

Article

Bioaccumulation of Heavy Metals in Water and Organs of *Stone moroko* (*Pseudorasbora parva*) in Freshwater in Turkey

Semra Küçük

Department of Fisheries and Aquacultural Engineering, Faculty of Agriculture, Adnan Menderes University, Aydın 09100, Turkey; skucuk@adu.edu.tr

Abstract: Anthropogenic activities have been causing pollution in the environment and aquaculture activities via the contamination of heavy metals from industrial developments. As a result, this environmental pollution may cause health problems in humans. In this study, water ($n = 3$) and fish ($n = 10\text{--}15$) samples were evaluated from Topçam Barrage to assess the heavy metal concentrations in the water and tissue samples of fish, *Pseudorasbora parva* (muscle, liver, kidney, spleen, gonads, and gills). All samples were measured using the ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometer) in conjunction with a standard solution (As, Cd, Cr, Cu, Zn, Ni, and Pb). The bioaccumulation factor (BCF), target hazard quotient (THQ), and hazard index (HI) were calculated for human health due to fish consumption. A significant degree of heavy metals was found, which followed the order of $\text{Zn} > \text{Cu} > \text{Pb} > \text{Ni} > \text{Cd} > \text{Cr}$ for fish tissues. Heavy metal amounts were found to be mostly higher for Cu and Pb. It was reported that their amounts were around the limit values established by the FAO (Food and Agriculture Organisation) and WHO (World Health Organisation). Further studies are needed on the precautions how to more increase the water quality level.

Keywords: heavy metals; bioaccumulation factor; water pollution; fish; *Pseudorasbora parva*



Academic Editors: Guining Lu and Ahmed Moufti

Received: 24 December 2024

Revised: 10 April 2025

Accepted: 15 April 2025

Published: 21 April 2025

Citation: Küçük, S. Bioaccumulation of Heavy Metals in Water and Organs of *Stone moroko* (*Pseudorasbora parva*) in Freshwater in Turkey. *Processes* **2025**, *13*, 1251. <https://doi.org/10.3390/pr13041251>

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Nowadays, fish is a good source to consume. They have many essential amino acids, minerals, vitamins (A, D, E, K B5, B6, B12), and unsaturated fatty acids (omega 3, omega 6) [1,2]. It is dedicated that human ought to eat fish twice a week by the American Heart Association to take the daily requirements for sufficient omega- 3 fatty acids [3]. Aquatic and terrestrial ecosystems have been threatened when rapid industrial developments continued. In the developing countries like Turkey, most of the industrial wastes have not total threatened, by treatment plants (solid, liquid pollutants) [4]. Heavy metal contents of water have appeared as ones of most dangerous contaminants by real structure, non-biodegradability, accumulating tendency as characteristics of them [5]. In water, heavy metal accumulates higher in tissues than water by means of surface of gills, liver, kidney, digestive tract and spleen of fish [6]. Biomagnification of heavy metals increases in tissues until the maximum allowed concentrations. An occurrence of human health risk such as damages of cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) causes toxicity to nervous system, kidney, liver [7]. Altimony (Sb) and Cr lead carcinogeneticity and toxicity of Pb is related to cognitive defects [5,8] and. Because of heavy metal pollution, human body health could be affected by fish consumption e.g. nephrotoxicity, hepatotoxicity, cardiovascular toxicity, neurotoxicity [9]. It is important to culture fish and consume them from pollution free environment or water ecosystems reduced industrial activities.

On the Earth, there has been reported that several rivers are contaminated by environmental pollution. There are two ways for heavy metal bioaccumulation of fish, digestive tract on body surface (gills and muscles) [10]. The most common reason of heavy metal pollution in aquatic ecosystems is industrial and agricultural wastes and atmospheric discharges [11]. Copper (Cu) and zinc (Zn) are used the first trace elements for fish metabolism via selective or active transport [12]. If number of metalloid and heavy metal accumulations increase, fish caused numbers of health problems. They can take them to body by diets. Cu and Zn are used for biochemical reactions as essential elements in fish, but Cd, Hg, Pb, Cr, Ni, As are toxic and non-essential elements and they can accumulate in fish [13]. Anthropogenic activities may pollute aquatic ecosystems, even all waters by heavy metals that may cause health problems to all livings. This study was conducted to evaluate amount of the heavy metals in water and fish (muscle, liver, kidney, spleen, gonads, and gills) of the Topçam Barrage and to assess the health risk of human due to fish consumption.

2. Materials and Methods

2.1. Sample Collections

Water and tissue samples were collected from three sites of Topçam Barrage in 6 times in December 2022–November 2023 (Figure 1). Some water variables were measured by portative water parameter (AZ 86031 Combo, Az Instrument Corp., Taichung, Taiwan) in the field. A species called stone moroko (*Pseudorasbora parva*) (Figure 2) only was captured by gillnets and then, fish samples were brought to the laboratory. Firstly, their total weight and length of fish were measured. Then, gills, liver, spleen, kidney, gonads and muscle tissues were taken out (250–280 mg) and labeled and stored in freezer at -20°C .

