information on rotifer diversity in Turkish inland waters has increased markedly in recent decades as faunistic and taxonomic surveys have covered a broader range of freshwater habitats. Kaya et al. (2007), based on samples from 36 freshwater localities in Türkiye, recorded 12 rotifer species that had not previously been reported from the country. In the same study, the genera *Aspelta*, *Eothinia*, *Itura*, and *Wulfertia* were also documented for the first time in Türkiye. Additional records were reported

in later studies, including Kaya and Altındağ (2010), who added 10 monogonont rotifer species to the known Turkish fauna.

A more comprehensive picture of rotifer diversity in Türkiye emerged with the national checklist prepared by Ustaoglu et al. (2012). According to this compilation, the first checklist published in 1999 included 167 rotifer taxa, and the number had risen to 229 by 2004. After additional faunistic records were incorporated, the total number of rotifer taxa reported from Turkish inland waters reached 341 in the 2012 checklist (Ustaoglu et al., 2012). This increase over time is likely related to both the study of previously underexplored aquatic habitats and the continued reporting of taxa not previously recorded from Türkiye.

Ustaoglu (2015) later updated the national zooplankton inventory by reviewing 263 publications on Turkish inland waters. This revision added 76 Rotifera taxa and five genera that had not previously been included in the national fauna, raising the number of recorded Rotifera taxa from 341 to 417. In total, the updated checklist included 661 zooplankton taxa, consisting of 417 Rotifera, 103 Cladocera, and 141 Copepoda taxa (Ustaoglu, 2015).

At the regional level, zooplankton research has also increased in the inland waters of Eastern and Southeastern Anatolia. Bulut and Saler (2014a) reviewed studies carried out in these regions between 1987 and 2013 and identified 185 zooplankton taxa in total, including 138 Rotifera, 31 Cladocera, and 16 Copepoda taxa. Rotifers clearly represented the largest group in this regional inventory, highlighting both their contribution to zooplankton diversity and the importance of inland waters in Eastern

and Southeastern Anatolia for faunistic studies (Bulut & Saler, 2014a).

A considerable number of studies have examined freshwater rotifers in Elazığ Province across a variety of inland-water habitats, including natural lakes, reservoirs, ponds, rivers, and streams. Research carried out in Hazar Lake, Keban Dam Lake, Cip Dam Lake, Kalecik Dam Lake, Beyhan Dam Lake, Kepektaş Dam Lake, as well as several lotic systems, has contributed substantially to current knowledge of rotifer occurrence, diversity, and distribution in both standing and running waters of the province Saler & Şen, 2002; Saler, 2009; Saler et al., 2011; İpek & Saler, 2012; Bulut & Saler, 2013, 2014b, 2014c, 2018, 2019; Saler et al., 2018; Çelik et al., 2022). However, these records are distributed across studies conducted in different water bodies and during different sampling periods. Some investigations have focused specifically on Rotifera, whereas others have examined rotifers as part of the broader zooplankton community (Saler & Şen, 2002, 2010; Bulut & Saler, 2014b, 2019). Therefore, bringing these records together provides an opportunity to evaluate rotifer diversity and distribution across the inland waters of Elazığ within a common framework. The main inland-water habitats investigated in rotifer studies in Elazığ Province are shown in Figure 2.

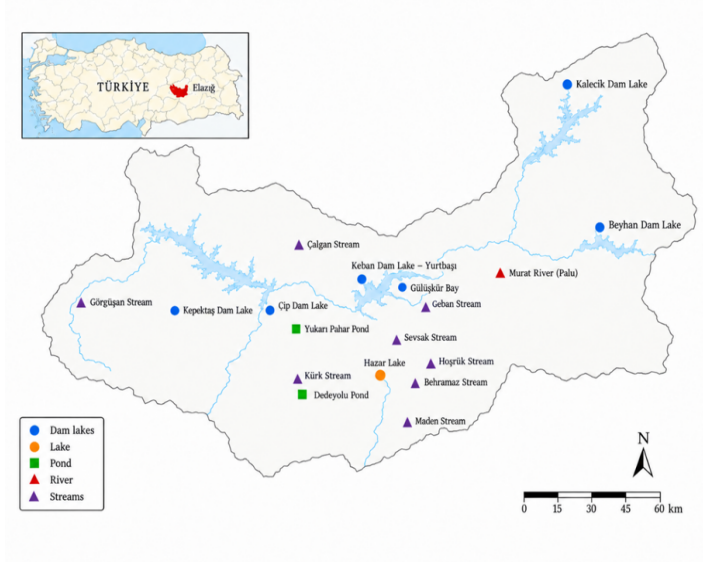


Figure 2. Inland-water habitats of Elazığ Province investigated in rotifer studies.

METHOD

This chapter brings together previous studies on rotifers from the inland waters of Elazığ Province and provides a general assessment of the available literature. Studies conducted in lakes, reservoirs, ponds, rivers, and streams were examined in terms of the Rotifera species reported, species richness, seasonal distribution, dominant or frequently recorded taxa, and findings related to environmental variables.

Information from these studies was considered together to identify general patterns in rotifer diversity and distribution across the inland waters of Elazığ. Species richness, seasonal changes, ecological indices, and environmental findings were taken into account.

FINDINGS

Development of Rotifer Research in the Inland Waters of Elazığ

Studies on the rotifer fauna of Elazığ inland waters have gradually moved beyond descriptive faunistic and seasonal surveys to include ecological indices, environmental variables, spatial analyses, and predictive approaches. At the same time, the range of habitats examined has broadened from reservoirs and large standing waters to ponds, rivers, and smaller streams. As a result, the available literature now provides a substantial basis for evaluating rotifer diversity in Elazığ not only from a taxonomic perspective, but also in relation to seasonal patterns, habitat features, and environmental conditions.

One of the earlier studies included in this assessment was conducted by Saler and Şen (2002), who examined seasonal changes in the Rotifera fauna of Cip Dam Lake from April 1994 to March 1995. They recorded 15 rotifer species belonging to 12 genera. Rotifer abundance was lower during winter and increased in spring and summer. Significant relationships were also found between rotifer abundance and both water temperature and total hardness.

