The individual and synergistic indexes for assessments of heavy metal contamination in global rivers and risk: A review

Hong-Giang Hoang[1], Chitsan Lin[2,*], Chow-Feng Chiang[3], Xuan-Thanh Bui [4,5,*], Wisanukorn Lukkhasorn[2], Thi-Phuong-Thuy Bui[6], Huu-Tuan Tran[2], Thi-Dieu-Hien Vo[7], Van-Giang Le[8], Long D. Nghiem[9]

[1]*Faculty of Health Sciences and Finance - Accounting, Dong Nai Technology University, Bien Hoa, Dong Nai 76100, Viet Nam*
[2]*Department of Marine Environmental Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 81157, Taiwan (R.O.C)*
[3]*Department of Public Health, China Medical University, Taichung 40402, Taiwan (R.O.C)*
[4]*Key Laboratory of Advanced Waste Treatment Technology, Vietnam National University Ho Chi Minh (VNU-HCM), Linh Trung Ward, Thu Duc City, Ho Chi Minh City, 700000, Viet Nam*
[5]*Faculty of Environment and Natural Resources, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thương Kiệt street, district 10, Ho Chi Minh City 700000, Viet Nam. Email: bxthanh@hcmut.edu.vn*
[6]*Faculty of Basic Sciences, Van Lang University, 45 Nguyen Khac Nhu street, Co Giang ward, District 1, Ho Chi Minh City 700000, Vietnam*
[7]*Faculty of Environmental and Food Engineering, Nguyen Tat Thanh University, Ho Chi Minh City 700000, Vietnam*
[8]*Department of Chemical Engineering, National Cheng Kung University, Tainan 701, Taiwan (R.O.C)*
[9]*Centre for Technology in Water and Wastewater, University of Technology Sydney, Ultimo, NSW, 2007, Australia.*

[*]*Corresponding authors:*

Chitsan Lin, National Kaohsiung University of Science and Technology, No. 142, Haizhuan Road, Nanzih District, Kaohsiung 81157, Taiwan (R.O.C); Tel: +886-7-3651472; Fax: +886-7-3651472; E-mail: ctlin@nkust.edu.tw

Xuan-Thanh Bui, Ho Chi Minh City University of Technology (HCMUT), Vietnam National University Ho Chi Minh (VNU-HCM), Ho Chi Minh City, 700000, Viet Nam; Tel: +84-965376073; E-mail: bxthanh@hcmut.edu.vn

Abstract

This article provides an overview of heavy metal contamination in rivers and assessment methods of their contamination and effects. According to literature, rivers with heavy metal contamination in surface water are mainly found in developing countries in Asia, Africa, and Latin America and the Caribbean area, while rivers with heavy metal contamination in sediments are mostly found in Europe. The increase in heavy metal contamination in rivers has led to the adoption of individual and synergistic assessment methods. Individual methods are useful in assessing the contamination and effects for a single heavy metal, while synergistic methods assess the combined contamination and effects of several heavy metals present in surface water and sediments. These two approaches have been commonly used together in recent studies to overcome the limitations of each other and provide a more comprehensive assessment. The developments, equations, advantages, limitations, and future perspectives of these methods are discussed in this review. Calculating indexes are simple, easy-to-implement, and effective methods to provide early alerts for the environmental changes and the adverse impacts on ecosystems and human health. However, calculating indexes still have limitations due to the lack of background concentrations of heavy metals in the study area. Therefore, this issue should be addressed to overcome the limitations of these methods in the future. This review provides a useful reference for future studies on heavy metal contamination in global rivers and the assessment methods for heavy metal contamination and effects.

Keywords: Ecological risk assessment; Heavy metal pollution; Human health risk assessment; Individual indexes; Synergistic indexes.

1. Introduction

Heavy metals released from the various sources eventually end up in the environment, especially in surface waters and sediments of rivers [1]. Rivers in highly industrialized regions, especially with several metal-related industries, often have higher concentrations of heavy metals in the water and sediments than in other regions ~~[2••]~~. Since heavy metals are generally stable and non-degradable, they accumulate more in sediments of rivers over time, causing serious pollution [3]. Therefore, the assessment of heavy metal contamination in rivers is essential.

Various heavy metals are released into the environment during the manufacturing process, such as As, Cd, Cr, Cu, Pb, Ni, Zn, and Hg [2••]. Several heavy metals in trace amounts are necessary for the growth of organisms, such as Cu, Fe, and Zn [4]. However, most heavy metals are toxic and can cause an imbalance in the ecosystem and even the death of organisms [4, 5]. For human health, heavy metal contamination may pose both carcinogenic and non-carcinogenic risks when they enter the human body. Some common effects of heavy metal contamination on human health are memory loss, mental confusion, allergies, fatigue, high blood pressure, skin rashes, and joint stiffness [6]. Hence, the assessment of heavy metal contaminations and their effects on the ecosystem and human health is attracting much attention from scientists worldwide.

Various methods have been developed to assess heavy metal contamination levels in rivers and their effects on the ecosystem and human health [7, 8, 9]. These methods are based on heavy metal concentrations in the environment, regulatory limit, background concentrations, and toxicity values. The indexes are usually divided into two groups: individual and synergistic indexes [10••]. The individual indexes were developed to assess the contamination level and the impact of a single heavy metal on the ecosystem and humans. These indexes include the geo-accumulation index (I_{geo}), contamination factor (*CF*), enrichment factor (*EF*), potential contamination index (*PCI*), hazard quotient (*HQ*), lifetime cancer risk index (*CR*), and modified hazard quotient (*mHQ*) [9, 7, 11, 12, 13, 14••, 15, 16]. The synergistic indexes were developed to evaluate the total contamination of several heavy metals in the environment and their cumulative risks on humans and the ecosystem. Some common synergistic indexes are the modified degree of contamination (*mCd*), pollution load index (*PLI*), metal index (*MI*), heavy metal pollution index (*HPI*), degree of contamination (*DC*), contamination severity index (*CSI*), potential ecological risk index (*PERI*), ecological contamination index (*ECI*), cumulative cancer risk (*CCR*), and total hazard index (*HI*) [17, 18, 8, 19, 7, 15, 16]. Nowadays, combining individual and synergistic indexes to provide detailed and comprehensive evaluation is a popular direction in heavy metal contamination assessment [10••, 20•, 21].

The use of indexes to assess heavy metal contamination has been applied to the most contaminated rivers in the world. For instance, indexes have been used to assess heavy metal contamination of the Tamirabarani River in India, the Korotoa River in Bangladesh, the Yangtze River in China, the Tigris River in Turkey, and the To Lich River in Viet Nam [22, 23, 21, 24, 25]. Several new indexes, such as *mHQ, ECI, PLI,* and *mCd*, were also developed and applied in recent studies [14••, 19]. However, there is still a lack of a comprehensive summary of available assessment indexes in a review. The assessments on the advantages and limitations of index methods are limited. Therefore, this study presents an overview of available indexes commonly used to assess heavy metal contaminations and their effects on the ecosystem and humans. The advantages, limitations, and future perspectives of index methods are also discussed in this review. The characteristics of heavy metals and their contamination in worldwide rivers are summarized as background information. This review provides an overall picture of the indexes used in heavy metal contamination assessment. It can be used as a useful reference for scientists in this field.

2. Data collection

The bibliographic databases of Web of Science, Google Scholar, and PubMed were collected for the article review. Web of Science is an online subscription that provides a comprehensive citation search and provides the full text of scientific articles worldwide. Google Scholar is a freely accessible web search engine that includes academic journals, books, conference papers, technical reports, and other scholarly peer-reviewed literature. PubMed is a free search developed by the National Center for Biotechnology Information (NCBI) and provides the full text of scientific articles and online books worldwide. The research articles and other literature included in this study were collected using different keywords. In total, 35 search terms (Table S1) were employed with different combinations. With no restriction of time, the literature review ended in December 2020 with approximately 100 documents selected after screening, including published journal articles, conference papers, books, and book chapters, as shown in the reference list. The information gathered from these previous studies was then incorporated into this study's tables, figures, and text. On that basis, the evaluations, discussions, conclusions, and future research perspectives for this area are provided.

