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RESEARCH ARTICLE

Health risk assessment of heavy metals in *Cyprinus carpio* (Cyprinidae) from the upper Mekong River

Ji Lai Zhang[1] · Li Fang[1] · Jing Yi Song[1] · Xia Luo[1] · Kai Dao Fu[1] · Li Qiang Chen[1]

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Abstract
The purposes of this research are to quantify the concentration of heavy metals (Zn, Cu, As, Pb, Cd, and Hg) in the water and fish tissues of common carp (*Cyprinus carpio*) in the upper Mekong River and to thereby elucidate the potential dietary health risks from fish consumption of local residents. Surface water and fish tissues (gill, muscle, liver, and intestine) from four representative sample areas (influence by a cascade of four dams) along the river were analyzed for heavy metal concentrations. Results revealed that the levels of heavy metals in fish were tissue-dependent. The highest Cu and As levels were found in the liver; the highest Zn and Pb levels occurred in the intestine, and the highest Hg level was found in the muscle. The total target hazard quotient (THQ) value for residents is > 1 for long-term fish consumption, and local residents are, therefore, exposed to a significant health risk. Results from the current study provide an overall understanding of the spatial and tissue distribution of heavy metals in water and fish body along the upper Mekong River under the influence of cascade dams and highlight the potential health risk of As for the local residents of long-term fish consumption.

Keywords Heavy metals · Distribution · Health risk assessment · Mekong River · Cascade dams

Introduction

Heavy metal contamination in aquatic ecosystems can have significant adverse health effects (Uysal 2011; Alhashemi et al. 2012; Mohan et al. 2012). Heavy metals cannot degrade, so they can accumulate in water, sediments, and fish through aquatic food chains and are toxic to aquatic organisms (Dehn et al. 2006; Bibi et al. 2016). Heavy metals can also be transferred and accumulated in human tissues through long-term food consumption, and this can cause toxic effects to the liver (hepatotoxicity), kidney (nephrotoxicity), central nervous system (neurotoxicity), and deoxyribonucleic acid (genotoxicity) (Sharma et al. 2014; Gupta et al. 2015). Different heavy metals possess unique physicochemical characteristics and have distinctive tissue distributions and accumulation in fish (Arnot and Gobas 2006; Uysal et al. 2008). For example, lead (Pb) is easily absorbed in fish blood and skeleton since it is lipophilic (Hodson 1976; Larsson et al. 1985). Different tissues vary in the metabolism and storage of heavy metals from the environment due to their distinct physiological functions (Ashraf 2005). Fish's gills and digestive tract have significant potential for heavy metal accumulation (Dural et al. 2007). Their heavy metal contents change with variation of heavy metal levels in the water and food. Both gills and intestine are directly exposed to environmental pollutants by respiration and food ingestion (Uysal et al. 2008). Muscle tissue accumulates fewer heavy metals, and this reflects the long-term heavy metal levels in the environment (Yi et al. 2008). Therefore, heavy metal concentrations in muscle are often used as an indicator to assess the pollution of aquatic environment and health risks of fish consumption (Islam et al. 2015).

Heavy metal levels in fish tissues are significantly correlated with heavy metal levels in the aquatic environment (Wagner and Boman 2003; Jezierska and Witeska 2006). This establishes a quantitative relationship between water pollutant parameters and fish tissue levels (Karatas 2008; Uysal et al. 2009; Danabas and Ural 2012; Ural et al. 2012). Most research has focused on the concentration of heavy metals in

Responsible editor: Philippe Garrigues

✉ Kai Dao Fu
kdfu@ynu.edu.cn

✉ Li Qiang Chen
chenlq@ynu.edu.cn

[1] Institute of International Rivers and Eco-security, Yunnan Key Laboratory of International Rivers and Trans-boundary Eco-security, Yunnan University, Kunming 650091, People's Republic of China

fish tissues and monitoring the spatial and temporal distribution of pollutants in reservoirs, lakes, and rivers (Yi and Zhang 2012; Zeng et al. 2012; Dhanakumar et al. 2015). Less information is available on the migration, transport, and transformation of heavy metals in the aquatic ecosystem along rivers by cascade dams (Müller et al. 2008; Käiro et al. 2011). Dam construction may restrict the transport of heavy metals in water column along rivers and affect the distribution and accumulation of heavy metals in the aquatic ecosystem.

Mekong River is the longest international river in Asia and the largest freshwater fishery base in the world. It has been divided into several huge reservoirs by cascade dams (Zhang et al. 2013). The safety of water environment and aquatic products from the Mekong affects the health of > 100 million local residents from six riparian countries (Cenci and Martin 2004). There are high levels of heavy metals in the water and sediment of the upper Mekong basin, and these are derived from mining, domestic wastewater, and agricultural drainage (Chen et al. 2011; Fu et al. 2012; Zhao et al. 2012). In the lower Mekong River basin, heavy metal pollution has been documented in the rice, vegetables, and fish sampled from Cambodia and Vietnam, indicating the potential health risks from long-term consumption of these foods (Phan et al. 2013b; Chanpiwat et al. 2016). Despite above mentioned studies and to the best of our knowledge, there appears to be no information available on the accumulation of heavy metals in fish in the upper reaches of the Mekong River.