Later studies extended rotifer research to other water bodies in Elazığ Province. Saler (2009) examined Kepektaş Dam Lake using monthly samples collected from January to December 2005 and identified 11 rotifer species. *Kellicottia longispina* showed the highest relative density (57%), while *Polyarthra vulgaris*, *Colurella uncinata*, *Asplanchna priodonta*, and *Keratella cochlearis* were reported among the dominant species. Rotifera

abundance was generally higher during spring and summer. Saler and Şen (2010) later investigated long-term changes in rotifer assemblages in Gülüşkür Bay of Keban Dam Lake by comparing two sampling periods, in which 27 and 24 Rotifera taxa were recorded, respectively.

During the following decade, rotifer studies in Elazığ increasingly included running-water habitats. In Kürk Stream, which flows into Hazar Lake, monthly sampling conducted from February 2007 to January 2008 revealed nine Rotifera species. Rotifers were present throughout the year, with *Keratella cochlearis* and *Polyarthra dolichoptera* recorded in seven and six months, respectively (Saler et al., 2011). Baysal and Saler (2014) identified 20 Rotifera species belonging to nine families in Çalgan Stream. İpek and Saler (2012) recorded 20 Rotifera species in Görgüşan Stream and 16 in Geban Stream. In both streams, *K. cochlearis* and *P. dolichoptera* were among the most frequently recorded species. Zooplankton species richness was generally highest in spring and lowest in winter, while Rotifera represented the dominant zooplankton group in both streams.

During the same period, studies of reservoirs in Elazığ became more detailed and increasingly considered community structure. Bulut and Saler (2013) recorded 25 Rotifera species in Kalecik Dam Lake, where rotifers represented 62.5% of the identified zooplankton taxa. The study also made an important faunistic contribution by reporting *Cephalodella forficata* for only the second time in Türkiye. Species diversity was lower in winter and increased considerably during spring and summer. In Beyhan Dam Lake, 24 Rotifera taxa were identified, and rotifers made up 93.38% of total zooplankton abundance.

Keratella cochlearis was the dominant rotifer, while *Polyarthra dolichoptera* was reported as co-dominant. Zooplankton abundance was highest in spring and lowest in winter (Bulut & Saler, 2014b). Bulut and Saler (2014c) also investigated the Murat River in the Palu district and recorded 25 Rotifera species among a total of 33 zooplankton taxa. Among these, *K. cochlearis* occurred in nine months and *Synchaeta pectinata* in seven months. Taken together, these studies show that by the mid-2010s, rotifer research in Elazığ covered both standing and running-water ecosystems.

More detailed taxonomic and ecological methods were also introduced in studies conducted during this period. Bulut and Saler (2018) examined the rotifer fauna of Hazar Lake and identified 24 species. They also used scanning electron microscopy to study diagnostically important trophic structures, which helped distinguish morphologically similar monogonont rotifers and provided greater taxonomic detail. Around the same period, research on Hoşrük Stream combined faunistic data with ecological diversity indices, including Shannon–Wiener, Simpson, and Margalef indices. Eighteen Rotifera species were recorded, and rotifers ranked first in terms of taxon richness, abundance, and frequency of occurrence. *Polyarthra dolichoptera* was the most frequently recorded species (Saler et al., 2018).

Ecological and environmental assessments became more common in rotifer studies conducted in Elazığ during this period. Bulut and Saler (2019) identified 27 Rotifera species among 40 zooplankton taxa in Keban Reservoir, with rotifers accounting for 67.5% of the recorded taxa. The study also included physicochemical

measurements and reported a *Brachionus*/*Trichocerca* (QB/T) ratio of 0.5, which the authors interpreted as an indication of oligotrophic conditions. In Dedeyolu Pond, Saler (2020) recorded 17 Rotifera species and assessed species diversity and richness using ecological indices, together with relationships involving temperature, pH, and dissolved oxygen. *Keratella cochlearis* was reported as the dominant species throughout the seasons. Saler and İpek Alış (2020) also identified 29 Rotifera species at the Yurtbaşı locality of Keban Dam Lake, where rotifers accounted for 83.5% of the recorded zooplankton taxa. Species diversity and richness were evaluated using the Shannon–Wiener and Margalef indices, respectively, and relationships between zooplankton abundance and temperature, pH, and dissolved oxygen were also examined. Recent studies have expanded both the range of habitats investigated and the methods used to examine rotifer diversity in Elazığ. A broad survey of Hazar Lake recorded 37 Rotifera taxa and showed that rotifers were the leading zooplankton group in terms of frequency of occurrence, species richness, and abundance. The study also used geographic information system approaches to examine their spatial distribution within the lake (Çelik et al., 2022). Research conducted in Sevsak and Behramaz streams likewise revealed a strong presence of Rotifera, with 19 and 32 species recorded, respectively. In both streams, higher numbers of zooplankton taxa and individuals were generally recorded during spring or the spring–summer period (Saler, 2022; Saler et al., 2022). In Maden Stream, 21 Rotifera species were identified, with species richness reaching its highest levels in spring and summer. *Polyarthra dolichoptera* was the most frequently recorded rotifer in this habitat (Saler, 2023).

A different analytical approach was used by Bulut (2023) in a study of Cip Reservoir. Monthly data collected during 2021–2022 were used to predict Rotifera, Cladocera, and Copepoda densities with artificial neural networks based on environmental variables. In addition to describing zooplankton composition, the study examined how changes in water-quality parameters could be used to predict zooplankton densities. This application of artificial neural networks introduced a predictive perspective to zooplankton research in the region and extended the use of quantitative methods in local limnological studies (Bulut, 2023).

The most recent faunistic study included in this review was conducted in Yukarı Pahar Pond. Öztürk and Saler (2026) identified 23 Rotifera species among 36 zooplankton taxa, with rotifers accounting for 79.91% of total zooplankton density. These findings add further evidence of the strong representation of Rotifera in the inland waters of Elazığ. The study also expanded the regional dataset by including another relatively small pond ecosystem.

Overall, studies conducted in Elazığ show that rotifer research has gradually expanded beyond basic faunistic and seasonal descriptions. More recent work has incorporated biodiversity indices, physicochemical variables, trophic-state assessment, scanning electron microscopy, spatial analyses, and predictive modeling alongside traditional species-based approaches (Bulut & Saler, 2018, 2019; Saler et al., 2018; Saler, 2020; Çelik et al., 2022; Bulut, 2023). The literature also covers a wide variety of inland-water habitats, including reservoirs, natural lakes, ponds, rivers, and streams. Together, these

studies provide a useful basis for comparing rotifer assemblages across different aquatic environments in Elazığ.