3. Heavy metal contamination in surface water and sediments

3.1. Sources and transport of heavy metals

Heavy metals in surface water and sediments of rivers may originate from natural sources (rock weathering and volcanic eruptions) and human-made activities (mining, metal processing, and agricultural activities) [26]. Industrial activities have become the main sources of heavy metal contamination in rivers [10••]. Different industrial activities can release different kinds of heavy metals into the environment (Table S2). Mining areas often have a high level of heavy metal contamination (As, Cd, Hg, and Pb) due to their release during the mining process [27]. Metallurgy, electroplating, and other metal-surface-processing can release various heavy metals into the environment such as As, Cd, Cr, Cu, Pb, Ni, Zn, and Hg during the manufacturing process [2••].

The transport of heavy metals in the environment is shown in Fig. S1. Rivers are often the final receptors for pollutants when released into the environment [1]. Heavy metals from natural and human-made activities enter rivers through waste discharge, leaching, and runoff [28•]. When heavy metals dissolve in water, they often carry a positive charge [5]. Heavy metals can combine with other anions to form heavy metal compounds in surface water. Heavy metals and their compounds in surface water can accumulate in sediments, tissues of aquatic organisms and enter the human body through the food chains [3, 29]. Subsequently, they may harm the ecosystem and human health.

3.2. Effects of heavy metal contamination on the ecosystem and human health

Heavy metal contamination may adversely affect the ecosystem and biodiversity of the receiving environment [29, 3]. Heavy metals in aquatic systems are often suspended or insoluble before accumulating in sediments and organisms [3]. This accumulation is irreversible and takes place over a long period. The accumulation of heavy metals in aquatic organisms' tissues may cause the death of organisms because of their toxicity, leading to the imbalance and the destruction of aquatic ecosystems [5].

Fishes, one of the main aquatic organisms in the food chain, usually accumulate large amounts of heavy metals in their tissues [5]. Therefore, they are commonly used in estimating ecological and human health risks [30]. Heavy metals, such as As, Cr, Cd, Zn, Pb, Hg, Cu, and Ni, are common toxic contaminants for fishes. Previous studies showed that heavy metals could alter biochemical and physiological functions in tissue and blood and cause cancer in some fish species [3, 5]. References for acute (LC_{50}) and chronic (NOEC or LOEC) toxicity of heavy metals to certain aquatic organisms, especially fish, are listed in Table S3.

Although heavy metals make an important and essential contribution to metabolism in the human body, they become toxic when they cannot be metabolized and accumulate in soft tissues [4]. Chronic toxicities of heavy metals to human health have been studied in previous researches (Table S3). The exposure pathways of heavy metals to humans are very diverse, including food and water consumption, dermal contact, and inhalation of polluted air. In the human body, most heavy metals are transported through the bloodstream and distributed in the tissues [5]. Because of their high degree of toxicity, some heavy metals, such as As, Cd, Cr, Pb, and Hg, are prioritized. These heavy metals are considered systemic toxicants that can damage many organs with less exposure than other metals. International Agency for Research on Cancer and the U.S. Environmental Protection Agency also classify them as human carcinogens [4]. Some popular effects of heavy metal contamination on human health are memory loss, mental confusion, allergies, fatigue, high blood pressure, skin rashes, and joint stiffness [6].

3.3. An overview of heavy metal contamination in global rivers

In recent decades, heavy metal contamination has become a global environmental problem [31••]. Rivers in urban areas, which receive wastewater, reflect the extent of heavy metal contamination in the environment [1]. Worldwide heavy metal contamination in surface water and sediments of rivers are summarized in Table 1a and b, respectively. Generally, the world's major river systems are severely contaminated with heavy metals, especially in Asia, Africa, Europe, and Latin America and the Caribbean area [31••]. Typical examples have shown that many rivers in the world are “dead rivers”.

Heavy metal contamination in the surface water is concentrated mainly in developing countries in Asia and Africa, where there are high industrial activities and a lack of contamination control measures. As shown in Table 1a, the concentration ranges of heavy metals in the surface water in Asia and Africa rivers were: As: 0.00097 - 0.05535 mg L^{-1}; Cd: 0.00008 - 0.1 mg L^{-1}; Cr: 0.0013 - 1.11; Cu: 0.000061 - 1.05 mg L^{-1}; Pb: 0.00058 - 7.5 mg L^{-1}; Ni: 0.00495 - 0.21 mg L^{-1}; Zn: 0.00038 - 21.71 mg L^{-1}; and Hg: 0.0002 - 0.0004 mg L^{-1}. Rivers in Asia with heavy metal contamination in surface water were concentrated mainly in China, Bangladesh, and India, e.g., the Yangtze and Pearl River in China [32, 33], the Buriganga and Bangshi River in Bangladesh [34, 35], the Gomti and Kali River in India [36, 37]. Meanwhile, the Challawa River in Nigeria and the Nairobi River in Kenya are heavy metal contaminated rivers in Africa [38, 39]. Most of these rivers have received wastewater from industrial activities, the most contributing source for heavy metal contamination. This has led to higher heavy metal concentrations in the surface water of Asia and Africa rivers than in other regions. For instance, the highest heavy metal concentrations in the surface water of rivers in Asia were Cd, Cr, Cu, Pb, Ni, and Zn with concentrations 3.0-17.3; 3.5 - 17.7; 1.0 - 4.4; 1.1 - 4.8; 3.1 - 23.2; and 1.1 - 3.5 times higher than that in rivers in Europe, South, and North America, respectively [31••]. The heavy metal concentrations in the surface water of rivers in Asia and

Africa also exceeded their respective standards. The concentrations were 0.02 - 12.02 times higher than the permissible values of the freshwater toxicity reference values, the US EPA human health ambient water quality criteria, and the WHO drinking water quality guidelines [40, 41].

Besides, heavy metal pollution in surface water of some typical rivers in Latin America and the Caribbean area also reached alarming levels higher than the respective standards [42, 43, 44]. For instance, As, Cd, Cr, Cu, and Ni concentrations in the surface water of the San Pedro River in Mexico were 1-22 times higher than the freshwater toxicity reference values and 0.1-16 times higher than the WHO drinking water quality guidelines [45, 41]. Concentrations of heavy metals in the surface water of these rivers were also higher than in North and South America, as shown in Table 1 a. The heavy metal pollution in rivers in Latin America and the Caribbean area mainly comes from mining activities [42, 43, 44].

Meanwhile, rivers with heavy metal contamination in sediments were mainly concentrated in developed areas such as European countries [31••], as shown in Table 1b. This region includes countries that have gone through a period of vigorous industrial development. This has led to the high accumulation of heavy metals in the sediments of rivers in Europe. These rivers, such as the Odra River in Poland, the Tinto River in Spain, the Tigris River in Turkey, the Tees River in the UK, and the Danube River in central and eastern Europe, have alarmingly high heavy metal concentrations in their sediments. The dominant heavy metals in the sediments were As (95.33 mg kg^{-1} dry wt. in the Odra River) [46], Cd and Cr (32.9 and 556.5 mg kg^{-1} dry wt., respectively in the Danube River) [47], Cu, Ni, and Zn (2860.25; 534.58; and 5,280 mg kg^{-1} dry wt., respectively in the Tigris River) [24], and Pb (13,400 mg kg^{-1} dry wt. in the Tinto River) [48]. The As, Cd, Cr, Cu, Pb, Ni, and Zn concentrations in sediments of rivers in Europe were 1.7 – 24.9; 1.1 – 4.0; 1.2 – 4.1; 3.9 – 28.9; 1.5 – 26.5; 14.5 – 48.5; and 2.7 – 29.8 times higher than that in rivers in Asia and Africa, respectively. Their concentrations were 0.52 – 46.85 times higher than the National Oceanic and Atmospheric Administration (NOAA)'s effects range low (ERL) and effects range median (ERM), and the freshwater toxicity reference value (TRV) of USEPA [45, 49].