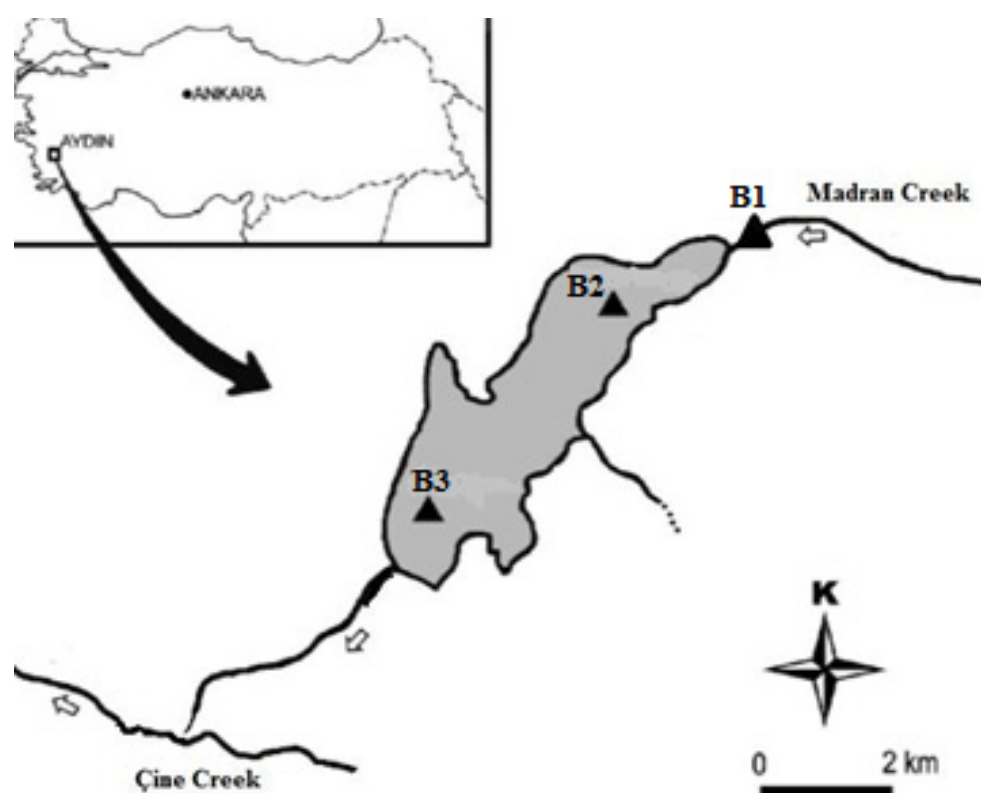


Figure 1. Three sampling sites of the Topçam Barrage (B1, B2, and B3), [14].



Figure 2. Stone moroko (*Pseudorasbora parva*) caught from the Topçam Barrage.

2.2. Preparation of Fish Tissues, Water Samples, and Reading Samples for ICP (Inductively Coupled Plasma Optical Emission Spectrometer)

First, the frozen samples were taken out for thawing from long-term storage. Samples were crushed on a porcelain Havana after 4–5 mins. Each tissue sample was prepared from 7 to 10 fish together. Then, 5 mL nitric acid (HNO_3) and 2 mL hydrogen peroxide (H_2O_2) were added to the tissue and burned for 1–2 min at 200 °C in microwave tubes (Multiwave 7301, Anton Paar Group AG, Ashland, VA, USA). Later on, the solutions were passed through qualitative filter papers (S and H Labware, 103 slow, 125 mm), and a solution of 5% nitric acid with a volume of 50 mL was finally achieved. After that, a sufficient amount of solution was transferred to the ICP tubes. Then, samples were read by ICP-OES (Agilent ICP-OES-5800, Agilent, Springfield, IL, USA) for 7 kinds of heavy metals (As, Cd, Cr, Cu, Zn, Ni, and Pb) using multi-element standard solution IV (1000 mg/L, Supelco, Merck, Rahway, NJ, USA). These six different concentrations were chosen and used (10, 20, 30, 40, 80, and 160 mg/L) during the (modified) reading [15].

2.3. Calculations of Heavy Metal Effects:

The bioaccumulation factor (BCF) was calculated using the following equation [16]:

$$\text{BCF} = \text{concentration of metal in the fish} / \text{concentration of metal in the matrix}$$

$$\text{Concentration of metal in the matrix} = \text{concentration in fish} + \text{water}$$

$$\text{BCF} = \text{bioaccumulation factor}$$

More than 80% of the total fish production is used for global consumption. The risk of toxic metal content in food can be calculated through the estimated daily intake (EDI) using the formula below [16].

Calculation of the biomagnification factor (BMF) is described as follows [17]:

$$\text{BMF} = \text{concentration of metal in the fish} / \text{concentration of metal in the diet}$$

$$\text{BMF} = \text{biomagnification factor}$$

$$EDI = (\text{concentration of metal} \times \text{weight of fish consumed per day}) / \text{body weight of consumer}$$

EDI = estimated daily intake (mg/kg body weight of fish consumed per day) as human consumption

Here, metal concentrations in fish muscles were converted into dry weights by dividing them by the conversion factor of 4.8 [18]. For calculation, the accepted average human weight in Turkey was approximately 80 kg [19].

2.4. Human Health Risk Assessment

An accumulation of heavy metals in a food chain may pose a health risk to humans. This may cause serious effects on the human body (the occurrence of cancer or damage to the nervous system) [20]. There are two more criteria: the target hazard quotient (THQ) and hazard index (HI). They demonstrate the potential health risks of consuming fish with heavy metals [16,21,22]. RFD represents the standard dose of a particular metal in a single day for humans (mg/kg body weight), that is, within a healthy and tolerable range [18].

$$THQ = EDI / RFD$$

RFD = tolerable ranges of a particular metal

$$HI = \sum THQ$$

The presence of a $THQ > 1$ displays some hazardous signals due to the exposure to contaminated fish. The HI refers to the risk for multiple metals in contaminated food.