Rotifer Diversity and Distribution in the Inland Waters of Elazığ

The number of Rotifera taxa reported from the inland waters of Elazığ varied considerably among water bodies and studies. The available records indicate differences in rotifer richness among lakes, reservoirs, ponds, rivers, and streams. A summary of the reported Rotifera richness values is presented in Table 1.

Table 1. Reported Rotifera species/taxon richness in the inland waters of Elazığ Province

Inland water body	Source	Reported number of Rotifera species/taxa
Cip Dam Lake	Saler & Şen (2002)	15
Kepektaş Dam Lake	Saler (2009)	11
Keban Dam Lake – Gülüşkür Bay	Saler & Şen (2010)	27 / 24
Çalgan Stream	Baysal & Saler (2014)	20
Kürk Stream	Saler et al. (2011)	9
Görgüşan Stream	İpek & Saler (2012)	20
Geban Stream	İpek & Saler (2012)	16
Kalecik Dam Lake	Bulut & Saler (2013)	25
Beyhan Dam Lake	Bulut & Saler (2014b)	24

Inland water body	Source	Reported number of Rotifera species/taxa
Murat River – Palu	Bulut & Saler (2014c)	25
Hazar Lake	Bulut & Saler (2018)	24
Hoşrük Stream	Saler et al. (2018)	18
Keban Dam Lake	Bulut & Saler (2019)	27
Dedeyolu Pond	Saler (2020)	17
Keban Dam Lake – Yurtbaşı	Saler & İpek Alış (2020)	29
Hazar Lake	Çelik et al. (2022)	37
Sevsak Stream	Saler (2022)	19
Behramaz Stream	Saler et al. (2022)	32
Maden Stream	Saler (2023)	21
Yukarı Pahar Pond	Öztürk & Saler (2026)	23

The studies reviewed here show substantial differences in Rotifera richness among the inland waters of Elazığ (Table 1). The highest richness was reported for Hazar Lake, with 37 taxa, followed by Behramaz Stream with 32 taxa and the Yurtbaşı locality of Keban Dam Lake with 29. Twenty-seven Rotifera taxa were reported from Keban Dam Lake, while 27 and 24 taxa were recorded in Gölüşkür Bay during two different sampling periods. Kalecik Dam Lake and the Murat River each had 25 recorded Rotifera species, while 24 were reported from Beyhan Dam Lake and from Hazar Lake in the 2018 study. Yukarı Pahar Pond contained 23 recorded species, and Maden Stream had 21. Lower numbers of Rotifera species were reported from Çalgan Stream and Görgüşan Stream, with 20 species in each, followed by Sevsak Stream with

19, Hoşrük Stream with 18, Dedeyolu Pond with 17, Geban Stream with 16, Cip Dam Lake with 15, Kepektaş Dam Lake with 11, and Kürk Stream with nine. These figures should be interpreted carefully, as the studies differed in sampling duration, number of stations, and sampling design. Therefore, differences in the reported species numbers should not be considered direct comparisons of rotifer richness among water bodies. This is also evident from studies conducted in the same water body; for example, separate surveys of Hazar Lake reported 24 and 37 Rotifera taxa.

DISCUSSION

Rotifers have been recorded from a wide range of inland-water habitats in Elazığ, indicating that they are well represented across different aquatic environments in the region. Differences in species richness among water bodies may be related to habitat characteristics and local environmental conditions. Considering lakes, reservoirs, ponds, rivers, and streams together also shows that rotifers occur in both standing and running-water systems. The frequent occurrence of species such as *Keratella cochlearis* and *Polyarthra dolichoptera* in different studies suggests that these taxa are widely distributed in the inland waters of Elazığ (Saler, 2009; Saler et al., 2011; İpek & Saler, 2012; Bulut & Saler, 2014b, 2014c; Saler et al., 2018; Saler, 2023). In addition, several studies reported higher species richness or abundance during spring and summer, suggesting that seasonal environmental conditions may play an important role in shaping rotifer communities (Saler & Şen, 2002; Saler,

2009; Bulut & Saler, 2013, 2014b; Saler et al., 2022; Saler, 2023).

Differences in reported species richness should be interpreted carefully because the studies varied in sampling duration and research design. For example, different studies conducted in Hazar Lake reported 24 and 37 Rotifera taxa. This suggests that the recorded level of species richness may vary depending on the scope of individual surveys (Bulut & Saler, 2018; Çelik et al., 2022).

Another notable point is that relatively high rotifer richness was reported in both standing and running-water habitats. While 37 taxa were reported from Hazar Lake, 32 taxa were recorded in Behramaz Stream (Çelik et al., 2022; Saler et al., 2022). This indicates that high rotifer diversity in Elazığ is not restricted to a single habitat type. In addition, the use of ecological indices, physicochemical measurements, scanning electron microscopy, spatial analyses, and predictive modeling shows that rotifer research in the region has gradually moved beyond purely faunistic studies toward broader ecological and analytical approaches (Bulut & Saler, 2018, 2019; Saler et al., 2018; Çelik et al., 2022; Bulut, 2023).

CONCLUSION AND RECOMMENDATIONS

The available literature shows that rotifers are an important component of zooplankton communities in the inland waters of Elazığ and occur in a wide variety of aquatic habitats. Studies conducted in the region have provided valuable information on rotifer species diversity, seasonal patterns, ecological conditions, and distribution.

Future studies examining different aquatic habitats using similar approaches may allow more reliable comparisons of rotifer diversity. Long-term monitoring, together with the combined use of morphological, molecular, and environmental data, may also contribute to a more detailed understanding of rotifer diversity and ecological responses in the region.