Besides, some rivers in Latin America and the Caribbean area also have severe heavy metal contamination in sediment, as shown in Table 1b. For instance, the Rimac River in Peru had high concentrations of As (1,543 mg kg^{-1} dry wt.), Cd (31 mg kg^{-1} dry wt.), Cr (71 mg kg^{-1} dry wt.), Cu (796 mg kg^{-1} dry wt.), Pb (2,281 mg kg^{-1} dry wt.), and Zn (8,076 mg kg^{-1} dry wt.) [27]. Long-time mining activities in this area are the cause of high heavy metal concentrations in the sediments.

4. Heavy metal contamination assessment

The increase of heavy metal pollution in rivers and their toxicity has led to concerns about quantifying their contamination and effects. The assessment methods for heavy metal contamination and their effects have been developed and used by scientists recently [10••, 14••]. In general, contamination assessments are normally conducted by the calculation of contamination indexes. These calculations are performed based on the heavy metal concentration in surface water and sediments and their background values in the environment, or their permissible values according to specific standards. Besides, the levels of the adverse impact on the ecosystem are also indicated through the calculation of these indexes. The assessment indexes can be divided into two groups, individual indexes and synergistic indexes (Table S4).

4.1. Individual indexes

Geo-accumulation index (I_{geo})

The I_{geo} was first introduced by Muller et al. [9] and has been widely used in the assessment of heavy metal abundance in sediments [22, 50]. To classify the contamination levels of heavy metals in sediments, I_{geo} is calculated based on the Eq. (1):

$$I_{geo} = log_2\left(\frac{C_{s_i}}{1.5C_{b_i}}\right) \quad (1)$$

where C_{s_i} is the measured concentration of heavy metal "*i*" in sediments, $C_{b_i}$is the background value of heavy metal "*i*", and the coefficient 1.5 is the correction coefficient due to lithogenic effects of background values. The average shale values [51] and heavy metal concentration in the continental crust [52, 53] are normally used as background values. The heavy metal contamination degree in sediments can be divided into seven levels based on I_{geo} values, as shown in Table 2.

Contamination factor (CF)

The contamination factor, *CF*, was proposed by Hakanson [7] to indicate the contamination level of individual heavy metals in sediment. Recent studies have also used *CF* to evaluate the heavy metal contamination level in surface water. *CF* is calculated by the ratio of heavy metal concentration (C_{s_i}) and its background concentration (C_{b_i}), as shown in the Eq. (2).

$$CF_i = \frac{C_{s_i}}{C_{b_i}} \quad (2)$$

The background concentrations are usually referred from Turekian, Wedepohl [51], Taylor [52], and Rudnick, Gao [53]. Besides, the local standards have also been used as background concentrations in recent studies [28•]. Contamination levels of heavy metals in the environments classified based on the *CF* values are shown in Table 2. Heavy metals are considered contaminated when C_{s_i} is higher than C_{b_i} and uncontaminated when C_{s_i} is lower than C_{b_i}.

Enrichment factor (EF)

The enrichment factor, *EF*, was proposed by Sinex, Helz [11] and is used to evaluate the human-made effects on heavy metal contamination in sediment. *EF* is also a good index to differentiate between heavy metal sources from natural and human-made activities. This index is calculated based on the normalization of heavy metal concentrations in sediments to background concentrations, as shown in Eq. (3). Many heavy metals are used for normalization, such as Fe, Al, Mn, Sc, Li, or Zr, due to their high natural abundance and lower probability of being enriched by anthropogenic activities [11]. The classification of *EF* is presented in Table 2.

$$EF_i = \frac{[C_{s_i}/C_n]s}{[C_{s_i}/C_n]b} \qquad (3)$$

where C_{s_i} is the concentration of heavy metal *i*; C_n is the background concentration of the normalizing metal; *s* is the study sample; *b* is the background.

Potential contamination index (PCI)

PCI is a new index developed by Dauvalter, Rognerud [12] based on the method of Hakanson [7] and is used to estimate the potential contamination of heavy metals in sediments. *PCI* has three contamination levels*:* low, moderate, severe, or very severe contamination (Table 2). *PCI* is calculated by the ratio of the maximum concentration of heavy metal "i" ($C_{s_{i-max}}$) and its background concentration (C_{b_i}), as shown in Eq. (4).

$$PCI_i = \frac{C_{s_{i-max}}}{C_{b_i}} \qquad (4)$$

Hazard quotient (HQ)

HQ has been used to estimate the potential hazards on the ecosystem of individual heavy metals in water and sediments [13]. *HQ* is estimated based on the ratio of the heavy metal concentration (C_{s_i}) in the environment and the environmental quality criteria (EQC) as shown in Eq. (5).

$$HQ_i = \frac{C_{s_i}}{EQC} \tag{5}$$

Normally, aquatic life criteria and sediment quality guideline (SQG) was used for water and sediment, respectively [13, 28•]. The ecosystem hazard levels based on *HQ* are classified from "no adverse effects" to "high hazard" (Table 2).

Modified hazard quotient (mHQ)

A newly developed index, *mHQ*, has been proposed to evaluate the adverse effects of individual heavy metals in sediments on the ecosystem [14••]. This new method allows the assessment of adverse effects by comparing the concentrations of individual metals in sediments with their probable effect level (PEL), threshold effect level (TEL), and severe effect level (SEL) values. The PEL, TEL, and SEL are used as reference values for contamination.

$$mHQ = \left[C_{s_i}\left(\frac{1}{TEL_i} + \frac{1}{PEL_i} + \frac{1}{SEL_i}\right)\right]^{1/2} \tag{6}$$

The proposed classification of *mHQ* for the individual heavy metal is presented in Table 2.

In short, the individual indexes were developed and widely applied early. These methods are uncomplicated and easy to calculate to provide contamination levels for each heavy metal. Individual indexes have been widely used to assess heavy metal contamination in typically contaminated rivers. For instance, *CF* and I_{geo} have been applied in a lot of previous studies to assess the heavy metal contamination level of different contaminated rivers in the world, for instance, Tamirabarani River (India), Korotoa River (Bangladesh), Yangtze River (China), Tigris River (Turkey), and To Lich River (Viet Nam) [22, 23, 21, 24, 25]. However, the individual indexes can only be applied to a single element and thus may not be sufficient in assessing contamination since heavy metals are more likely to have synergistic effects on the environment [10••]. The limitations of the individual indexes have led to the development of synergistic indexes that have been widely applied to assess water and sediment quality.

4.2. Synergistic indexes

Degree of contamination (DC)

DC was proposed by Hakanson [7] to estimate the levels of synergistic contamination of all heavy metals in the environments. *DC* is the sum of the contamination factors (*CF*) of "*n*" heavy metals present in the contamination area.

$$DC = \sum_{i=1}^{n} CF_i \qquad (7)$$

The synergistic contamination of heavy metals in water and sediments is classified into four levels: low to a very high degree of contamination, as shown in Table 2.

Modified degree of contamination (mCd)

The modified degree of contamination (*mCd*) index is based on *CF* and indicates synergistic contamination of heavy metals. The *mCd* index was introduced by Abrahim [16] and calculated using Eq. (8):

$$mCd = \frac{1}{n} \sum_{i=1}^{n} CF_i \qquad (8)$$

Based on *mCd*, heavy metal contamination of a study site can be classified into seven synergistic contamination levels (Table 2).

Pollution load index (PLI)

The *PLI* is calculated as the "*n*" square root of the multiplication of the *CF* values for "*n*" heavy metals in a specific site [17].

$$PLI = (CF_1 \text{ x } CF_2 \text{ x } CF_3 \text{ x} \ldots \text{x } CF_n)^{1/n} \qquad (9)$$

Like *DC* and *mCd*, *PLI* can estimate the synergistic effects of all metals in surface water or sediments of rivers. The study site is assessed to have heavy metal pollutant load when the *PLI* value is higher than 1. Contrariwise, when the *PLI* value is less than 1, there is no heavy metal pollution load at the study site (Table 2).