The purpose of this study was to investigate the heavy metal contents in different tissues (gill, liver, intestine, and muscle) of the common carp (*Cyprinus carpio*) and to use these data to estimate the health risk of heavy metal pollution in the section of the upper Mekong River under the influence of the cascade dams. Target hazard quotient (THQ) based risk assessment method, widely used to evaluate health risks of environmental pollutants (Chien et al. 2002; Wang et al. 2005; Yi et al. 2011), was applied to estimate the health risk of consuming fish with heavy metal contamination.

Materials and methods

Study area description and sample collection

All sampling sites for the surface water and fish tissue collection in different segments of the upper Mekong River were located in western of Yunnan province, China (Fig. 1). Large reservoirs are present behind five dams (Miaowei, Dachaoshan, Gongguo, Xiaowan, and Dachaoshan) along the upper Mekong River. Two of the upper reservoirs (Gongguo Dam and Xiaowan Dam) receive local runoff from nearby mine tailings, such as the Pb, As, and Zn mines. The lower two reservoirs are mainly polluted by human activities such as agricultural drainage, industrial wastewater, and urban domestic sewage (Zhang et al. 2014).

All the water samples and fish samples were collected according to the standard methods from previous literature (Yi et al. 2011). Briefly, the surface water was sampled twice a year at the same time with the fish sampled. Surface water samples were collected in clean 500-mL polyethylene bottles, to which concentrated nitric acid was added (1% of the total water volume), and then frozen for storage. *C. carpio* fish were sampled from August 2013 to February 2015 by fishermen at different sample sites along the upper Mekong River. The body mass and standard length of each individual fish were measured and recorded. Then, the fish were dissected, and samples of the gill, liver, intestine, and muscle were removed and rinsed two times with pure water. Tissue samples were placed in polyethylene plastic bags and stored at − 20 °C immediately upon laboratory receipt.

Sample digestion and testing

Fish tissues (0.5 ± 0.01 g) of gills, muscle, liver, and intestine were weighed and transferred into acid-washed Teflon microwave digestion vessels. Ultrapure nitric acid (4 mL) and deionized water (4 mL) were added to the vessels, and they were heated with a microwave digestion system for 2-h digestion. Digested samples were transferred to an electric hot plate (180 °C) to evaporate excess acid. Once cooled, the digested samples were transferred to a 25-mL volumetric flask and the volume was increased to 25 mL with deionized water. The water samples were passed through filter paper to remove sediments and diluted with 2% nitric acid. Concentrations of arsenic (As), cadmium (Cd), mercury (Hg), copper (Cu), lead (Pb), and zinc (Zn) in water and fish tissues were measured using an inductively coupled plasma mass spectrometer (ICP-MS) (Agilent 7800, USA).

THQ determination

The health risk assessment for local residents in consuming fish was assessed based on the basis of the THQ (Wang et al. 2005). The method used to estimate the THQ of each heavy metal is described as follows:

$$THQ = \frac{E_F \times E_D \times F_{\mathrm{IR}} \times C}{R_{\mathrm{FD}} \times W_{\mathrm{AB}} \times T_A} \times 10^{-3}$$

where the standard frequency exposure is E_F (365 days/year) and the exposure duration is E_D (70 years) as a standard for the average human life expectancy. F_{IR} is the fish ingestion rate, considered for local people to be 36 g/person/day (Storelli 2008). W_{AB} represents the average weight (60 kg) of the study population. C is the mean metal concentration in the fish muscles. R_{FD} indicates the oral reference dose (Cu = 0.04 mg/kg/