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DETERMINATION OF OTOLITH BIOMETRY OF SIRAZ IN THE PERTEK REGION OF KEBAN DAM LAKE

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INTRODUCTION

Otoliths are one of the reliable bony structures used in age determination in fish. Otoliths are three pairs of bony structures made of calcium carbonate located in the inner ear. These structures have different morphological structures depending on the species and can be affected by factors such as nutrition, fish size, different environmental conditions, and stress. They are among the most commonly used bony structures to study the conditions that characterize the life cycles of many fish species. The growth of bony structures in fish is proportional to the fish size. Especially in recent years, taking measurements such as length, width, and weight of bony structures and relating them to the length of the fish, and determining the growth rates of the fish accordingly, are common studies. The relationship between otolith length and fish length allows for the estimation of fish size from otolith length found in archaeological sites and in predator stomachs in fish stomach content analysis systems. When an unexpected value is obtained in age determination using otoliths, it can be verified with fish length. It has also been reported that fish age can be determined from otolith weight (Samsun & Samsun, 2006; Dörtbudak & Özcan, 2015).

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Establishing and implementing successful fisheries management primarily depends on reliable data (Ünal et al., 2001; Yüksel et al., 2014). Besides being used for age determination, otoliths also provide information about the growth, ontogenetics, and biological history of fish. This is because otoliths form with the fish and continue to grow throughout its life. Otoliths are quite important in fisheries biology. Many studies exist on the otolith biometrics of fish, including: researched by Eroğlu & Şen (2009), Başusta et al. (2013a, b), Dörtbudak & Özcan (2015), Düşükcan et al. (2015), Düşükcan (2018), Düşükcan & Çalta (2018), Başusta & Tan (2019), Kontaş et al. (2019), Kurucu et al. (2019), İlhan & Akalın (2019), Özpiçak et al. (2019), Şimşek et al. (2019), İşmen et al. (2020), Saygın et al. (2020), Yazıcı et al. (2020), Yılmaz & Sakallı (2021), Akbay et al. (2022), Başusta & Bıyıklı (2022), Suiçmez & Şen (2022), Yılmaz et al. (2022), Dörtbudak et al. (2023), Karakuş & Tıraşın (2023), Koca & Küçükköse (2023), Reis et al. (2023), Yüksel & Aydın, 2023; Bostancı et al. (2024), Bulut et al. 2024, Düşükcan et al. (2024), Serdar & Özcan, 2025.

There are no previous studies on the otolith biometry of the siraz (*Capoeta damascina*) in the Pertek region of the Keban Dam Lake. This proposed project focuses on determining the otolith biometry of *Capoeta damascina*, a species of economic importance and popular among the local population in the Pertek region of the Keban Dam Lake. By determining the otolith biometry of this species, it will contribute to future studies, particularly to researchers investigating the interaction between stomach contents and food, and to the existing literature.

MATERIALS AND METHODS

The Keban Dam was constructed between 1965 and 1975 on the Euphrates River in Elazığ to generate electricity. At its normal water level, the dam has a volume of 31,000.00 hm³ and an area of 675.00 km². The Keban Dam is one of the largest dams in the world and in Türkiye. In addition to electricity generation, fish farming is also carried out at the Keban Dam (Bulut & Saler, 2019; Bulut & Saler, 2024). The study area, the Pertek Region of the Keban Dam Lake, is a region with a ferry terminal between Elazığ and Tunceli, where fishing is intensively practiced (Figure 1). Sampling to determine the otolith biometrics of the citronella fish was started between May 2025 and July 2025. *Capoeta damascina* specimens from the Pertek Region of the Keban Dam Lake were collected as dead fish from local fishermen engaged in commercial fishing. Dead fish collected for otolith biometrics were placed in transparent plastic bags and brought to the Pertek Sakine Genç Vocational School laboratory in a transport container. Smaller fish, which will be preserved as samples, were placed in 4% formalin, while larger fish (those larger than 15 cm) were injected with 4% formalin orally and anally using a syringe into their abdominal area to prevent their internal organs from spoiling.



Figure 1. Keban Dam Lake, Pertek Region

The total lengths of the fish brought to the laboratory were measured and recorded using a measuring board with ± 1 mm accuracy and a digital caliper; their weights were measured and recorded using an electronic balance with ± 1 gr accuracy. The sex of the fish was determined by opening their abdomens and examining their gonads. Using forceps, the right and left otoliths were removed by entering the gill cavity of the fish. The removed otoliths were cleaned and dried in petri dishes containing 10% NaOH solution, and the right and left otoliths were stored separately. Otolith length (OL) was defined as the longest part between the postrostrum and rostrum axes passing through the center of the otolith. Otolith width (OW) was defined as the longest dimension between the dorsal and ventral parts (Tuset et al., 2008). Using an ocular micrometer attached to a stereo zoom microscope, the otolith length and otolith width of each otolith (right otolith and left otolith) were measured in millimeters on the same axis and on the distal surface.

Otolith weights (OWe) were measured using a precision balance with an accuracy of ± 0.0001 g. All measurements were recorded on forms or entered into a computer. The difference between right and left otolith pairs was investigated using a paired t-test. If there was no difference between otolith pairs, a single regression was created for each parameter by averaging the measurements. If there were differences between right and left measurements, a separate regression was created for each parameter. To determine the relationship between otolith dimensions and fish length, a linear regression model $y = ax + b$ was created according to sex (Total Length–Otolith Length, Total Length–Otolith Width, Total Length–Otolith Weight, Otolith Weight–Otolith Length, Otolith Width–Otolith Length and Otolith Weight–Otolith Width). The model with the highest R^2 coefficient was selected to describe the relationships mentioned above.

CONCLUSION AND RECOMMENDATIONS

To investigate the otolith biometrics of the siraz (*Capoeta damascina*) in the Pertek region of Keban Dam Lake, 92 fish (49 females and 43 males) were examined. The measurements of the examined fish were determined to range from TL: 187-490 mm; OL: 1.3-2.54 mm; OW: 1.01-1.78 mm; and OWe: 2.6-9.89 mg.

The smallest otolith length in *C. damascina* obtained during the study was 1.3 mm, observed in a female fish with a total length of 199 mm and a weight of 71.4 g. The largest otolith length was 2.54 mm, observed in a female fish with a total length of 490 mm and a weight of 999 g. The differences between the right and left otoliths, as well as otolith length, otolith width, and otolith weight, were

found to be statistically insignificant according to sex ($p>0.05$). Therefore, since there was no difference between the right and left otoliths, the right otolith was used in the study. The otolith length, otolith width, otolith weight, and total length values of the citronella *Capoeta damascina* from the Pertek region of Keban Dam Lake, according to sex, are given in Table 1.