Nemerow pollution index ($PI_{Nemerow}$)

Another approach to determine the synergistic contamination level of heavy metals at a study area is to use the Nemerow pollution index ($PI_{Nemerow}$) [54]. Similar to *mCd*, this index is also calculated based on the mean value of the contamination factors (*CF*), as shown in Eq. (10). However, a weighted average is given based on the maximum contamination factor (CF_{max}) of a single metal to emphasize the effect of that single metal on the synergistic contamination degree. The $PI_{Nemerow}$ index is a weighted multi-factor index for environmental quality assessment. It can help to highlight the main heavy metal in the study area.

$$PI_{\boldsymbol{Nemerow}} = \sqrt{\frac{CF_{average}^2 + CF_{max}^2}{2}} \tag{10}$$

where $CF_{average}$ is the mean value of the contamination factors of heavy metals; CF_{max} is the highest value of the contamination factors of heavy metals in the study area.

Classification of pollution levels based on $PN_{Nemerow}$ is shown in Table 2. The assessment thresholds of this index are quite low compared to other indexes, which may lead to inaccurate pollution assessment results [55]. Besides, the complex behavior of sediments is not considered when the pollution level is calculated based on *CF*. Therefore, an improved method, the modified pollution index (*MPI*), is proposed based on enrichment factor (*EF*).

Modified pollution index (MPI)

Proposed by Brady et al. [55], the *MPI* is calculated based on *EF* and enables the sediment quality assessment to take into account the complex behavior of heavy metals (Eq. (11)).

$$MPI = \sqrt{\frac{EF_{average}^{2} + EF_{max}^{2}}{2}} \tag{11}$$

Six pollution levels are classified based on *MPI* (Table 2). The thresholds of sediments quality assessment have been adjusted to provide more accurate pollution levels.

Metal index (MI)

MI proposed by Caeiro et al. [18], is often used to estimate the synergistic contamination of heavy metals in river water, canal water, drinking water, and sediment using Eq. (12).

$$MI = \sum_{i=1}^{n} \frac{C_{s_i}}{UAC_i} \tag{12}$$

where C_{s_i} is the measured concentration of heavy metal "*i*" in sediment; UAC_i is the upper allowable concentration of heavy metal "*i*" in water and sediment quality guidelines. *MI* is categorized into six classes, as shown in Table 2.

Heavy metal pollution index (HPI)

HPI is an index commonly used to evaluate the aggregate effect of heavy metals on the overall water quality. The arithmetic quality average method was used to develop *HPI* by Mohan et al. [8]. There are two steps to developing this index (1) constituting a rating scale for each selected parameter to give the weightage and (2) choosing the contaminant parameter on which the index is based. The unit weightage for each heavy metal is given based on its relative influence on water quality for the consumer, resulting from the creation of values inversely proportional to the standard value of the corresponding metal [8, 56•]. *HPI* is calculated by the following Eq. (13) & (14):

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{13}$$

$$Q_i = \sum_{i=1}^{n} \frac{\left|C_{s_i} - I_i\right|}{S_i - I_i} \mathrm{x} 100 \tag{14}$$

where "*n*" is the number of heavy metals, C_{s_i} is the concentration, I_i is the expected limit, S_i is the permissible limit, Q_i is the sub-index, and W_i is the unit weightage ($W_i = 1/S_i$) of heavy metal "*i*" in surface water.

Contamination severity index (CSI)

The contamination severity index (*CSI*) is a new index for assessing heavy metal contaminated-sediments developed by Pejman et al. [19]. It is based on the effects range low (ERL) and effects range median (ERM) values [49]. The proposed equation of *CSI* is shown in Eq. (15) & (16).

$$CSI = \sum_{i=1}^{n} W_t \left[\left(\frac{C_{s_i}}{ERL_i} \right)^{\frac{1}{2}} + \left(\frac{C_{s_i}}{ERM_i} \right)^{2} \right] \tag{15}$$

$$W_t = \frac{L_{f_i} \mathrm{x}\, E_v}{\sum_{i=1}^{n} (L_{f_i} \mathrm{x}\, E_v)} \tag{16}$$

where W_t is the weighted value for heavy metals, L_{f_i} is the factor loading associated with heavy metal "*i*", E_v is the eigenvalue. There are nine contamination levels classified based on *CSI,* as shown in Table 2.

Ecological contamination index (ECI)

The ecological contamination index (*ECI*) is a new and reliable index that can assess the cumulative ecological risk of heavy metal contamination in sediments [14••]. *ECI* is an aggregative experimental approach based on modified hazard quotient (*mHQ*), as shown in the following equation:

$$ECI = B_n \sum_{i=1}^{n} mHQ_i \quad (17)$$

where B_n is the reciprocal of the derived eigenvalue of heavy metal concentrations. The heavy metal contamination levels are classified into seven levels, shown in Table 2.

Potential ecological risk index (PERI)

The *PERI* was proposed by Hakanson [7] to assess the cumulative ecological risk due to heavy metal contamination in the study area. *PERI* is calculated based on the contamination factors (CF_i) and the toxic-response factors (T_i) of the heavy metals, as shown in Eq. (18).

$$PERI = \sum_{i=1}^{n} T_i \ x \ CF_i \quad (18)$$

The potential ecological risk can be classified into four levels: low, moderate, high, and significantly high risk (Table 2).

Modified risk assessment code (mRAC)

The *mRAC* index is proposed to evaluate heavy metal contamination based on their toxicity and bioavailability in sediments [57, 14••]. The toxicity and bioavailability of heavy metals are important characteristics for determining the risk information of heavy metals associated with sediments [14••]. The *mRAC* is estimated by Eq. (19).

$$mRAC = \frac{\sum_{i=1}^{n} T_i \, RAC_i}{\sum_{i=1}^{n} T_i} (\%) \quad (19)$$

where T_i is the toxic response factor, RAC_i is the percentage concentration of heavy metal "*i*" that can exchange and combine with the carbonate fraction, "*n*" is the number of heavy metals. The classification of *mRAC* is presented in Table 2.

The mean probable effects level quotient ($mPEL_Q$) and the mean effect range median quotient ($mERM_Q$)

The $mPEL_Q$ and $mERM_Q$ were developed based on the probable effect level (PEL) and the effect range median (ERL) values, respectively [14••, 58, 59]. These indexes are used to estimate the possible adverse biological effects of multiple heavy metals present in the sediment. Classifications of adverse biological effects based on $mPEL_Q$ and $mERM_Q$ are shown in Table 2. Their calculations are presented in Eq. (20) and (21).

$$mPEL_Q = \frac{\sum_{i=1}^{n}(C_{s_i}/PEL_i)}{n} \tag{20}$$

$$mERM_Q = \frac{\sum_{i=1}^{n}(C_{s_i}/ERM_i)}{n} \tag{21}$$

where PEL_i and ERM_i are the probable effect level and effects range median, respectively; C_{s_i} is the concentration of heavy metal "i" in the sediment; "n" is the number of heavy metals present in the sediments.

In general, the synergistic indexes can provide an overall assessment of heavy metal contamination because they can indicate the combined contamination level of all heavy metals present in surface water and sediments. This is the advantage of synergistic indexes compared to individual indexes. With their advantages, synergistic indexes have been widely used in recent studies to evaluate the synergistic contamination level of heavy metals in surface water and sediments. For instance, mCd and PN calculations were used to assess the synergistic effects of heavy metals in water and sediments of the Yellow River in China and the Houjing River in Taiwan [60, 10••]. The HPI index has been used for synergistic assessment of heavy metal contamination in many different rivers such as the Swarnamukhi River Basin in India [56•], the Bogacayi River in Turkey [61], the Uglješnica River in Serbia [62], the Wen-Rui Tang River in China [63]. Besides, several synergistic indexes were also commonly used in previous studies to evaluate the synergistic effect of heavy metal contamination on aquatic ecosystems such as *PERI, mRAC*, *ECI*, and *RI* [7, 14••, 57].