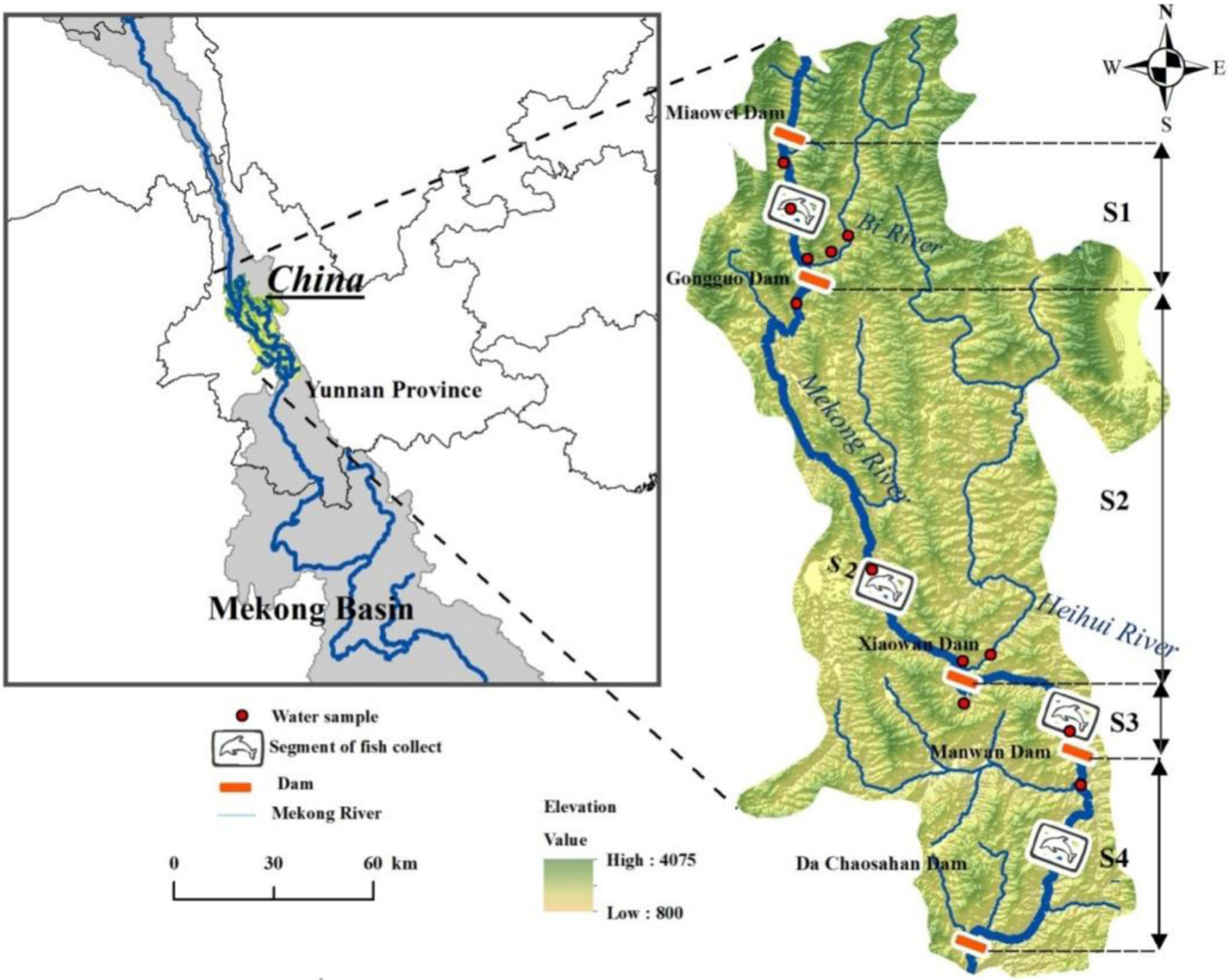

Fig. 1 Locations of the sampling sites for water and fish on the upper Mekong River, China

day, Zn = 0.3 mg/kg/day, As = 0.0003 mg/kg/day, Cd = 0.001 mg/kg/day, Hg = 5 × 10^{-4} mg/kg/day, Pb = 0.004 mg/kg/day) (USEPA 2000, 2009). T_A represents the average exposure time for non-carcinogens (365 days/year numbers of exposure years, assuming 70 years in this study). A THQ value above one indicates an exposure level that is bigger than the reference dose; a daily exposure at this level is believed to be likely to induce negative effects during a human's life time period.

When the organism's exposure is due to more than one pollutant, it may result in additive and/or interactive effects (Wang et al. 2005). The total THQ (TTHQ) of heavy metals for fish is the sum of the following compositions, derived from the method of (Yi et al. 2011):

$$TTHQ(individual\ fish) = THQ(toxicant1) + THQ(toxicant2) + THQ(toxicantn)$$

Statistical analysis

Results are shown by mean value ± standard deviation, and IBM SPSS 20.0 software was used for statistical analyses. One-way ANOVA was applied to study regional differences in heavy metal content in water and fish. A significant difference was established at $p < 0.05$.