Table 1. Otolith length, otolith width, otolith weight, total length and fish weight values of *Capoeta damascina* according to sex in the Pertek Region of Keban Dam Lake

Sex		n	Minimum	Maximum	Average	Standard Error
Female	Otolith length (mm)	49	1.3	2.54	1.650	0.035
	Otolith width (mm)	49	1.03	1.78	1.244	0.026
	Otolith weight (mg)	49	2.82	9.89	5.530	0.250
	Total length (mm)	49	187	490	284.93	10.065
Male	Otolith length (mm)	43	1.31	1.99	1.602	0.027
	Otolith width (mm)	43	1.01	1.56	1.213	0.022
	Otolith weight (mg)	43	2.6	8.63	5.236	0.221
	Total length (mm)	43	189	366	274.08	9.250
All	Otolith length (mm)	92	1.3	2.54	1.651	0.026
	Otolith width (mm)	92	1.01	1.78	1.244	0.018
	Otolith weight (mg)	92	2.6	9.89	5.530	0.182
	Total length (mm)	92	187	490	284.93	7.345

The relationship between total length and otolith length was found to $y = 0.0033x + 0.7195$ ($R^2 = 0.8996$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 2).

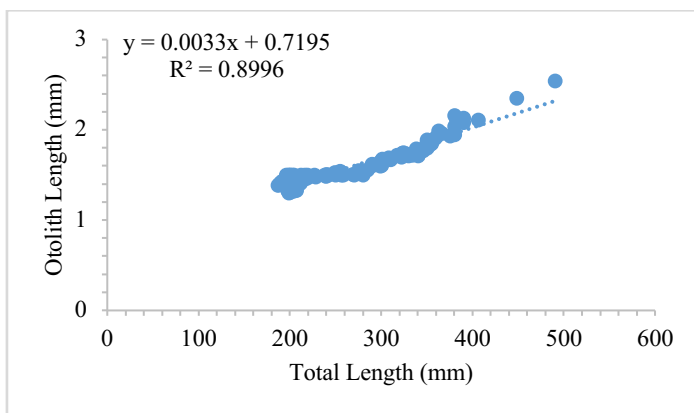


Figure 2. Relationship between total length and otolith length in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

The relationship between total length and otolith width was found to $y = 0.0024x + 0.5684$ ($R^2 = 0.8631$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 3).

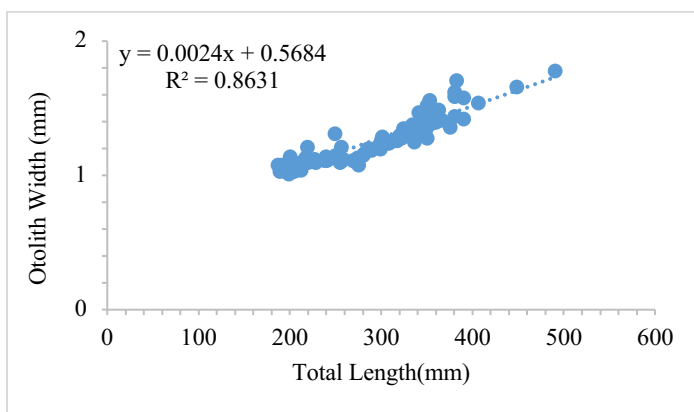


Figure 3. Relationship between total length and otolith width in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

The relationship between total length and otolith weight was found to $y = 0.0221x - 0.7797$ ($R^2 = 0.7975$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 4).

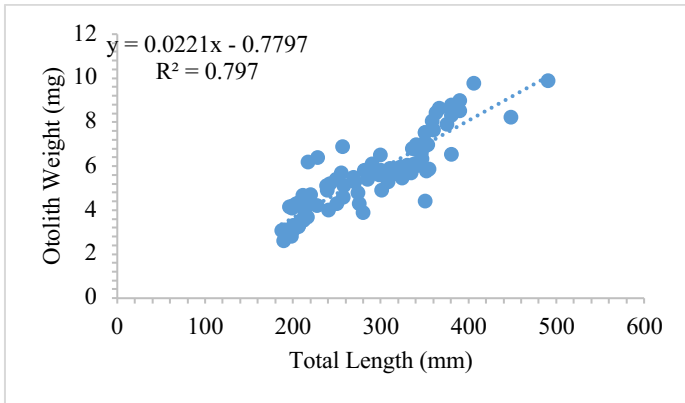


Figure 4. Relationship between total length and otolith weight in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

The otolith length-otolith width relationship was found to $y = 0.6917x + 0.1029$ ($R^2 = 0.8701$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 5).

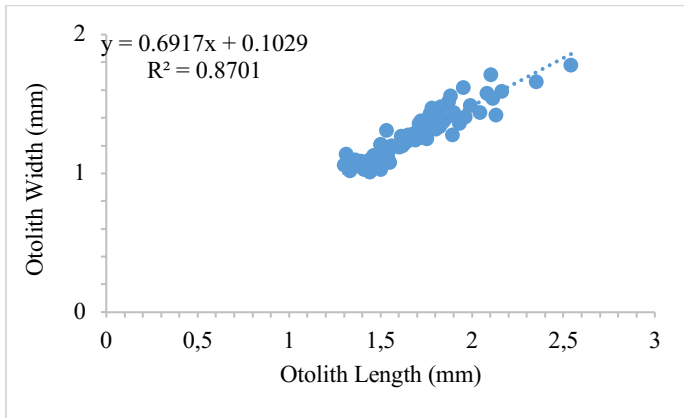


Figure 5. Relationship between otolith length and otolith width in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

The otolith length-otolith weight relationship was found to $y = 6.3513x - 4.9505$ ($R^2 = 0.779$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 6).

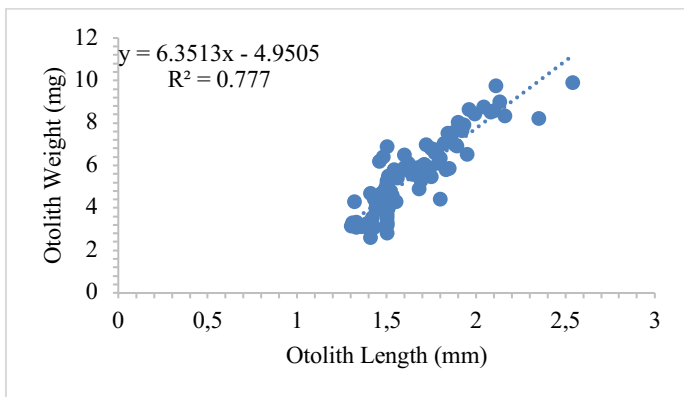


Figure 6. Relationship between otolith length and otolith weight in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

The otolith width-otolith weight relationship was found to $y = 8.198x - 4.6706$ ($R^2 = 0.7126$) in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake (Figure 7).