2.5. Statistical Analysis

The average of the results was used to represent the data. Heavy metals of water and fish tissues (gills, liver, spleen, kidney, gonads, and muscle) were assessed with one-way ANOVAs (SPSS-v.29) and MS Excel 2010. The significance ($p < 0.5$) for different fish tissues and their variations in metal concentrations was investigated.

3. Results and Discussion

This study was conducted in the Topçam Barrage at three sites (B1, B2, and B3) to measure some physicochemical variables of water in December 2022–November 2023 (Figure 3 and Table 1). The water variables showed that Topçam Barrage was some kind of polluted area. Temperatures were in the range of 12.1–31.3, pH was 6.35–9.67, DO (dissolved oxygen) was 8.01–13.5 mg/L, EC (electrical conductivity) was around 225.0–409.5 $\mu\text{S}/\text{cm}$, and salinity was 0.07–0.15%. According to physicochemical variables, pH fluctuation and a high range of EC demonstrated that water could be polluted in the Topçam Barrage.

Table 1. Physicochemical variables of water in the Topçam Barrage at the B1, B2, and B3 sites (mean $\pm$ std) in a year.

Sites	Temp ($^{\circ}\text{C}$)	pH	DO (mg/L)	EC ($\mu\text{S}/\text{cm}$)	Salinity (0%)	COD (mg/L)
B1	17.28	7.39	11.80	227.82	11	28.67
B2	19.07	7.92	9.47	237.50	12	31.99
B3	19.03	8.10	9.63	243.58	13	35.03

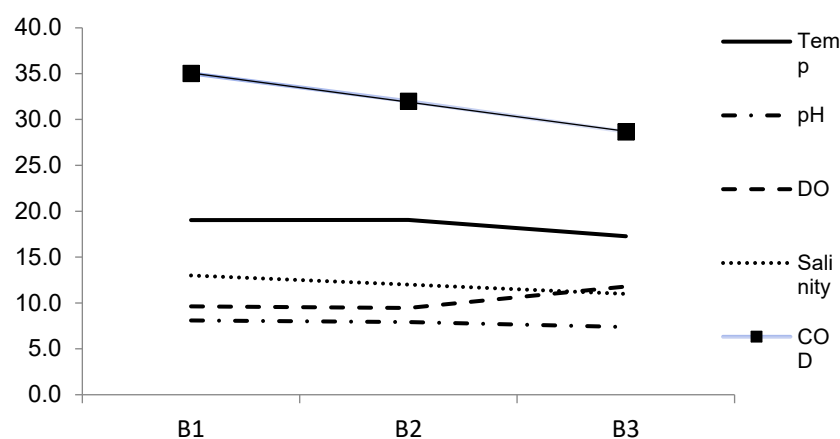


Figure 3. Physicochemical parameters of water at 3 sites of the Topçam Barrage (mean $\pm$ std) in a year.

The average total length and weight of fish were 15.73 mm and 49.75 mg (Table 2). The six different organs were collected from a total of 48 *Stone moroko* (*Pseudorasbora parva*), and water was investigated for the concentration of seven metals (As, Cd, Cr, Cu, Zn, Ni, and Pb). The average heavy metal contents of fish and the average heavy metal concentrations of water were detected (Tables 3 and 4).

Table 2. Length and weight of fish (mean $\pm$ std).

Species	Type	Total Length (mm)	Body Weight (mg)
<i>Stone moroko</i> (<i>Pseudorasbora parva</i>)	Wild	15.73 $\pm$ 3.95	49.75 $\pm$ 46.31

Table 3. Concentrations of heavy metals in miscellaneous tissues (mean $\pm$ std, mg/kg) in a year.

Heavy Metals	Gills	Muscle	Liver	Kidney	Spleen	Ovary
Cr	1.45 $\pm$ 0.07 ^a	4.75 $\pm$ 1.77 ^a	3.10 $\pm$ 0.28 ^a	1.80 $\pm$ 0.14 ^a	3.00 $\pm$ 0.042 ^a	1.80 $\pm$ 0.14 ^a
Ni	5.55 $\pm$ 0.07 ^b	6.15 $\pm$ 0.49 ^b	5.35 $\pm$ 0.07 ^a	6.65 $\pm$ 0.78 ^a	6.50 $\pm$ 0.28 ^a	5.85 $\pm$ 1.20 ^a
Cd	0.35 $\pm$ 0.07 ^a	0.55 $\pm$ 0.07 ^b	0.43 $\pm$ 0.04 ^a	0.65 $\pm$ 0.07 ^a	1.70 $\pm$ 0.14 ^a	1.85 $\pm$ 0.07 ^a
Cu	98.35 $\pm$ 10.82 ^c	93.6 $\pm$ 15.41 ^c	100.15 $\pm$ 2.62 ^b	105.5 $\pm$ 6.51 ^b	98.60 $\pm$ 6.22 ^b	56.45 $\pm$ 6.72 ^b
Pb	9.10 $\pm$ 0.85 ^b	7.30 $\pm$ 0.71 ^b	9.20 $\pm$ 0.42 ^a	9.05 $\pm$ 0.92 ^a	9.25 $\pm$ 0.78 ^a	16.05 $\pm$ 5.87 ^a
Zn	132.60 $\pm$ 11.88 ^c	139.05 $\pm$ 20.01 ^c	175.95 $\pm$ 19.87 ^b	140.7 $\pm$ 13.44 ^b	132.45 $\pm$ 5.02 ^b	129.90 $\pm$ 7.21 ^b

^{a-c} were used to demonstrate significance among them.