Results

Distribution of heavy metals in fish tissues

Table 1 shows that the concentration of the different metals is associated with fish tissue types. Significant metal concentrations were observed in different tissues: These were Cu and As in the liver, Zn and Pb in the intestine, and Hg in the muscle. Most of fish tissues had significant high Zn and Cu levels, which may be due to the fact that these two

Table 1 Summary statistics of heavy metal content in the tissues of fish (*Cyprinus carpio*) and fish sample information in the upper Mekong River (mg/kg)

Sample area	Number of individuals	Body length (cm)	Tissue	Cu	Zn	As	Cd	Hg	Pb
S1	11	27.00 ± 5.72	Gill	1.72 ± 0.71	182.51 ± 66.35	0.76 ± 0.67	0.07 ± 0.09	0.05 ± 0.03	0.87 ± 0.78
			Liver	36.84 ± 19.59	61.03 ± 27.51	0.65 ± 0.44	0.09 ± 0.073	0.03 ± 0.03	0.33 ± 0.07
			Intestine	2.60 ± 0.69	206.76 ± 194.87	0.64 ± 0.38	0.12 ± 0.085	0.07 ± 0.03	0.52 ± 0.25
			Muscle	1.22 ± 0.62	7.86 ± 3.67	0.82 ± 0.59	0.01 ± 0.00	0.05 ± 0.04	0.42 ± 0.21
S2	9	34.49 ± 4.87	Gill	1.59 ± 0.42	175.78 ± 56.32	0.66 ± 0.58	0.016 ± 0.01	0.03 ± 0.02	0.42 ± 0.13
			Liver	13.37 ± 7.57	135.40 ± 80.96	1.06 ± 0.96	0.47 ± 0.42	0.09 ± 0.09	0.67 ± 0.39
			Intestine	2.69 ± 0.83	271.64 ± 191.26	1.04 ± 0.83	0.088 ± 0.06	0.05 ± 0.04	0.82 ± 0.35
			Muscle	1.42 ± 0.67	8.29 ± 2.39	0.56 ± 0.30	0.01 ± 0.01	0.17 ± 0.16	0.46 ± 0.20
S3	7	30.07 ± 6.98	Gill	1.42 ± 0.59	202.95 ± 66.68	0.27 ± 0.18	0.04 ± 0.03	0.03 ± 0.02	0.47 ± 0.20
			Liver	15.54 ± 4.13	119.98 ± 47.17	0.80 ± 0.69	0.45 ± 0.39	0.04 ± 0.01	0.37 ± 0.15
			Intestine	4.19 ± 2.36	243.77 ± 194.85	0.42 ± 0.32	0.51 ± 0.36	0.05 ± 0.03	0.72 ± 0.37
			Muscle	1.25 ± 0.68	9.10 ± 1.71	0.41 ± 0.25	0.01 ± 0.00	0.08 ± 0.03	0.49 ± 0.20
S4	4	33.78 ± 11.37	Gill	1.29 ± 0.27	263.82 ± 28.87	0.48 ± 0.30	0.02 ± 0.01	0.02 ± 0.01	0.51 ± 0.17
			Liver	12.75 ± 5.53	67.07 ± 16.86	0.83 ± 0.45	1.36 ± 1.29	0.04 ± 0.01	0.34 ± 0.10
			Intestine	2.58 ± 0.64	405.62 ± 274.18	0.59 ± 0.26	0.65 ± 0.57	0.05 ± 0.02	0.73 ± 0.47
			Muscle	0.99 ± 0.14	8.06 ± 0.46	0.72 ± 0.44	0.01 ± 0.00	0.07 ± 0.02	0.31 ± 0.048

metals are the essential elements for many fish physiological activities. The accumulation order of the Zn in fish tissue was intestine > gill > liver > muscle (Fig. 2a). The highest concentration of Zn (405.62 ± 274.18 mg/kg) was found in the intestine. The next tissue possessing a high level of Zn was gill, with an average content ranging from 175.78 to 263.82 mg/kg. The lowest level of Zn occurred in

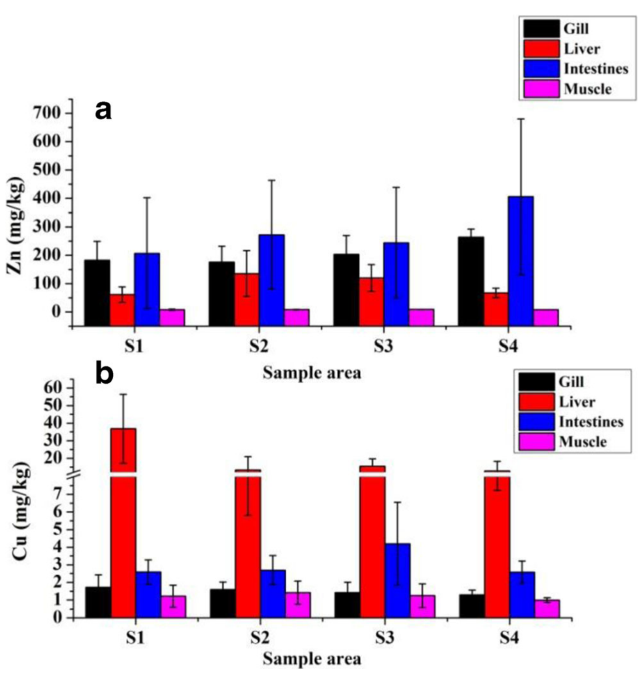

Fig. 2 Tissue-dependent distribution of Cu (**a**) and Zn (**b**) in fish along the river