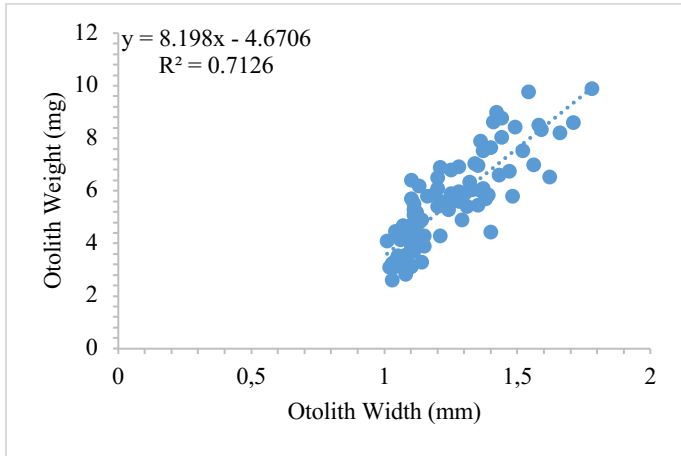


Figure 7. Relationship between otolith width and otolith weight in all individuals of *Capoeta damascina* in the Pertek Region of Keban Dam Lake

Şen et al. (2001), in their study on otolith biometry in the *Capoeta umbla* population in Lake Hazar, stated that there was a high positive correlation between total length and otolith length.

Başusta et al. (2013a), in their study investigating the relationship between otolith dimensions and fish length in red-spotted trout (*Salmo trutta macrostigma*) in the Munzur River, reported a parallelism between fish length and otolith length and found a high correlation value.

Başusta et al. (2013b), in their study on otolith biometry and fish length of *Lepidotrigla dieuzeidei* living in the Mediterranean, stated that there was no statistically

significant difference ($p>0.05$) between the right and left otolith dimensions and that they could be used without distinguishing between them.

Dörtbudak & Özcan (2015), in their study on the relationship between otolith biometry and fish length in the ciraz fish (*Capoeta umbla*) in the İkizce Stream (Şırnak), reported that there was no statistically significant difference in otolith length and otolith width between the right and left regions.

Düşükcan & Çalta (2018), in their study on total length and otolith biometry in the *Barbus gyrpus* fish species caught in Karakaya Dam Lake, found a strong positive correlation between total fish length and otolith biometry.

Yüksel & Aydın (2023) conducted a regression analysis between otolith size and total length in the ciraz (*C. umbla*) population in Uzunçayır Dam Lake. According to this, they found a very high level of positive correlation between total length and otolith length, otolith width, and otolith weight.

Düşükcan et al. (2024) reported that according to regression relationship analyses between total length and otolith measurements in the *Capoeta umbla* population in Özlüce Dam Lake, there were strong positive correlations between total length and otolith length, width, and weight.

In conclusion, this study investigated the relationships between otolith dimensions and fish dimensions of *Capoeta damascina* in the Pertek Region of Keban Dam Lake for the first time. It can be said that otolith growth occurs along with fish growth, and otolith length and fish length increase in parallel. This study will guide future

otolith biometric studies on *Capoeta damascina* living in different water sources.

Acknowledgement

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THE EVOLUTION OF UNDERWATER IMAGING TECHNOLOGIES

Sinan Özcan*

INTRODUCTION

Oceans and other bodies of water, covering approximately 71% of the Earth's surface, constitute the planet's largest ecosystems yet remain largely unexplored. Many activities, such as seabed mapping, monitoring marine biodiversity, documenting underwater archaeological remains, coastal management, inspecting energy infrastructure, and defense applications, require reliable imaging technologies. However, the underwater environment presents a far more complex field of study for imaging than terrestrial environments due to its physical characteristics that limit light propagation (Jaffe, 2015).

The optical properties of water are among the fundamental factors determining image quality. As light travels through water, it is subject to absorption and scattering effects, which leads to a decrease in image contrast, color loss, and a significant reduction in visibility. The rapid absorption of red wavelengths, in particular, causes images to turn blue-green as depth increases. Furthermore, scattering effects caused by suspended particles result in blurriness and noise in images. Therefore, underwater images often exhibit low contrast and distorted characteristics (Lu et al., 2017). These physical limitations have led to the continuous development of underwater imaging technologies

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throughout history. While research initially focused primarily on underwater photography, the development of acoustic methods made it possible to collect data at depths inaccessible to optical systems. The development of sonar technologies, in particular, has marked a significant turning point in underwater research by enabling the mapping of large areas of the seabed and object detection in low-visibility environments (Jaffe, 2015).

Advances in digital imaging technologies since the 1990s have ushered in a new era in underwater research. The widespread use of CCD and CMOS sensors has enabled the acquisition of higher-resolution images, allowing for real-time processing. Simultaneously, the development of remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has allowed for long-duration imaging operations at depths inaccessible to humans. Thus, imaging systems have transformed from mere observation tools into data collection and environmental analysis platforms (Massot-Campos & Oliver-Codina, 2015).

In recent years, one of the most significant advancements in underwater imaging has been the widespread adoption of three-dimensional reconstruction and active optical systems. Laser line scanning, structured light systems, stereo vision, and Structure-from-Motion (SfM) methods enable the creation of highly accurate three-dimensional models of the seabed and underwater structures. These technologies are widely used, particularly in fields such as marine archaeology, coral reef monitoring, and industrial infrastructure inspections (Massot-Campos & Oliver-Codina, 2015).

However, today, research focuses not only on image acquisition but also on the automatic interpretation of the acquired data. Thanks to deep learning and artificial intelligence-based methods, significant successes have been achieved in tasks such as image enhancement, object recognition, classification of marine organisms, and autonomous navigation. Computational imaging approaches contribute to obtaining higher quality images by compensating for the degradations caused by the underwater environment (Lu et al., 2017).