Table 4. Concentrations of heavy metals in the water of the Topçam Barrage (mean $\pm$ std, mg/kg) in a year.

Heavy Metals	B1	B2	B3	Averages
Cr	0.07 $\pm$ 0.01	0.88 $\pm$ 0.14	3.79 $\pm$ 0.13	1.58 $\pm$ 1.96 ^a
Ni	1.09 $\pm$ 0.04	1.25 $\pm$ 0.07	4.07 $\pm$ 0.19	2.14 $\pm$ 1.67 ^a
Cd	0.62 $\pm$ 0.04	0.82 $\pm$ 0.08	3.66 $\pm$ 0.08	1.70 $\pm$ 1.70 ^a
Cu	3.03 $\pm$ 0.11	3.12 $\pm$ 0.05	5.91 $\pm$ 0.28	4.02 $\pm$ 1.64 ^a
Pb	1.06 $\pm$ 0.09	1.64 $\pm$ 0.20	4.12 $\pm$ 0.26	2.27 $\pm$ 1.62 ^a
Zn	3.86 $\pm$ 0.35	4.06 $\pm$ 0.15	6.87 $\pm$ 0.47	4.93 $\pm$ 1.69 ^a

^a was used to demonstrate significance among them.

The results showed that the averages of the heavy metal concentrations for Cu and Zn in water were higher than for other heavy metals. Their concentrations followed the

order of $Zn > Cu > Pb > Ni > Cd > Cr$. The heavy metal bioaccumulation coefficients for six different tissues at three sites are demonstrated in Figure 4. The bioaccumulation of *Stone moroko* demonstrated that the heavy metal concentration in fish was very high comparing to concentration of water. For consumers, the health risk of heavy metals in fish was quite high.

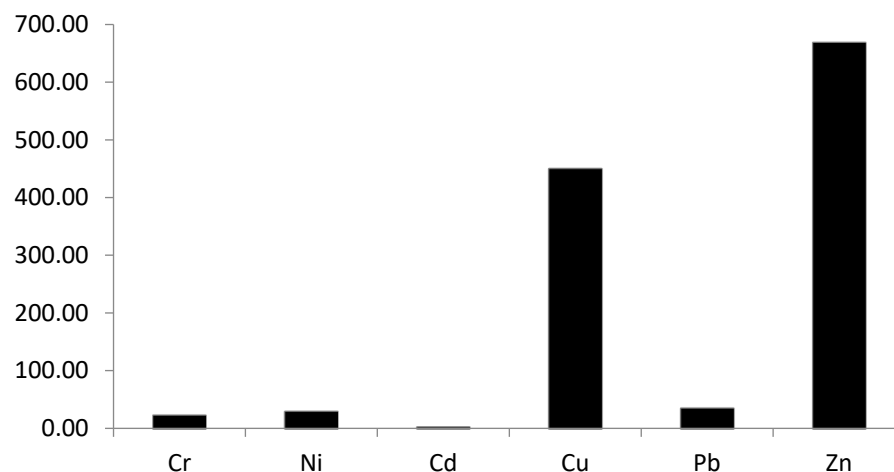


Figure 4. Bioaccumulation factor (BCF) of heavy metals in the muscle tissue of *Stone moroko* over a year.

The detailed results of the human health risk evaluation are depicted in Table 5. After comparison analyses, the EDI values of Cu and Zn metals were higher, indicating that they provide the highest exposure of heavy metals to adults and children. The EDI values of both metals were higher, and RIF was the highest. THQ was the highest for Cr and Cu and the lowest for Zn. The HI value was found to be >1 for all six metals. There is some probability of health risk from fish consumption. A high HI value suggested that they probably experience some health problems.

Table 5. Health risk of heavy metals (EDI, RFD, THQ, and HI) for *Stone moroko* in a year.

Heavy Metals	Muscle (mg/kg)	EDI	RIF	THQ	HI
Cr	22.80	7.13	1.12	6.36	22.43
Ni	29.52	9.23	2.59	3.56	
Cd	2.64	0.83	0.30	2.75	
Cu	449.28	140.40	22.80	6.16	
Pb	35.04	10.95	4.64	2.36	
Zn	667.44	208.58	168.97	1.23	

Heavy metals could be toxic to different organs of fish. They can be put into water in different ways, such as through drainage, the atmosphere, soil erosion, and human activities. Heavy metals may concentrate in the environment and cause water pollution. They take part in biochemical reactions. Although some heavy metals (Cu and Zn) are essential for fish, plants, and other organisms, some of them (Pb, Hg, Cd, Ni, As, and Cr) may have toxic effects on metabolic functions and cause mutagenesis in living organisms, even fish and humans (Table 6).

Table 6. Limit values of heavy metals (mg/kg) [18,23].

	Cu	Zn	Cd	Pb	Cr	Ni
FAO	30	40	5	5	-	-
WHO (fish)	-	-	2	3	-	5–6
WHO (water)	1.3	3	0.003	0.010	0.10	-
ANHMRC	30	1000	2	2	-	-
WAFDR	10	-	5.5	2	10	5.5

WAFDR—Western Australian Food and Drug Regulations; ANHMRC—Australian National Health and Medical Research Council.