the muscle where the average concentration ranged from 7.86 to 9.10 mg/kg. The order of Cu accumulation in the fish tissue ranked as liver > intestine > gill > muscle (Fig. 2b). The content of Cu in the liver was extremely high, being almost 20-fold higher than the level in other tissues. For instance, the Cu content in the liver was up to 36.84 ± 19.59 mg/kg in the section of S1, while the concentrations of Cu in intestine, gill, and muscle were only 2.60 mg/kg, 1.72 mg/kg, and 1.22 mg/kg, respectively.

The spatial differentiation of total heavy metals accumulated in different tissues showed distinct distribution patterns along the upper Mekong River (Fig. 3). In muscle, the spatial differentiation of various elements among different segments was minor and showed a similar distribution. It is found that Zn was the most abundant element in muscle, followed by Cu, As, Pb, Hg, and Cd (Fig. 3a). This result indicated that the content of heavy metals in the muscle was quite stable, which can reflect the long-term contents of metals in the water environment. In the liver, the total heavy metal content of each segment varied greatly and no consistent distribution pattern was identified. Regardless of the spatial distribution, Zn and Cu were two of the most abundant elements accumulated in the liver (Fig. 3b). In the intestine and gills, the total metal content increased from upstream to downstream, and all fish tissues showed higher concentration of Zn (Fig. 3c, d).

Heavy metal concentrations in the muscles of fish based on the present work and from other rivers are listed in Table 2. Data from literatures showed that heavy metal concentrations in muscles of fish varied widely from different rivers. The As concentration in the muscle of upper Mekong River fish was

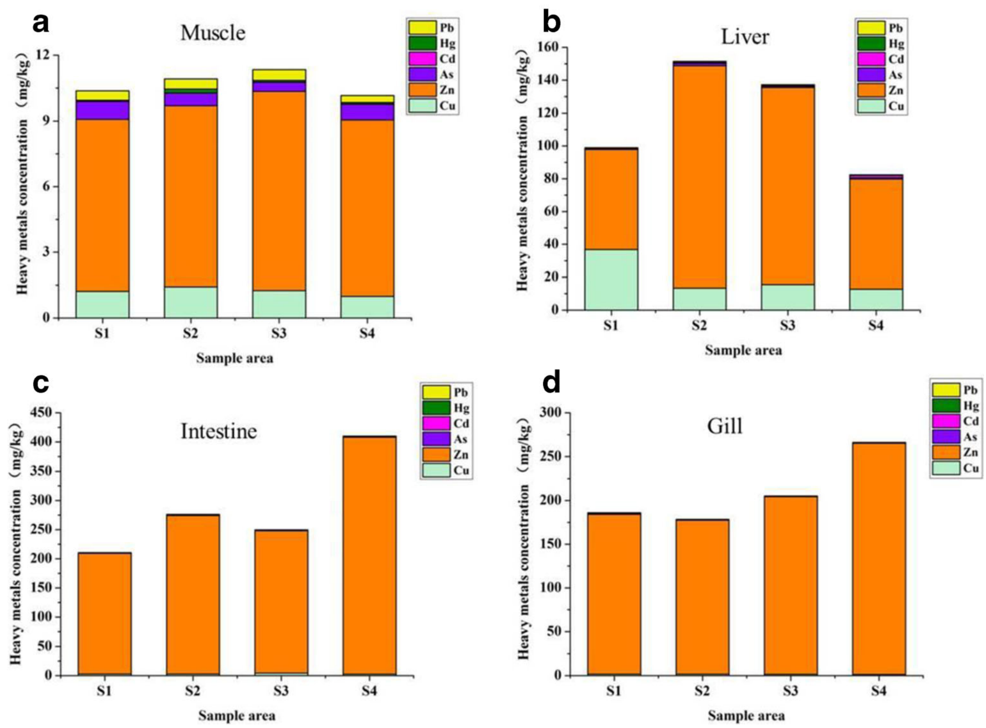

Fig. 3 Temporal distributions of total heavy metals in the different fish tissues along the river

the highest documented. In contrast, the Cu, Zn, Pb, and Hg concentrations in muscles of fish collected from Yellow River were significantly higher than levels found in the current study. Interestingly, most of the heavy metal contents in the muscle of the upper Mekong were higher than those in the lower Mekong, indicating that heavy metal contamination in the upstream portion of the Mekong was more serious than downstream.