Although there are numerous studies in the literature that examine specific subfields of underwater imaging technologies, the number of studies that comprehensively evaluate the transformation of technological development throughout history, from optical systems to artificial intelligence-supported imaging methods, is limited. Therefore, the aim of this review study is to examine the historical development of underwater imaging technologies, compare the basic imaging approaches used, and reveal the prominent research trends today. In this context, the evolutionary process, ranging from the first underwater photography applications to sonar systems, from digital imaging technologies to three-dimensional reconstruction methods and artificial intelligence-supported image processing techniques, will be evaluated in detail.

The Evolution of Sonar Technologies

Although the initial development stages of underwater imaging technologies relied on optical systems, the interaction of water with light confined the performance of these systems within fundamental physical limits. Light propagation in water is rapidly attenuated due to

absorption and scattering processes, which particularly limits the visibility distance to a few meters (Figure 1). Jaffe (2015) emphasizes that the fundamental problem of underwater optical imaging is both the direct attenuation of light and the loss of contrast due to scattering.

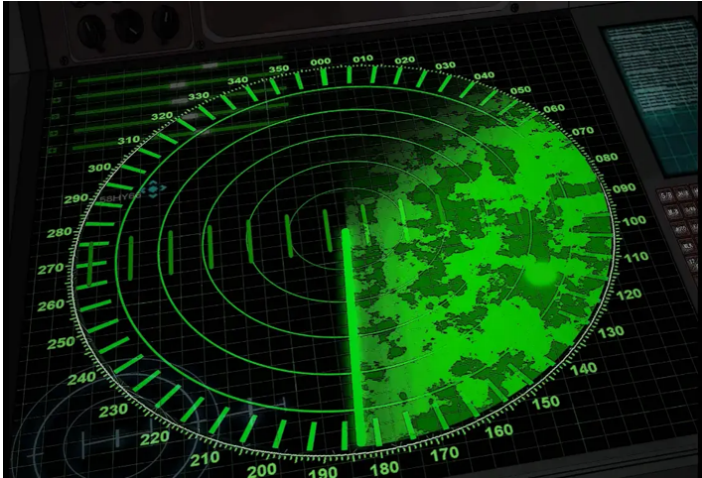


Figure 1. SONAR technology (Sound Navigation and Ranging)
(URL-1, 2026)

Two methods are commonly used for obtaining underwater images: sonar systems, which utilize various acoustic sensors, and camera systems, which use optical sensors. Sonar, used by dolphins for communication and bats for navigation, is an abbreviation of the English phrase "Sound Navigation and Ranging." It is a technical method that utilizes the underwater propagation properties of sound waves to enable navigation both underwater and on the surface, distance calculation, communication, and obtaining information about other objects (Au, 1993). Sonar systems are commonly used in detecting schools of fish, identifying and classifying targets, mapping the seabed, and detecting mines. In sonar systems, the patterns

obtained from acoustic sensors present difficulties in detecting targets, objects, and obstacles due to environmental noise (Kılınç & Metlek, 2021). Similarly, Mobley (1994) demonstrated that the optical properties of water change depending on the wavelength, and that the red spectrum is rapidly absorbed over short distances. This situation causes the images to shift towards blue-green tones as the depth increases.

While optical waves attenuate rapidly in water, acoustic waves can propagate with much lower energy loss. This physical difference has made it possible to develop sound-based imaging systems in underwater research. Blondel (2009) states that acoustic systems are one of the most effective methods for mapping the underwater environment and that sonar technologies are divided into three basic categories: single-beam sonar, side-scan sonar, and multi-beam sonar (Figure 2).

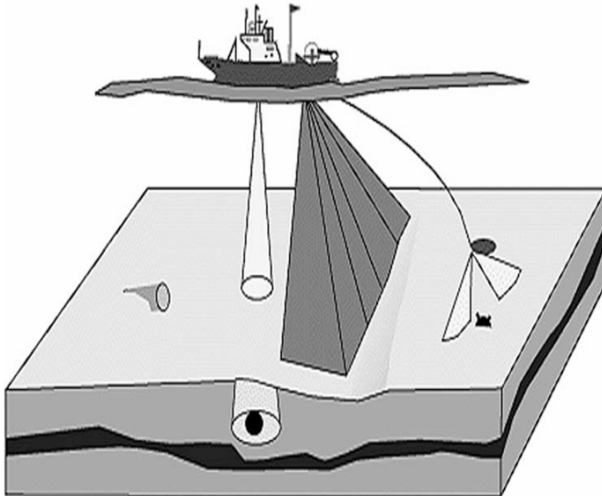


Figure 2. Sonar mapping systems (Blondel, 2009)



Figure 3. Fish Finder Smart Sonar Technology, Fish Detection Device (URL-2, 2026)

These systems use sound waves instead of light to generate images from signals reflected from the seabed and underwater objects (Figure 3).

Developed since the 1980s, multibeam sonar (multibeam echosounder) systems have marked a significant turning point in underwater imaging technologies. These systems enable three-dimensional mapping of large areas by performing numerous measurements simultaneously with a single sound pulse (Tannaz et al., 2018). Multibeam sonar technology has become a standard method in modern hydrographic mapping, seabed morphology analysis, and geological research. Furthermore, Brown & Blondel (2009) stated that multibeam systems have provided a revolutionary advance in the classification of benthic habitats.

Today, underwater imaging systems do not rely on a single sensor type. Instead, a sensor fusion approach has been adopted. In this approach, optical cameras, sonar systems, and other sensors are used together to increase the environmental sensing capacity. Singh et al. (2000) demonstrated that the combined use of optical and acoustic sensors in underwater archaeology studies provides critical advantages in terms of both wide-area exploration and high-resolution documentation. This approach has become a standard architecture, especially with the development of autonomous underwater vehicles (AUVs). The evolution of underwater imaging technologies from optical to acoustic systems has been primarily determined by the limitations of the physical environment. The strong attenuation of light in water limits the range of optical systems, while the ability of sound waves to propagate over longer distances has made the development of sonar technologies possible.

The Era of Artificial Intelligence and Computational Imaging in Underwater Imaging Technologies

One of the most significant paradigm shifts in underwater imaging technologies is the transition from hardware-centric systems to computational imaging and AI-based methods. While traditional optical and acoustic systems are directly dependent on physical limitations, the new approach relies on a hybrid structure that optimizes image quality using both hardware and algorithms. Jaffe (2015) emphasized that the underwater imaging problem has become not only a physical but also a computational problem, and noted that algorithmic modeling of image distortions is particularly critical.