There were two main analyses in this study. One is the water quality analysis in the Topçam Barrage. There were some measurements of the water quality variables. Only EC and COD values were the highest. They showed that pollution may occur. The other analysis was the bioaccumulation of heavy metals in *P. parva*. Previous studies also indicated that different tissues had different accumulation levels. Heavy metal pollution also caused histological alterations in fish and led to bioaccumulation, which affected fish health and human health due to fish consumption. Previous research studies on fish histological alterations [24–26] and accumulation have been conducted [25–27]. Some species had higher heavy metal accumulation values (Co, Cu, Cd, Ni, and Zn) in Turkey and some waterbodies. Risks to human health can occur via aquatic animals such as *mussels* (*Mytilus galloprovincialis*), *crab* (*Nephrops norvegicus*), *red mullet* (*Mullus barbatus*), and *anchovy* (*Engraulis engraulis*), which have high concentrations of metal ions (Zn, Mn, Cu, Cd, Pb, and Hg) in the Northern Tyrrhenian Sea [28]. However, nine different fish species were evaluated for seven heavy metals (As, Hg, Cu, Pb, Cr, Cd, and Zn) in Pulicat Lake. They have low values and do not pose any risk to human health [29]. The Topçam Barrage is one of the most important water sources of Aydın. Bioaccumulation was evaluated for one of the fish species of the Topçam Barrage in Aydın. The results were compared with FAO and WHO limits. There is no risk in consuming the species of fish called *Pseudorasbora parva*. The metal accumulation can be ordered as Cu > Cr > Zn > Pb in fish of Pulicat Lake, India. The metal concentrations of Cu were high for *L. fulviflamma*, *C. chanos*, *Arias* sp., and *T. jarbus*. It was reported 10.5, 25.5, 19.0, 23.1 µg/g, respectively. The EDI values of Cu and Zn were the highest (140 and 208 mg/kg) compared to others [29].

Consumption of Black Sea fish may be risky to human health. Zn had a negative correlation with the fat content of fish, as no effects on the fatty tissues were found for As (arsenic) in anchovy (*Engraulis engraulis*). Zn and Cu values were high in Bartın (8.58 µg/g and 45.6 µg/g) and Samsun (3.8 µg/g and 221 µg/g) areas [30]. The concentrations of heavy metals were examined in the Bulgarian Black Sea. They followed the pattern of Zn > Pb > Cu > Ni > Cd [17]. In this study, Zn and Cu values were 139 and 93 mg/kg in muscle. Heavy metal concentrations were found to follow the order of Zn > Cu > Pb > Ni > Cd > Cr.

Cr does not accumulate in fish because it was found to have low concentrations in water and fish, even in polluted areas. It was reported that the uptake amount was higher in younger fish, but it decreased in older fish because of rapid elimination [31]. The lowest level of Cr in *Notopterus notopterus* (0.47 mg/kg wet weight), and the highest level of Cr in *Punctius ticto* (2.07 mg/kg wet weight) were reported [17]. Our results also showed low concentrations ranging from 1.45 to 4.75 mg/kg wet weight. These concentrations were found to be much lower in some areas, such as the Chashma Barrage [32] and Pearl River [33]. This indicated less contamination of fish. The WAFDR (Western Australian Food and Drug Regulations) [34] reported a Cr concentration of 5.5 mg/kg wet weight, which was not much higher than that found in this study. Also, the observed concentrations of Cr in the fish samples of the Bangashi River were not high [17].

Cd is an element responsible for producing chronic toxicity at a concentration of 1 mg/kg wet weight [35]. There are concerns that cadmium is potentially more toxic than any other metal [36]. It is accepted that Cd in seafood is allowable at 2.0 mg/kg wet weight according to the ANHMRC (Australian National Health and Medical Research Council). Cd was found to have a concentration of 5.5 mg/kg wet weight by the WAFDR [34]. The highest amount of Cd was found in *Corica soborna* (0.87 mg/kg wet weight), and the lowest amount of Cd was found in *Notopterus notopterus* (0.09 mg/kg wet weight). Cd in the selected fish from the Bangashi River was below the limit values [18]. In this study, Cd values in muscle were slightly higher than the WHO, ANHMRC, FAO, and WAFDR values. A long period of accumulation of Cd in fish could pose health hazards.

Ni is found at low levels in the soil and water and may adversely affect lung health (inflammation and cancer) [37]. The highest amount of Ni was found in *Puntius ticto* (4.36 mg/kg wet weight), and the lowest amount of Ni was found in *Clupisoma pseudotropius* (0.69 mg/kg wet weight). The values were lower than 5.5–5.6 mg/kg wet weight according to the WAFDR [34] and FAO [23]. The result showed that there was a considerable variation in the concentration of the Ni element from one sample to another. The Ni and its salts are disposable in several industrial applications (electroplating, batteries, cars, aircraft parts, electrodes, cooking utilities, pigments, polisher cosmetics, and textile and printing products). In this present study, the value of Ni in muscle was 6.15 mg/kg wet weight, which was a little higher than values in the WAFDR [34] and FAO [23]. The industrial discharges were the main sources of Ni contamination for the aquatic environments.

Cu is one of the essential metals for several enzymes and the synthesis of haemoglobin [38]. However, a high intake of Cu may cause health problems [39]. Cu was found in high amounts in *Notopterus notopterus* (43.18 mg/kg wet weight) and *Clupisoma pseudotropius* (8.33 mg/kg wet weight). The permissible limits of Cu were reported as 30 mg/kg wet weight by the ANHMRC, FAO [40,41], and UKFSCR (UK Food Standards Committee Report) [42]. Cu concentration in food should not be more than 20 mg/kg wet weight. The maximum amount of Cu in the Turkish legislation was 5 mg/kg wet weight. There is also legislation in other countries (Spanish legislation) where the maximum amount is 20 mg/kg wet weight [43]. The maximum values were given by the WAFDR for Cu at 10 mg/kg wet weight [44].