However, to assess the contamination level of each heavy metal, the individual indexes still play an important role when the synergistic index cannot solve this problem. The advantages of the individual indexes can overcome the disadvantages of the synergistic indexes and vice versa if used in combination [10••]. Therefore, using these two index groups in combination is widely used in recent studies on heavy metal contamination assessment. For instance, *HPI*, *CF*, and I_{geo} were used to assess the heavy metal contamination levels of Cu, Ni, Fe, and Mn in the Swarnamukhi River Basin in India [56•]. The contamination of heavy metals in the Korotoa River in Bangladesh was evaluated using the *PLI*, I_{geo}, and *EF* [23]. Heavy metal contamination in the Yangtze River's surface water was estimated by calculating *EF*, I_{geo}, and *DC* [21]. The assessment from individuals to synergistic heavy metal contamination in sediments of the Tigris River in Turkey was also conducted using *EF*, *CF*, *PLI*, and I_{geo} [24].

5. Human health risk assessment indexes

Because of the rapid increase in the effects of heavy metal pollution on human health in recent times, the human health risk assessment of heavy metal exposure is essential. Many adverse effects of heavy metals on human health, including carcinogenic and non-carcinogenic risks, have been reported [64]. Various methods for estimating human health risks have been developed, including carcinogenicity and non-carcinogenicity for both individual and cumulative effects [32]. Carcinogenic risks are usually estimated by the lifetime cancer risk index (*CR*), and the cumulative cancer risk (*CCR*) [65], as shown in Eq. (22) & (23). While the hazard quotient (*HQ*) and the total hazard index (*HI*) are used to assess non-carcinogenic risks [64, 65], as shown in Eq. (24) & (25). There are no adverse non-carcinogenic effects on human health if HQ and HI values are ≤ 1 and possible negative health risks if HQ and HI values are > 1. The carcinogenic risk is negligible if CR_i and CCR values are ≤ 10^{-6}, unacceptable if they are > 10^{-4}, and acceptable if these values are between 10^{-6} and 10^{-4}.

$$CR_i = ADD_i \text{ x } CSF_i \tag{22}$$

$$CCR = \sum_{i=1}^{n} CR_i \tag{23}$$

$$HQ_i = \frac{ADD_i}{RfD_i} \tag{24}$$

$$HI = \sum_{i=1}^{n} HQ_i \tag{25}$$

where: "n" is the number of heavy metals; ADD_i is the average daily dose; CSF_i is the cancer slope factor; RfD_i is the reference dose for each heavy metal "i".

The average daily dose (ADD) is usually estimated based on the exposure pathway of heavy metals to humans. The main exposure pathways of heavy metals in rivers to humans are food ingestion, water ingestion, and dermal contact while swimming, and the equations to estimate ADD are Eq. (26), (27), & (28), respectively [29, 15, 66].

Food ingestion:

$$ADD_{FI} = U \text{ x } C_{food} \text{ x } \frac{EF_{FI} \text{ x } ED_{FI}}{AT \text{ x } BW} \text{ (mg kg}^{-1}\text{d}^{-1}\text{)} \tag{26}$$

where: ADD_{FI} is the average daily dose of food ingestion; U is the food ingestion rate; C_{food} is the concentration of heavy metals in food (mg kg^{-1}); EF_{FI} is the exposure frequency (EF_{FI} = 365 d yr^{-1}); ED_{FI} is the exposure duration; AT is the averaging time (AT = 365 d yr^{-1} x ED_{FI}); BW is the body weight.

Dermal contact while swimming:

$$ADD_{DC} = SA \text{ x } PC \text{ x } CF \text{ x } C_{water} \text{ x } \frac{ET_{SW} \text{ x } EF_{SW} \text{ x } ED_{SW}}{AT \text{ x } BW} \text{ (mg kg}^{-1}\text{d}^{-1}\text{)} \tag{27}$$

where: ADD_{DC} is the average daily dose for dermal contact during swimming; SA is the skin area available for contact; PC is the permeability constant of heavy metals (cm h^{-1}); CF is the unit conversion factor (CF = 1 L (1000 $cm^3)^{-1}$); C_{water} is the heavy metal concentration in surface water; ET_{SW} is the exposure time for swimming; EF_{SW} is the exposure frequency for swimming; ED_{SW} is the exposure duration.

Incidental water ingestion while swimming:

$$ADD_{WI} = CR \text{ x } C_{water} \text{ x } \frac{ET_{SW} \text{ x } EF_{SW} \text{ x } ED_{SW}}{AT \text{ x } BW} \text{ (mg kg}^{-1}\text{d}^{-1}\text{)} \quad (28)$$

where ADD_{WI} is the average daily dose for incidental water ingestion during swimming; CR is the contact rate while swimming.

Individual and cumulative human health risk assessments of heavy metal contamination in the global rivers have been widely presented in previous studies [32, 64, 43]. For instance, human health risks due to fish consumption in the Yangtze River, China, were estimated to pose adverse health effects to adults (HI = 2.17) [32]. Water consumption from the Pardo River, Brazil, is a health concern for the local population due to the non-carcinogenic risks exceeding the maximum recommended level [64]. Conclusions of the level of risk have been drawn based on the risk quantification to provide accurate assessments. Combining the individual indexes (CR_i, HQ_i) and the cumulative index (CCR, HI) in different exposure scenarios can comprehensively assess heavy metal effects on human health.

6. Advantages and limitations of indexes and future perspectives

The use of indexes in assessing heavy metal contamination and its adverse effects on the ecosystem and human health is widely adopted for various advantages. For example, indexes are simple, easy-to-implement, and effective methods to provide preliminary assessments of the adverse impacts of contamination on ecosystems and human health. Calculating indexes may help to quantify the magnitude of heavy metal contamination levels. This means that large data sets will be represented in a simpler way that minimizes data volume. While complex information is simplified, the index results can be easily communicated to the public.

However, using indexes to assess the contamination level and adverse effects also present certain limitations. The calculation formulas of the indexes are built based on some characteristics of the contaminants, such as heavy metal abundance in the environment and normalization of heavy metal concentrations to background concentrations. The calculation formulas of the indexes are also based on the different types of samples (surface water or sediments). These bases oversimplify the complexity of heavy metal pollution in the environment. In other words, the overall assessment cannot be provided by an index. Besides, the lack of background values for each locality leads to less accurate results. Choosing which background values and standards to use for specific situations also often confuses decision-makers.

Therefore, future perspectives for overcoming current limitations in this research area are proposed as follows:

a). Research on the quantification of the heavy metal background concentrations needs to be promoted for each local area to provide the input data for the index calculation methods. This helps the determination of pollution and risk levels of heavy metals more accurately for each locality.

b). Standards, regulations, thresholds, and toxicity values for heavy metals need to be continuously researched, developed, and updated to improve the reliability of the heavy metal pollution assessment based on the index calculation.

c). To assess pollution or risk levels for several pollutants in multiple media, new developments for multitasking and multipurpose indexes that can integrate several purposes (e.g., assessing pollution or risk levels for the diversity of pollutants) and can use in different environments (e.g., water, soil, and air), are highly recommended in the near future.

d). Nowadays, with the development of computer science, the integration of the indexes into models is an effective direction. This direction can help to limit errors during the calculation process and save time.

7. Conclusions

In this study, basic information on heavy metals, their effects on ecosystems and humans, and contamination status in rivers worldwide have been summarized. Contamination and the effect levels of heavy metals on the environment are increasing, especially in Asia, Africa, and Europe. This leads to more attention from scientists on methods to assess the heavy metal contamination and effect levels. Individual and synergistic indexes have been developed that are simple and efficient assessment methods. The individual indexes, including I_{geo}, *CF*, *EF*, *PCI*, *HQ*, and *mHQ* were used for each heavy metal. The synergistic indexes, including *DC*, *mCd*, *PLI*, $PI_{Nemerow}$, *MPI*, *MI*, *HPI*, *CSI*, *ECI*, *PERI*, *mRAC*, $mPEL_Q$, $mERM_Q$ were employed for all heavy metals in the environment. The indexes can quantify the contamination levels and the effects of heavy metals in rivers, contributing to having a more accurate assessment. However, the lack of background values for the specific areas limits these methods. This review provides comprehensive information on heavy metal contaminations and their assessment methods. These results will be a useful reference for future studies, especially for index calculation methods.