In the early 2010s, underwater image enhancement studies relied mostly on physics-based models and statistical approaches. These methods included histogram equalization, color correction, and wavelength compensation techniques. Chiang & Chen (2012) developed a physics-based color correction model by showing that color distortion in underwater images is wavelength-dependent. However, these methods experienced generalization problems in different water types and variable environmental conditions.

In recent years, the most important research direction has been physics-informed artificial intelligence models, instead of purely data-driven methods. Akkaynak and Treibitz (2019) developed the “Sea-thru” method by explaining the underwater imaging problem with a physical light propagation model and showed that depth-dependent color correction is possible. This approach highlights the importance of combining physics-based and learning-based methods in underwater imaging.

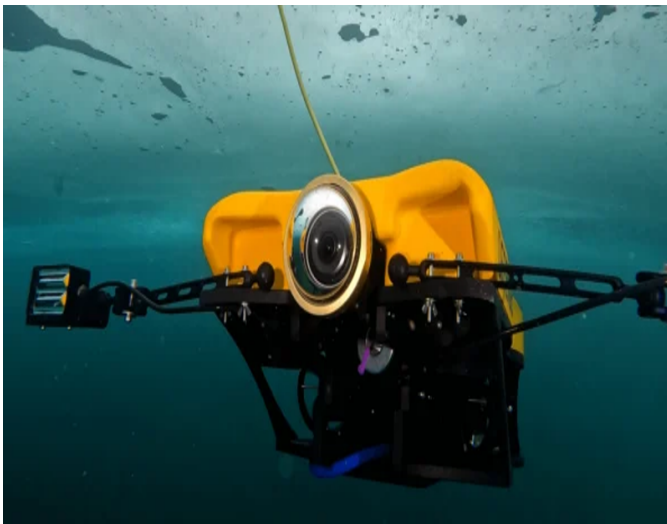




Figure 4. Underwater imaging systems (URL-3, 2026)

In the underwater environment, such models are used especially in tasks such as:

- Classification of marine organisms
- Wreck and object detection
- Pipeline inspection
- Environmental monitoring (Figure 4) (Islam et al., 2020).

Current studies in the literature show that the future of underwater imaging will develop along three main axes:

- Fully autonomous underwater robots (AUV swarm systems)
- Physics-informed deep learning models
- Real-time 3D digital twin systems

Wynn et al. (2014) state that autonomous underwater vehicles will be the main platform for marine exploration in the future.

Artificial intelligence and computational imaging have created a new turning point in the evolution of underwater imaging technologies. Traditional physics-based systems are increasingly being replaced by data-driven and hybrid models. This transformation has not only improved image quality but has also turned underwater systems into autonomous platforms that “sens and decide.”

General Assessment and Conclusion

When the evolution of underwater imaging technologies is examined, it is seen that the development is not a single linear progression; it is a multi-layered transformation process in which optical, acoustic, and computational systems complement each other. Jaffe (2015) emphasizes that the future of underwater imaging depends not only on developing better sensors but also on the integration of physical modeling and computational methods.

In this context, the current trend has shifted towards an “algorithm-driven perception” approach rather than hardware-centric systems.

The most important development in underwater research in recent years is the integration of autonomous underwater vehicles with artificial intelligence. Wynn et al. (2014) demonstrated that AUV systems significantly reduce the cost of data collection in marine sciences and make long-duration autonomous missions possible.

It is predicted that in the future, these systems will evolve into structures that:

- Can make real-time decisions
- Are adaptable to environmental conditions
- Can operate in swarms.

While traditional deep learning approaches are dependent on large datasets, the current trend is the development of models integrated with physics knowledge. Akkaynak & Treibitz (2019) developed the “Sea-thru” approach by solving the underwater imaging problem with a physics-based light propagation model and showed that this field can yield more accurate results with physics-based learning. This approach forms the basis of next-generation algorithms, especially in problems such as:

- Color correction
- Depth estimation
- Image restoration.

Another rising trend in underwater research is digital twin technologies. In this approach, continuously updated digital models of the physical underwater environment are created. Structure-from-Motion (SfM) and multi-image-based 3D reconstruction methods form the basis of this technology (Westoby et al., 2012). In the future, these systems are expected to become widespread in areas such as:

- Continuous monitoring of marine ecosystems
- Infrastructure deformation analysis
- Autonomous navigation support systems.

Although significant progress has been made, underwater imaging technologies still face some fundamental challenges:

- Real-time high-resolution processing load
- Lack of labeled data
- Generalization problem to different water types
- Difficulty in physical modeling of optical distortions
- Energy limitations (especially in AUV systems)

The evolution of underwater imaging technologies shows a multi-stage development process, starting from optical photography, to sonar-based acoustic systems, and then to AI-powered computational imaging and autonomous robotics systems.

Although underwater imaging technologies are critical in many fields such as marine sciences, oceanography, underwater archaeology, environmental monitoring, and industrial inspection, they have faced significant technical limitations for many years due to the optical and physical constraints of the aquatic environment. Underwater imaging systems are an indispensable part of modern maritime and engineering. Without these systems, we cannot protect our infrastructure, transport energy, or respond to emergencies. The best results depend not on a single technology, but on the combined use of all technologies. This review examines the evolution of underwater imaging technologies from a multi-stage perspective, ranging from sonar-based approaches and digital imaging technologies to three-dimensional reconstruction systems and finally to AI-powered computational imaging methods. In recent years, AI and

deep learning-based methods have led to significant advancements in areas such as improving underwater images, color correction, object detection, and autonomous navigation. Consequently, the evolution of underwater imaging technologies points to a multidisciplinary transformation based not only on advancements in sensor technologies but also on the integration of physical modeling, computational imaging, and artificial intelligence. It is predicted that in the future, this field will be shaped around fully autonomous underwater systems, real-time 3D mapping, and physics-information integrated artificial intelligence models.

As a result, underwater imaging technologies have evolved from being merely a tool for "obtaining visual data" to becoming intelligent systems that perceive, interpret, and make decisions about their environment. Future studies are expected to focus on hybrid systems where physics-based models and artificial intelligence methods are more tightly integrated.

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