Pb is not an essential element, and it is well reported that Pb could adversely affect the nervous and nephron systems [45]. A high amount of Pb was detected in *Corica soborna* (10.27 mg/kg wet weight) and a low amount of it was in *Clupisoma pseudotropius* (1.76 mg/kg wet weight) in the Bangashi River due to it being discharged from industrial effluents from various industries (printing, dyeing, oil refineries, and textiles) [18]. The maximum permitted concentration for Pb indicated by the ANHMRC is 2.0 mg/kg wet weight [34,40], namely 9.6 mg/kg as dry weight converted with a factor of 4.8 (79% moisture content) to wet weight. The Pb value according to the UKFSCR should not be more than 2 mg/kg wet weight [42]. In the Spanish legislation, the maximum concentration of Pb is 2 mg/kg wet weight [43].

Zn, being a heavy metal, has a tendency to accumulate in the fatty tissues of fish, and it is known to affect reproductive physiology in fish. Some studies have reported that chronic exposure to Cu and Zn is related to Parkinson's disease in humans [39,46]. The concentration in fish samples of the Bangashi River ranged from 42.83 to 418.05 mg/kg dry weight. The highest amount of Zn was found in *Corica soborna* (418.05 mg/kg dry weight), and the lowest was found in *Notopterus notopterus* (42.83 mg/kg) in the Bangashi River [18]. The amount of Zn determined in all the fish samples was below the value of 1000 mg/kg indicated by the ANHMRC [34,40] and 40 mg/kg by the WHO [23]. Also, two fish species

were reported in Dachen Fishing Ground, China, which did not have much higher values in their muscle tissues (27–29 mg/kg of Zn) [47].

4. Conclusions

This study will provide important knowledge on the dimensions of water pollution. Water quality analysis demonstrated that the COD variable was high in the Topçam Barrage. Bioaccumulation was measured, calculated, and evaluated for one fish species called the stone moroko. Muscle bioaccumulation factors (BCFs) were compared with those established by the FAO and WHO and other limit values. It was found that some health risks were present for the consumption of stone moroko. Additionally, the hazard index (HI) value was also found to be high. There are many previous publications about heavy metal pollution in water. Heavy metal pollution caused bioaccumulation and histological alterations in fish. These effects on fish caused harmful outcomes on human health when consuming fish as a food source. The literature showed the same results for different fish species for the accumulations of Co, Cu, Cd, Ni, and Zn in Turkey and other countries in the world. Consequently, it can be concluded that heavy metal accumulation on the edible parts of *Stone moroko* may have a much higher health risk during consumption. Therefore, the continuous monitoring of heavy metals in Topçam Barrage is suggested for ensuring the health and safety of humans during consumption.

Funding: This research was funded by the Scientific Research Project [Adnan Menderes University] and grant number [ZRF-22020].

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Habib, S.S.; Batool, A.I.; Rehman, M.F.U.; Naz, S. Comparative analysis of the haemato-biochemical parameters and growth characteristics of *Oreochromis niloticus* (Nile tilapia) cultured under different feed and habitats (biofloc technology and earthen pond system). *Aquacult. Res.* **2022**, *53*, 6184–6192. [\[CrossRef\]](#)
2. Fazio, F.; Habib, S.S.; Naz, S.; Ullah, M.; Nawaz, G.; Nava, V.; Piccione, G.; Arfuso, F. *Withania coagulans* fruit extract: A possible useful additive in ameliorating growth and immunity of *Labeo rohita* (Hamilton, 1822). *Nat. Prod. Res.* **2022**, *10*, 803–808. [\[CrossRef\]](#)
3. London, B.; Albert, C.; Anderson, M.E.; Giles, W.R.; Van Wagoner, D.R.; Balk, E.; Billman, G.E.; Chung, M.; Lands, W.; Leaf, A.; et al. Omega-3 fatty acids and cardiac arrhythmias: Prior studies and recommendations for future research: A report from the National Heart, Lung, and Blood Institute and Office of Dietary Supplements Omega-3 Fatty Acids and their Role in Cardiac. *Arrhythmogenesis Workshop Circulat.* **2007**, *116*, 320–335. [\[CrossRef\]](#)
4. Habib, S.S.; Batool, A.I.; Rehman, M.F.U.; Naz, S. Evaluation and association of heavy metals in commonly used fish feed with metals concentration in some tissues of *O. niloticus* cultured in biofloc technology and earthen pond system. *Biol. Trace Elem. Res.* **2022**, *201*, 3006–3016. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Naz, S.; Fazio, F.; Habib, S.S.; Nawaz, G.; Attaullah, S.; Ullah, M.; Hayat, A.; Ahmed, I. Incidence of heavy metals in the application of fertilizers to crops (Wheat and Rice), a Fish (Common carp) pond and a human health risk assessment. *Sustainability* **2022**, *14*, 13441. [\[CrossRef\]](#)
6. Habib, S.S.; Batool, A.I.; Rehman, M.F.; Naz, S. Assessment and Bioaccumulation of Heavy Metals in Fish Feeds, Water, and Some Tissues of *Cyprinus carpio* Cultured in Different Environments (Biofloc Technology and Earthen Pond System). *Biol. Trace Elem. Res.* **2022**, *201*, 3474–3486. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Ali, H.; Khan, E. Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs-concepts and implications for wildlife and human health. *Hum. Ecol. Risk Assess.* **2019**, *25*, 1353–1376. [\[CrossRef\]](#)
8. Okocha, R.C.; Adediji, O.B. Overview of cadmium toxicity in fish. *J. Appl. Sci. Res.* **2011**, *7*, 1195–1207.
9. Hader, D.P.; Banaszak, A.T.; Villafane, V.E.; Narvarte, M.A.; Gonzalez, R.A.; Helbling, E.W. Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Sci. Total Environ.* **2020**, *713*, 136586. [\[CrossRef\]](#)