Acknowledgments

The authors are grateful to Dr. Nicholas Kiprotich Cheruiyot, from the Department of Marine Environmental Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 81157, Taiwan (R.O.C), for the valuable suggestions and English writing improvement to this manuscript. We acknowledge the support of time and facilities from Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for this study.

Conflicts of interest declaration:

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

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Khadse G, Patni P, Kelkar P, Devotta S. Qualitative evaluation of Kanhan river and its tributaries flowing over central Indian plateau. Environmental Monitoring and Assessment. 2008;147(1-3):83-92. doi:http://doi.org/10.1007/s10661-007-0100-x.
2.•• Selvi A, Rajasekar A, Theerthagiri J, Ananthaselvam A, Sathishkumar K, Madhavan J, et al. Integrated remediation processes toward heavy metal removal/recovery from various environments-a review. Frontiers in Environmental Science. 2019;7:66. doi:https://doi.org/10.3389/fenvs.2019.00066. **This study provides the characteristics and sources of heavy metals in environments**
3. Ashraf W. Accumulation of heavy metals in kidney and heart tissues of Epinephelus microdon fish from the Arabian Gulf. Environmental Monitoring and Assessment. 2005;101(1-3):311-6. doi:https://doi.org/10.1007/s10661-005-0298-4.
4. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy metal toxicity and the environment. In: Luch A, editor. Molecular, Clinical and Environmental Toxicology. Experientia Supplementum. vol 101. Basel, Switzerland: Springer; 2012. p. 133-64.
5. Jia Y, Wang L, Qu Z, Wang C, Yang Z. Effects on heavy metal accumulation in freshwater fishes: species, tissues, and sizes. Environmental Science Pollution Research. 2017;24(10):9379-86. doi:https://doi.org/10.1007/s11356-017-8606-4.
6. Jaishankar M, Tseten T, Anbalagan N, Mathew BB, Beeregowda KN. Toxicity, mechanism and health effects of some heavy metals. Interdisciplinary Toxicology. 2014;7(2):60-72. doi:https://doi.org/10.2478/intox-2014-0009.
7. Hakanson L. An ecological risk index for aquatic pollution control. A sedimentological approach. Water Research. 1980;14(8):975-1001. doi:https://doi.org/10.1016/0043-1354(80)90143-8.
8. Mohan SV, Nithila P, Reddy SJ. Estimation of heavy metals in drinking water and development of heavy metal pollution index. Journal of Environmental Science and Health Part A: Environmental Science and Engineering and Toxicology. 1996;31(2):283-9. doi:https://doi.org/10.1080/10934529609376357.
9. Muller G, Chen C, Kao C, Chen C, Dong C. Schwermetalle in den sediments des Rheins-Veranderungen seitt. Umschan. 1971;79:778–83.
10.•• Vu CT, Lin C, Shern CC, Yeh G, Tran HT. Contamination, ecological risk and source apportionment of heavy metals in sediments and water of a contaminated river in Taiwan. Ecological Indicators. 2017;82:32-42. doi:https://doi.org/10.1016/j.ecolind.2017.06.008. **This study mentions pollution index group classification and applies a combination of individual and synergistic indexes to assess heavy metal pollution in a river**
11. Sinex S, Helz G. Regional geochemistry of trace elements in Chesapeake Bay sediments. Environmental Geology. 1981;3(6):315-23.

12. Dauvalter V, Rognerud S. Heavy metal pollution in sediments of the Pasvik River drainage. Chemosphere. 2001;42(1):9-18. doi:https://doi.org/10.1016/S0045-6535(00)00094-1.

13. Finger SE, Farag AM, Nimick DA, Church SE, Sole TC. Synthesis of water, sediment, and biological data using hazard quotients to assess ecosystem health. US Geological Survey professional paper. 2004;1652:29-48.

14.•• Benson NU, Adedapo AE, Fred-Ahmadu OH, Williams AB, Udosen ED, Ayejuyo OO, et al. New ecological risk indices for evaluating heavy metals contamination in aquatic sediment: a case study of the Gulf of Guinea. Regional Studies in Marine Science. 2018;18:44-56. doi:https://doi.org/10.1016/j.rsma.2018.01.004. **This article presents a list of indexes for heavy metal pollution in aquatic sediment and their application in case study**

15. USHHS. Health consultation: evaluation of surface water data. Atlanta, Georgia 30333, USA: Agency for Toxic Substances and Disease Registry, U.S. Department of Health and Human Services/Division of Health Assessment and Consultation2006 August 8. Report No.: NCD062555792.

16. Abrahim G. Holocene sediments of Tamaki Estuary: Characterisation and impact of recent human activity on an urban estuary in Auckland [PhD]. New Zealand: The University of Auckland; 2005.

17. Tomlinson D, Wilson J, Harris C, Jeffrey D. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. Helgoland Marine Research. 1980;33(1):566-75. doi:https://doi.org/10.1007/BF02414780.

18. Caeiro S, Costa MH, Ramos T, Fernandes F, Silveira N, Coimbra A, et al. Assessing heavy metal contamination in Sado Estuary sediment: an index analysis approach. Ecological indicators. 2005;5(2):151-69. doi:https://doi.org/10.1016/j.ecolind.2005.02.001.

19. Pejman A, Bidhendi GN, Ardestani M, Saeedi M, Baghvand A. A new index for assessing heavy metals contamination in sediments: a case study. Ecological Indicators. 2015;58:365-73. doi:http://dx.doi.org/10.1016/j.ecolind.2015.06.012.

20.• Hoang HG, Lin C, Tran HT, Chiang CF, Bui XT, Cheruiyot NK, et al. Heavy metal contamination trends in surface water and sediments of a river in a highly-industrialized region. Environmental Technology Innovation. 2020;20:101043. doi:https://doi.org/10.1016/j.eti.2020.101043. **Many indexes are used to evaluate heavy metal contamination in this case study**

21. Wang H, Wang J, Liu R, Yu W, Shen Z. Spatial variation, environmental risk and biological hazard assessment of heavy metals in surface sediments of the Yangtze River estuary. Marine Pollution Bulletin. 2015;93(1-2):250-8. doi:https://doi.org/10.1016/j.marpolbul.2015.01.026.

22. Chandrasekaran A, Mukesh M, Chidambaram S, Singarasubramanian S, Rajendran S, Muthukumarasamy R, et al. Assessment of heavy metal distribution pattern in the sediments of Tamirabarani river and estuary, east coast of Tamil Nadu, India. Environmental Earth Sciences. 2015;73(5):2441-52. doi:http://doi.org/10.1007/s12665-014-3593-y.

23. Islam MS, Ahmed MK, Raknuzzaman M, Habibullah-Al-Mamun M, Islam MK. Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. Ecological Indicators. 2015;48:282-91. doi:https://doi.org/10.1016/j.ecolind.2014.08.016.

24. Varol M, Şen B. Assessment of nutrient and heavy metal contamination in surface water and sediments of the upper Tigris River, Turkey. Catena. 2012;92:1-10. doi:https://doi.org/10.1016/j.catena.2011.11.011.

25. Thuong NT, Yoneda M, Ikegami M, Takakura M. Source discrimination of heavy metals in sediment and water of To Lich River in Hanoi City using multivariate statistical approaches. Environmental Monitoring and Assessment. 2013;185(10):8065-75. doi:https://doi.org/10.1007/s10661-013-3155-x.

26. Ji H, Li H, Zhang Y, Ding H, Gao Y, Xing Y. Distribution and risk assessment of heavy metals in overlying water, porewater, and sediments of Yongding River in a coal mine brownfield. Journal of Soils and Sediments. 2018;18(2):624-39. doi:http://doi.org/10.1007/s11368-017-1833-y.

27. Mendez W. Contamination of Rimac River basin, Peru, due to mining tailings [Master]. Stockholm, Sweden: The Royal Institute of Technology; 2005.