Target hazard quotients from fish consumption

The average concentration of heavy metals in fish muscle was used to calculate the THQs of heavy metals through fish consumption for local residents in the upper Mekong River. The estimated THQ for individual metal decreased in the following sequence: As > Zn > Hg > Pb > Cu > Cd. The THQ values of As were > 1 in most of the sections and accounted for about 85% of the total THQ. This indicates that people are subject to significant health risk from consumption of As-contaminated fish (Table 3). The next higher risk contributor element was Zn, contributing about 9% to the total THQ. The risk contributions of other four elements were relatively low, and together, they contributed no more than 6% of the total THQ. These data demonstrate that the dominant risk contribution was As and relatively minor risk contributions were made by Hg, Pb, Cu, and Cd for the inhabitants of the study areas. The total THQ for the local residents ranged from 1.205 to 1.933, indicating that they may experience adverse health effect due to consumption of fish from the upper Mekong River.

Table 2 Comparison of heavy metal concentrations in fish muscles with values taken from literatures

Sample area	Fish species	Cu	Zn	As	Cd	Pb	Hg	References
Yangtze River[b]	*Cyprinus carpio*	0.25 ± 0.10	5.88 ± 2.49	0.039 ± 0.03	0.003 ± 0.004	0.017 ± 0.02	–	Yu et al. (2013)
Pearl River[a]	16 species	1.17–6.72	2.62–20.20	0.17–1.46	ND – 0.033	0.05–1.94	0.001–0.008	Xie et al. (2010)
Yellow River[b]	*Common carp*	4.39 ± 2.23	61.41 ± 16.03	0.23 ± 0.02	ND	0.91 ± 0.04	0.46 ± 0.25	Cui et al. (2011)
Lower Mekong River[b]	*Common carp*	0.37 ± 0.03	11.47 ± 1.60	0.09 ± 0.00	ND	ND	–	Chanpiwat et al. (2016)
Upper Mekong River[b]	*Cyprinus carpio*	1.22 ± 0.15	8.33 ± 0.47	0.63 ± 0.15	0.09 ± 0.048	0.42 ± 0.07	0.09 ± 0.05	Present research

[a] Values represent the ranges expressed as mg/kg dry wt

[b] Values represent the mean ± standard deviation expressed as mg/kg wet wt

Table 3 Target hazard quotient (THQ) evaluation for individual heavy metals and total THQ of muscles from upper Mekong River

Exposed group	Cu	Zn	As	Cd	Hg	Pb	TTHQ
S1	0.018	0.157	1.634*	0.005	0.055	0.063	1.933*
S2	0.021	0.166	1.126*	0.007	0.209	0.069	1.598*
S3	0.019	0.182	0.828	0.006	0.097	0.073	1.205*
S4	0.015	0.161	1.443*	0.005	0.087	0.045	1.757*

*THQ value > 1. If THQ value surpasses one, the exposed population may experience an obvious adverse effect

Heavy metal concentrations in surface water

The spatial and temporal distributions of heavy metals in the surface water of four sites along the upper Mekong River are shown in Fig. 4. The spatial distribution of total heavy metal contents decreased from upper to lower reaches with an exception of S4 segment. The levels of Cu, As, Zn, and Hg were decreased from S1 to S3 (Fig. 4a–e). The relatively higher heavy metal levels in S4 can be ascribed to the tributary influx. There is a large city located upstream of this tributary and the frequent sediment dredging activities in the downstream, resulting in the spiking of heavy metals. There was no significant difference in the spatial distribution of individual heavy metals along the river (Fig. 4f). Water levels of As and Cu in February 2015 were significantly higher than those in other three periods and exceed the limit of the Water Quality Standard for Fisheries of China (GB11607-89) (Fig. 4a, d). The average water concentration of heavy metals followed the order Cu > As > Zn > Hg > Cd > Pb. It is noteworthy that the concentration of Hg consistently failed to meet the Water Quality Standard for Fisheries of China, but Pb was not detected at any of the sampling sites.

Discussion

We studied the distribution of heavy metals in surface water and fish tissues in the upper Mekong River and elucidated the potential dietary health risks to local residents from fish consumption. The accumulation of heavy metals in fish had a tissue-dependent distribution pattern, whereas the highest Cu