10. Kumar, S.; Prasad, S.; Yadav, K.K.; Shrivastava, M.; Gupta, N.; Nagar, S.; Bach, Q.V.; Kamyab, H.; Khan, S.A.; Yadav, S.; et al. Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches-A review. *Environ. Res.* **2019**, *179*, 108792. [CrossRef]
11. Sonone, S.S.; Jadhav, S.; Sankhla, M.S.; Kumar, R. Water contamination by heavy metals and their toxic effect on aquaculture and human health through food Chain. *Lett. Appl. NanoBioScience* **2020**, *10*, 2148–2166.
12. Rajeshkumar, S.; Li, X. Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. *Toxicol Rep.* **2018**, *5*, 288–295. [CrossRef] [PubMed]
13. Domingo, J.L. Developmental Toxicity of Metal Chelating agents. *Reprod. Toxicol.* **1998**, *12*, 499–510. [CrossRef] [PubMed]
14. Sömek, H.; Balık, S.; Ustaoglu, M.R. Topçam Baraj Gölü (Çine-Aydın) Fitoplanktonu ve Mevsimsel Değişimleri. *Acta Aquat. Turcica* **2005**, *1*, 26–32.
15. Ghanthimathi, S.; Aminah, A.; Salmijah, S.; Ujang, T.; Nurrul Izzah, A. Comparison of microwave assisted acid digestion methods for ICP-MS determination of total arsenic in fish tissue. *Sains Malays.* **2012**, *41*, 1557–1564.
16. Habib, S.S.; Naz, S.; Fazio, F.; Cravana, C.; Ullah, M.; Rind, K.H.; Attaullah, S.; Filiciotto, F.; Khayyam, K. Assessment and Bioaccumulation of Heavy Metals in Water, Fish (wild and Farmed) and Associated Human Health Risk. *Biol. Trace Elem. Res.* **2024**, *202*, 725–735. [CrossRef]
17. Zaharieva, Z. Bioaccumulation of heavy metals in cetaceans and fish from the Bulgarian Black Sea Coast. *Turk. J. Fish. Aquat. Sci.* **2024**, *24*, TRJFAS25820. [CrossRef]
18. Rahman, M.S.; Molla, A.H.; Saha, N.; Rahman, A. Study on heavy metal levels and its risk assessment in some edible fishes from Bangashi River, Dhaka, Bangladesh. *Food Chem.* **2012**, *134*, 1847–1854. [CrossRef]
19. Turkish Statistical Institute (TUIK). 2022. Available online: <https://data.tuik.gov.tr/Bulten/DownloadIstatistikselTablo?p=WEBW229PP/91tMV2m71fU6pRWq2F1ZD/lzOFFk0bNDi2rjAC8QDCRN62nr2M3n1K> (accessed on 1 May 2024).
20. Faroon, O.; Ashizawa, A.; Wright, S.; Tucker, P.; Jenkins, K.; Ingberman, L.; Rudisill, C. *Toxicological Profile for Cadmium*; Agency for Toxic Substances and Disease Registry (US): Atlanta, GA, USA, 2012.
21. Hough, R.L.; Breward, N.; Young, S.D.; Crout, N.M.; Tye, A.M.; Moir, A.M.; Thornton, I. Assessing potential risk of heavy metal exposure from consumption of home-produced vegetables by urban populations. *Environ. Health Pers.* **2004**, *112*, 215–221. [CrossRef]
22. Chary, N.S.; Kamala, C.T.; Raj, D. Assessing risk of heavy metals from consuming food grown on sewage irrigated soils and food chain transfer. *Ecotoxicol. Environ. Saf.* **2008**, *69*, 513–524. [CrossRef]
23. Küçük, S.; Çoban, D. Balıklarda Ağır Metal Birikimlerinin İncelenmesi, Uluslararası Su ve Çevre Kongresi. *Sözlü Bildiri* **2018**, SB229, 1783–1788.
24. Akgün, M.; Gül, A.; Yılmaz, M. Sakarya Nehri Çeltikçe Çayı'nda yaşayan *Leuciscus cephalus* L., 1758 dokularında ağır metal birikimi. *J. Gazi Univer. Gazi Educ. Fac.* **2007**, *27*, 179–189.
25. Figueiredo-Fernandes, A.; Ferreira-Cardoso, J.V.; GarciaSantos, S.; Monteiro, S.M.; Carrola, J.; Matos, P.; Fernandes, A.F. Histopathological changes in liver and gill epithelium of Nile tilapia, tilapia, *Oreochromis niloticus*, exposed to waterborne copper. *Pesqui Vet. Bras.* **2007**, *27*, 103–109. [CrossRef]
26. Velcheva, I.G.; Arnaudov, A.D.; Georgieva, E.S. Influence of Zinc on Gill Morphology of Gibelio Carp (*Carassius gibelio*). *Ecolog. Balkanica* **2010**, *2*, 19–23.
27. Santos, D.C.M.; Cupertino, M.C.; Matta, S.L.P.; Oliveira, J.A.; Santos, J.A.D. Histological alterations in liver and testis of *Astyanax aff. bimaculatus* caused by acute exposition to zinc. *Rev. Ceres* **2015**, *62*, 133–141. [CrossRef]
28. Leonzio, C.; Bacc, E.; Focaedi, S.; Renzoni, A. Heavy metal in organisms from the Northern Tymhenian Sea. *Sci. Total Environ.* **1981**, *20*, 131–146. [CrossRef]
29. Akila, M.; Anbalagan, S.; Lakshmisri, N.M.; Janaki, V.; Ramesh, T.; Merlin, R.J.; Kamala-Kannan, S. Heavy metal accumulation in selected fish species from Pulicat Lake, India, and health risk assessment. *Environ. Technol. Innovat.* **2022**, *27*, 102744. [CrossRef]
30. Bat, L.; Öztekin, H.C.; Üstün, F. Heavy metal levels in four commercial fishes caught in Sinop coasts of the Black Sea, Turkey. *Turk. J. Fish. Aquat. Sci.* **2015**, *15*, 393–399. [CrossRef]
31. Dara, S.S. *Environmental Chemistry and Pollution Control*; S. Chand and Company Ltd.: New Delhi, India, 1995.
32. Ahmad, H.A.H.; Naim, S.I. Heavy Metals in Eleven Common Species of Fish from the Gulf of Aqaba, Red Sea. *Jordan J. Biol. Sci.* **2008**, *1*, 13–18.
33. Xie, Q.; Gui, D.; Liu, W.; Wu, Y. Risk for Indo-Pacific humpback dolphins (*Sousa chinensis*) and human health related to the heavy metal levels in fish from the Pearl River Estuary, China. *Chemosphere* **2020**, *240*, 124844. [CrossRef]
34. Plaskett, D.; Potter, I.C. Heavy metal concentrations in the muscle tissue of 12 species of teleost from Cockburn Sound, Western Australia. *Aust. J. Mar. Freshwater. Res.* **1979**, *30*, 607–616.
35. Friberg, L.; Piscator, M.; Nordberg, G. *Cadmium in the Environment*; The Chemical Rubber Company: Cleveland, OH, USA, 1971.
36. Christensen, F.C.; Olson, E.C. Cadmium poisoning; report of a fatal case, with discussion of pathology and clinical aspects. *Arch. Ind. Health* **1957**, *16*, 8–13.