28.• Yeh G, Hoang HG, Lin C, Bui XT, Tran HT, Shern CC, et al. Assessment of heavy metal contamination and adverse biological effects of an industrially affected river. Environmental Science and Pollution Research. 2020:1-11. doi:https://doi.org/10.1007/s11356-020-07737-0. **The using of common indexes to assess the heavy metal contamination levels and adverse biological effects is presented in this article**

29. Koki IB, Bayero AS, Umar A, Yusuf S. Health risk assessment of heavy metals in water, air, soil and fish. African Journal of Pure Applied Chemistry. 2015;9(11):204-10. doi:https://doi.org/10.5897/AJPAC2015.0654.

30. Farkas A, Erratico C, Vigano L. Assessment of the environmental significance of heavy metal pollution in surficial sediments of the River Po. Chemosphere. 2007;68(4):761-8. doi:https://doi.org/10.1016/j.chemosphere.2006.12.099.

31.•• Li Y, Zhou Q, Ren B, Luo J, Yuan J, Ding X, et al. Trends and health risks of dissolved heavy metal pollution in global river and lake water from 1970 to 2017. In: Voogt Pd, editor. Reviews of Environmental Contamination and Toxicology. Berlin, Germany: Springer Verlag; 2019. **This review provides an overview of heavy metals pollution in surface water and sediments of the river worldwide**

32. Yi Y, Yang Z, Zhang S. Ecological risk assessment of heavy metals in sediment and human health risk assessment of heavy metals in fishes in the middle and lower reaches of the Yangtze River basin. Environmental Pollution. 2011;159(10):2575-85. doi:https://doi.org/10.1016/j.envpol.2011.06.011.

33. Zhen G, Li Y, Tong Y, Yang L, Zhu Y, Zhang W. Temporal variation and regional transfer of heavy metals in the Pearl (Zhujiang) River, China. Environmental Science Pollution Research. 2016;23(9):8410-20. doi:http://www.10.1007/s11356-016-6077-7.

34. Bhuiyan MAH, Dampare SB, Islam M, Suzuki S. Source apportionment and pollution evaluation of heavy metals in water and sediments of Buriganga River, Bangladesh, using multivariate analysis and pollution evaluation indices. Environmental Monitoring and Assessment. 2015;187(1):4075. doi:http://www.doi.org.10.1007/s10661-014-4075-0.

35. Rahman MS, Saha N, Molla AH. Potential ecological risk assessment of heavy metal contamination in sediment and water body around Dhaka export processing zone, Bangladesh. Environmental Earth Sciences. 2014;71(5):2293-308. doi:https://doi.org/10.1007/s12665-013-2631-5.

36. Gupta SK, Chabukdhara M, Kumar P, Singh J, Bux F. Evaluation of ecological risk of metal contamination in river Gomti, India: a biomonitoring approach. Ecotoxicology Environmental Safety. 2014;110:49-55. doi:https://doi.org/10.1016/j.ecoenv.2014.08.008.

37. Mishra S, Kumar A, Yadav S, Singhal M. Assessment of heavy metal contamination in water of Kali River using principle component and cluster analysis, India. Sustainable Water Resources Management. 2017;4(3):573-81. doi:https://doi.org/10.1007/s40899-017-0141-4.

38. Dan'Azumi S, Bichi M. Industrial pollution and heavy metals profile of Challawa River in Kano, Nigeria Journal of Applied Sciences in Environmental Sanitation. 2010;5(1).

39. Budambula N, Mwachiro E. Metal status of Nairobi river waters and their bioaccumulation in Labeo cylindricus. Water, Air, and Soil Pollution. 2006;169(1-4):275-91. doi:https://doi.org/10.1007/s11270-006-2294-x.

40. USEPA. National recommended water quality criteria - Human health criteria table. Washington, DC, USA: United States Environmental Protection Agency; 2015.

41. WHO. Guidelines for drinking-water quality. Geneva 27, Switzerland: World Health Organization; 2011.

42. Garcia ME, Betancourt O, Cueva E, Gimaraes JR. Mining and seasonal variation of the metals concentration in the Puyango River basin—Ecuador. Journal of Environmental Protection. 2012;3:1542-50. doi:http://dx.doi.org/10.4236/jep.2012.311170.

43. Gutiérrez RL, Rubio-Arias H, Quintana R, Ortega JA, Gutierrez M. Heavy metals in water of the San Pedro River in Chihuahua, Mexico and its potential health risk. International Journal of Environmental Research and Public Health. 2008;5(2):91-8. doi:http://www.doi.org.10.3390/ijerph5020091

44. Custodio M, Álvarez D, Cuadrado W, Montalvo R, Ochoa S. Potentially toxic metals and metalloids in surface water intended for human consumption and other uses in the Mantaro River watershed, Peru. Soil and Water Research. 2020;15(4):237-45. doi:https://doi.org/10.17221/152/2019-SWR.

45. USEPA. Screening level ecological risk assessment protocol for hazardous waste combustion facilities. Washington, DC, USA: United States Environmental Protection Agency, Solid Waste and Emergency Response;1999 August. Report No.: EPA530-D-99-001C.

46. Gielar A, Helios-Rybicka E, Möller S, Einax JW. Multivariate analysis of sediment data from the upper and middle Odra River (Poland). Applied Geochemistry. 2012;27(8):1540-5. doi:https://doi.org/10.1016/j.apgeochem.2012.04.004.

47. Woitke P, Wellmitz J, Helm D, Kube P, Lepom P, Litheraty P. Analysis and assessment of heavy metal pollution in suspended solids and sediments of the river Danube. Chemosphere. 2003;51(8):633-42. doi:https://doi.org/10.1016/S0045-6535(03)00217-0.

48. Morillo J, Usero J, Gracia I. Heavy metal fractionation in sediments from the Tinto River (Spain). International Journal of Environmental Analytical Chemistry. 2002;82(4):245-57. doi:https://doi.org/10.1080/03067310290009523.

49. Long ER, MacDonald DD, Smith SL, Calder FD. Incidence of adverse biological effects within ranges of chemical concentrations in marine and

estuarine sediments. Environmental Management. 1995;19(1):81-97. doi:https://link.springer.com/content/pdf/10.1007%2FBF02472006.pdf.

50. Ali MM, Ali ML, Islam MS, Rahman MZ. Preliminary assessment of heavy metals in water and sediment of Karnaphuli River, Bangladesh. Environmental Nanotechnology, Monitoring & Management. 2016;5:27-35. doi:https://doi.org/10.1016/j.enmm.2016.01.002.

51. Turekian KK, Wedepohl KH. Distribution of the elements in some major units of the earth's crust. Geological Society of America Bulletin. 1961;72(2):175-92. doi:https://doi.org/10.1130/0016-7606(1961)72[175:DOTEIS]2.0.CO;2.

52. Taylor S. Abundance of chemical elements in the continental crust: a new table. Geochimica et Cosmochimica Acta. 1964;28(8):1273-85.

53. Rudnick R, Gao S. Composition of the continental crust. The crust, vol 3. Oxford, UK: Elsevier; 2003.

54. Nemerow NL. Stream, lake, estuary, and ocean pollution. 2nd edition ed. New York, US: Van Nostrand Reinhold; 1991.

55. Brady JP, Ayoko GA, Martens WN, Goonetilleke A. Development of a hybrid pollution index for heavy metals in marine and estuarine sediments. Environmental Monitoring and Assessment. 2015;187(5):306. doi:http://doi.org/10.1007/s10661-015-4563-x.

56.• Patel P, Raju NJ, Reddy BSR, Suresh U, Sankar D, Reddy T. Heavy metal contamination in river water and sediments of the Swarnamukhi River Basin, India: risk assessment and environmental implications. Environmental Geochemistry and Health. 2018;40(2):609-23. doi:https://doi.org/10.1007/s10653-017-0006-7. **The application of many indexes to assess the pollution level of heavy metals in rivers is indicated in this study**

57. Saeedi M, Jamshidi-Zanjani A. Development of a new aggregative index to assess potential effect of metals pollution in aquatic sediments. Ecological Indicators. 2015;58:235-43. doi:https://doi.org/10.1016/j.ecolind.2015.05.047.