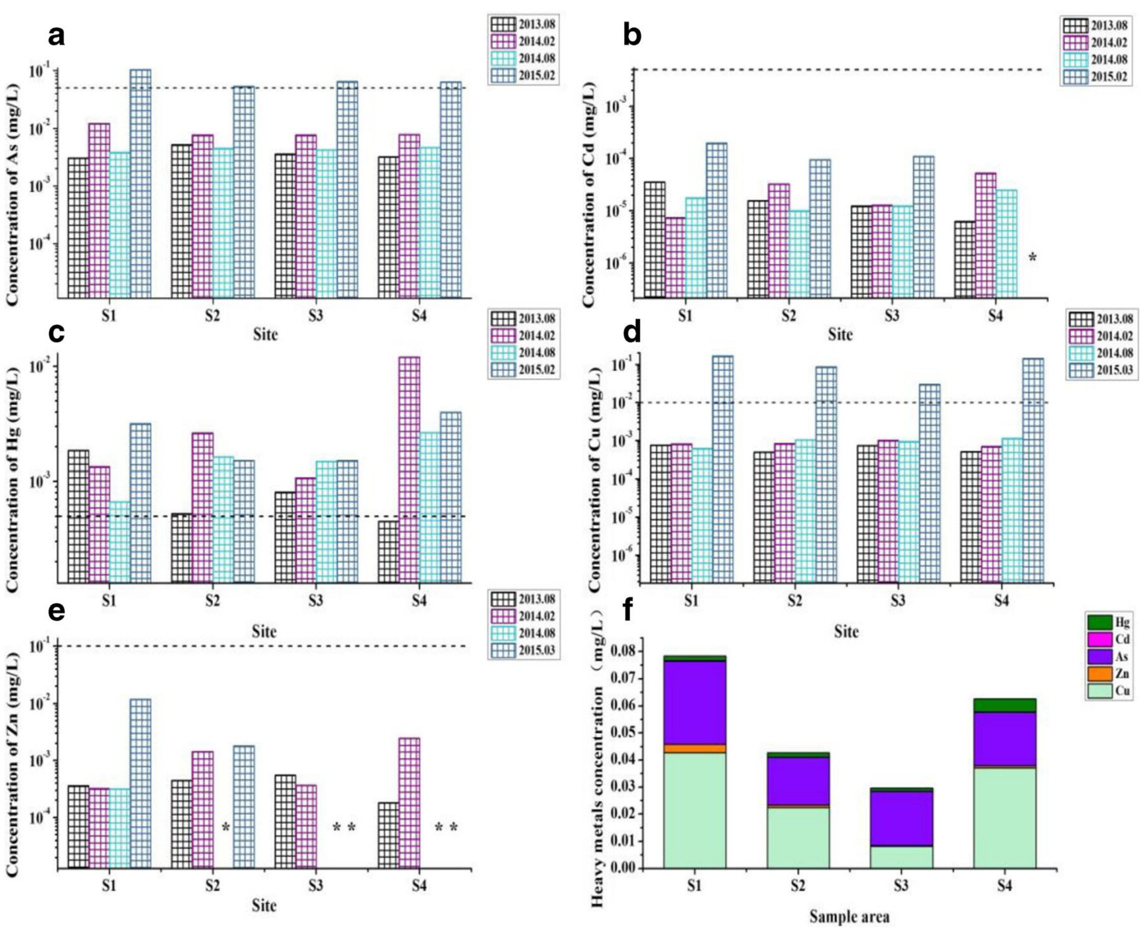

Fig. 4 Spatial and temporal distribution of individual heavy metals in surface water. Dash line indicates the limit of the water quality standard for fisheries in China (GB11607-89). Asterisk in graph **e** indicates that the contents of Zn in the sites of S2, S3, and S4 were not checked out, below the limit of detection. Each asterisk represents one data

and As levels were found in the liver, the highest Zn and Pb levels occurred in the intestine, and the highest Hg level was found in the muscle. Most importantly, the data showed that there are risks to local residents exposed to high levels of As due to long-term fish consumption. Previous studies have documented the accumulation of heavy metals in the Yangtze River (Yi and Zhang 2012), Yellow River (Lü et al. 2011), and Pearl River (Cheng et al. 2013), but this is the first study to determine heavy metal levels, their distribution in fish, and their health risk for local residents of the upper Mekong River. The Mekong River basin has a very large human population (> 100 million), and there are high levels of heavy metals in the water, soil, and vegetable food of this area (Fu et al. 2012; Phan et al. 2013a, b). Our results highlight the environmental risks of heavy metals in the region and their implication for human health.

Different fish organs possess variable capacity for storage and metabolism of heavy metals from aquatic environment due to the different migration ability of metals in the organ functions (Ashraf 2005). We found that the liver and intestine were likely to accumulate more heavy metals (Cu, As, Cd, and Pb) than the gill and muscle (Table 1), which is consistent with the previous study of Begum et al. 2013. The liver and intestine are the major organs for food digestion, and this may lead to greater heavy metal concentrations (Farkas et al. 2003; Chowdhury et al. 2005). Relatively higher concentrations of heavy metals in the liver and intestine could stem from exposure to bottom food and sediment, because *C. carpio* is a demersal fish, obtaining food in the sediment environment (Bordajandi et al. 2003; Yi et al. 2008). High background levels of Cu, As, Cd, and Pb in the sediments occur in the upper Mekong River basin (Fu et al. 2012; Liu et al. 2014), and these metals may transfer into fish via the zoobenthic food chain (Begum et al. 2013). In addition to the liver and intestine, the concentration of heavy metals in fish muscles was relatively low and stable, suggesting that the upper Mekong River may be exposed to long-term heavy metal contamination (Gbem et al. 2001). We found that a high As content occurred in fish muscle suggested that fish can accumulate and store a large amount of As from the aquatic environment. This has been confirmed by the higher As content in the water (Castro-Gonzáleza and Méndez-Armenta 2008). To clarify the As resources, it is also necessary to simultaneously measure the metal concentrations in sediment and foods (Cheng et al. 2013).