37. Forti, E.; Salovaara, S.; Cetin, Y.; Bulgheroni, A.; Pfaller, R.W.; Prieto, P. In vitro evaluation of the toxicity induced by nickel soluble and particulate forms in human airway epithelial cells. *Toxicol. Vitro* **2011**, *25*, 454–461. [[CrossRef](#)]
38. Sivaperumal, P.; Sankar, T.V.; Viswanathan-Nair, P.G. Heavy metal concentrations in fish, shellfish and fish products from internal markets of India vis-a-vis international standards. *Food Chem.* **2007**, *102*, 612–620. [[CrossRef](#)]
39. Gorell, J.M.; Johnson, C.C.; Rybicki, B.A.; Peterson, E.L.; Kortsha, G.X.; Brown, G.G.; Richardson, R.J. Occupational exposures to metals as risk factors for Parkinson's disease. *Neurology* **1997**, *48*, 650–658. [[CrossRef](#)]
40. Bebbington, G.N.; Mackay, N.J.; Chvojka, R.; Williams, R.J.; Dunn, A.; Auty, E.H. Heavy metals, selenium and arsenic in nine species of Australian commercial fish. *Aust. J. Mar. Freshw. Res.* **1977**, *28*, 277–286. [[CrossRef](#)]
41. Dural, M.; Goksu, M.Z.L.; Ozak, A.A. Investigation of heavy metal levels in economically important fish species captured from the Tuzla lagoon. *Food Chem.* **2007**, *102*, 415–421. [[CrossRef](#)]
42. Cronin, M.; Davies, I.M.; Newton, A.; Pirie, J.M.; Topping, G.; Swan, S. Trace metal concentrations in deep sea fish from the North Atlant. *Mar. Environ. Res.* **1998**, *45*, 225–238. [[CrossRef](#)]
43. Demirak, A.; Yilmaz, F.; Tuna, A.L.; Özdemir, N. Heavy metals in water, sediment and tissues of *Leciscus cephalus* from a stream in southwestern Turkey. *Chemosphere* **2006**, *63*, 1451–1458. [[CrossRef](#)]
44. Alam, M.G.M.; Tanaka, A.; Allinson, G.; Laurenson, L.J.B.; Stagnitti, F.; Snow, E.T. A comparison of trace element concentrations in cultured and wild carp (*Cyprinus carpio*) of Lake Kasumigaura, Japan. *Ecotoxicol. Environ. Saf.* **2002**, *53*, 348–354. [[CrossRef](#)]
45. Garcia-Leston, J.; Mendez, J.; Pasaro, E.; Laffon, B. Genotoxic effects of lead: An updated review. *Environ. Int.* **2010**, *36*, 623–636. [[CrossRef](#)] [[PubMed](#)]
46. Prasad, A.S. The role of zinc in gastrointestinal and liver disease. *Clin. Gastroenterol.* **1983**, *12*, 713–741. [[CrossRef](#)]
47. Huang, H.; Li, Y.; Zheng, X.; Wang, Z.; Wang, Z.; Cheng, X. Nutritional value and bioaccumulation of heavy metals in nine commercial fish species from Dachen Fishing Ground, East China Sea. *Sci. Rep.* **2022**, *12*, 6927. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.