The THQ-based assessment method has been successfully used to estimate heavy metal health risks for local residents (Chien et al. 2002; Wang et al. 2005; Yi et al. 2011). In the Yangtze River basin, the total THQ value was estimated at 1.13. This value is lower than the THQ value of the present work, and the Pb, Cd, and Hg were the three greatest contributors to the total THQ (Yi et al. 2011). We found that heavy metal accumulation in fish muscle resulted in high total THQ values that ranged from 1.205 to 1.933 (Table 3). This suggests that residents may already be experiencing adverse health effects from the heavy metal contamination. The single THQ value of As exceeds one in three of the reservoirs (1.634, 1.126, and 1.443 for S1, S2, and S4, respectively), indicating that the primary component of health risks is As. There is no quality standard limit for total arsenic in fish tissues, but the negative health effects of arsenic exposure are of great concern (Islam et al. 2015). Numerous studies have been conducted to assess the accumulation of As in human beings through food consumption and its effects on human health including melanosis, leuco-melanosis, keratosis, dorsum, gangrene, and skin cancer (Sharma et al. 2014; Vilizzi and Tarkan 2016). The potential adverse health effect of As exposure is the highest in the present work. This may be ascribed to its lower oral reference dose because the toxicity of As depends on the percentage of the inorganic As and the activity of arsenic in food (Sevcikova et al. 2011; Cheng et al. 2013; Saha and Zaman 2013). Higher As contamination in groundwater and surface soil of agriculture fields in the Mekong Delta in Vietnam (Huang et al. 2016) and higher health risk of As from daily food consumption (rice, vegetable, and fish) in the lower Mekong River basin of Cambodia have been reported (Phan et al. 2013b). These findings indicate the potential health threat from As pollution in the entire Mekong River basin. Our results also highlight the potential health risk of As from long-term fish consumption by residents in the upper Mekong River basin.

There is limited information about the effects of cascade dams on the migration, transport, and transformation of heavy metals in the water and fish tissues along the river (Müller et al. 2008; Käiro et al. 2011). The construction of cascade dams in the upper Mekong River disrupted the original migration and accumulation pattern of heavy metals in the river ecosystems (Fu et al. 2012; Liu et al. 2014), which provides an opportunity to study the effects and mechanism of the new pattern. We found a gradual decline of heavy metals in the water from upstream to downstream indicating that cascade dams interfere with the downstream migration of heavy metals. The step-down decline effects of cascade dams on heavy metals in the water were obvious, especially with Pb, Cu, and Zn (Fig. 4a), which are easily absorbed by suspended solids or deposited in sediments (Tealdi et al. 2011). This may be attributed to the dams blocking most of sediments, which then settle down in the front of dams. This significantly decreases the total amounts of heavy metals in the water downstream (Wei et al. 2009; Zhao et al. 2013). Previous research has documented that heavy metal (Pb, As, and Cd) concentrations were reduced in water as it moved down into the lower reaches of Lancang River due to the trapping effects of one large reservoir (Song et al. 2013; Wang et al. 2012). However, we found no decrease in heavy metals in fish muscles suggesting that the cascade dams provide less interference with the transformation and accumulation of heavy metals in the fish body. It is possible that a large amount of the heavy metals associated with sediments has been deposited into the deep bottoms of the reservoirs. These heavy metal deposits cannot be directly absorbed by fish gills or enter fish via the food chain (Gupta et al. 2009).

Conclusion

This study documents heavy metal distribution in the water and in *C. carpio* fish tissues in a section of the upper Mekong River under the influence of cascade dams. We found that the accumulation of heavy metals in fish exhibited a tissue-dependent distribution pattern, whereas the highest Cu and As were detected in the liver, the highest Zn and Pb were measured in the intestine, and the highest Hg was found in the muscle. In terms of health risk, the total target hazard quotient value for residents ranged from 1.205 to 1.933, suggesting high potential health risk of local residents due to long-term fish consumption in the upper Mekong River. To clarify the impact of cascade dams on heavy metal accumulation and migration in the river system, it will be necessary to also measure the metal concentrations on sediment simultaneously even it is not included as a part of this study. Regular and long-term monitoring of heavy metal pollution in the aquatic ecosystem of the upper Mekong River is highly recommended, and a variety of fish species should be sampled to provide a comprehensive health risk assessment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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