58. Long ER. Calculation and uses of mean sediment quality guideline quotients: a critical review. Environmental Science & Technology. 2006;40(6):1726-36. doi:https://www.doi.org/10.1021/es058012d.

59. Long ER, MacDonald DD, Severn CG, Hong CB. Classifying probabilities of acute toxicity in marine sediments with empirically derived sediment quality guidelines. Environmental Toxicology and Chemistry. 2000;19(10):2598-601. doi:https://www.doi.org/10.1002/etc.5620191028.

60. Yan N, Liu W, Xie H, Gao L, Han Y, Wang M, et al. Distribution and assessment of heavy metals in the surface sediment of Yellow River, China. Journal of Environmental Sciences. 2016;39:45-51.

61. Cengiz MF, Kilic S, Yalcin F, Kilic M, Yalcin MG. Evaluation of heavy metal risk potential in Bogacayi River water (Antalya, Turkey). Environmental Monitoring and Assessment. 2017;189(6):248. doi:http://www.10.1007/s10661-017-5925-3.

62. Milivojević J, Krstić D, Šmit B, Djekić V. Assessment of heavy metal contamination and calculation of its pollution index for Uglješnica River, Serbia. Bulletin of Environmental Contamination and Toxicology. 2016;97(5):737-42.

63. Qu L, Huang H, Xia F, Liu Y, Dahlgren RA, Zhang M, et al. Risk analysis of heavy metal concentration in surface waters across the rural-urban interface of

the Wen-Rui Tang River, China. Environmental Pollution. 2018;237:639-49. doi:https://doi.org/10.1016/j.envpol.2018.02.020.

64. Alves RI, Sampaio CF, Nadal M, Schuhmacher M, Domingo JL, Segura-Muñoz SI. Metal concentrations in surface water and sediments from Pardo River, Brazil: human health risks. Environmental Research. 2014;133:149-55. doi:https://doi.org/10.1016/j.envres.2014.05.012.

65. Ahmed MK, Baki MA, Islam MS, Kundu GK, Habibullah-Al-Mamun M, Sarkar SK, et al. Human health risk assessment of heavy metals in tropical fish and shellfish collected from the river Buriganga, Bangladesh. Environmental Science and Pollution Research. 2015;22(20):15880-90. doi:https://doi.org/10.1007/s11356-015-4813-z.

66. USEPA. Risk assessment guidance for superfund volume I: human health evaluation manual (Part E, Supplemental guidance for dermal risk assessment). Washington, DC, USA: United States Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation2004 July. Report No.: EPA/540/R/99/005.

67. Kumar V, Sharma A, Kumar R, Bhardwaj R, Kumar Thukral A, Rodrigo-Comino J. Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. Human and Ecological Risk Assessment: An International Journal. 2018;26(1):1-16. doi:https://doi.org/10.1080/10807039.2018.1497946.

68. Pandey M, Pandey AK, Mishra A, Tripathi B. Assessment of metal species in river Ganga sediment at Varanasi, India using sequential extraction procedure and SEM–EDS. Chemosphere. 2015;134:466-74. doi:https://doi.org/10.1016/j.chemosphere.2015.04.047.

69. Nazeer S, Hashmi MZ, Malik RN. Heavy metals distribution, risk assessment and water quality characterization by water quality index of the River Soan, Pakistan. Ecological Indicators. 2014;43:262-70. doi:https://doi.org/10.1016/j.ecolind.2014.03.010.

70. Nasrabadi T. An index approach to metallic pollution in river waters. International Journal of Environmental Research. 2015;9(1):385-94.

71. Goher ME, Hassan AM, Abdel-Moniem IA, Fahmy AH, El-sayed SM. Evaluation of surface water quality and heavy metal indices of Ismailia Canal, Nile River, Egypt. The Egyptian Journal of Aquatic Research. 2014;40(3):225-33. doi:https://doi.org/10.1016/j.ejar.2014.09.001.

72. Banzi FP, Msaki PK, Mohammed NK. Assessment of heavy metal concentration in water around the proposed Mkuju River Uranium Project in Tanzania. Tanzania Journal of Science. 2015;41(1):8-18.

73. Krika A, Krika F. Evaluation of the status of heavy metal pollution in surface water and sediments of the Nil River (North Eastern Algeria). Pollution. 2017;3(2):301-10. doi:http://www.doi.org.10.7508/pj.2017.02.011.

74. Reyhani P, Ansari MR, Saeb K, Tonekabon I. Assessment of heavy metals contamination in surface water of the upstream Sardabrud River, North of Iran. Life Science Journal. 2013;10(7s).

75. Mendiguchía C, Moreno C, García-Vargas M. Evaluation of natural and anthropogenic influences on the Guadalquivir River (Spain) by dissolved heavy metals and nutrients. Chemosphere. 2007;69(10):1509-17. doi:https://doi.org/10.1016/j.chemosphere.2007.05.082.

76. Aguasanta S, Miguel N, Manuel O, Carlos C. Environmental impact of mining activities in the Odiel river basin (SW Spain). Mine Water and the Environment. 2005;24(1):1.

77. Masson M, Blanc G, Schäfer J. Geochemical signals and source contributions to heavy metal (Cd, Zn, Pb, Cu) fluxes into the Gironde Estuary via its major tributaries. Science of the Total Environment. 2006;370(1):133-46. doi:https://doi.org/10.1016/j.scitotenv.2006.06.011.

78. Annibaldi A, Illuminati S, Truzzi C, Libani G, Scarponi G. Pb, Cu and Cd distribution in five estuary systems of Marche, central Italy. Marine Pollution Bulletin. 2015;96(1-2):441-9. doi:https://doi.org/10.1016/j.marpolbul.2015.05.008.

79. Maloku F, Ahmeti A, Kopali A, Doko A, Malltezi J, Brahushi F, et al. Water and sediment heavy metal pollution in Ereniku River of Kosovo. Albanian Journal of Agricultural Sciences. 2015;14(2):137.

80. Bussan DD, Ochs CA, Jackson CR, Anumol T, Snyder SA, Cizdziel JV. Concentrations of select dissolved trace elements and anthropogenic organic compounds in the Mississippi River and major tributaries during the summer of 2012 and 2013. Environmental Monitoring and Assessment. 2017;189(2):73. doi:http://doi.org/10.1007/s10661-017-5785-x.

81. Mathis B, Cummings T. Selected metals in sediments, water, and biota in the Illinois River. Journal (Water Pollution Control Federation). 1973;45:1573-83.

82. Gaillardet J, Viers J, Dupré B. Trace elements in river waters. Treatise on Geochemistry. 2003;5:605. doi:https://doi.org/10.1016/B0-08-043751-6/05165-3.

83. Fu J, Zhao C, Luo Y, Liu C, Kyzas GZ, Luo Y, et al. Heavy metals in surface sediments of the Jialu River, China: their relations to environmental factors. Journal of Hazardous Materials. 2014;270:102-9. doi:https://doi.org/10.1016/j.jhazmat.2014.01.044.

84. Liu C, Xu J, Liu C, Zhang P, Dai M. Heavy metals in the surface sediments in Lanzhou Reach of Yellow River, China. Bulletin of Environmental Contamination and Toxicology. 2009;82(1):26-30. doi:http://www.doi.org.10.1007/s00128-008-9563-x.

85. Li X, Liu L, Wang Y, Luo G, Chen X, Yang X, et al. Integrated assessment of heavy metal contamination in sediments from a coastal industrial basin, NE China. PLOS One. 2012;7(6):e39690. doi:https://doi.org/10.1371/journal.pone.0039690.

86. Giri S, Singh AK, Tewary B. Source and distribution of metals in bed sediments of Subarnarekha River, India. Environmental Earth Sciences. 2013;70(7):3381-92. doi:https://doi.org/10.1007/s12665-013-2404-1.

87. Nasrabadi T, Bidhendi GN, Karbassi A, Mehrdadi N. Evaluating the efficiency of sediment metal pollution indices in interpreting the pollution of Haraz River sediments, southern Caspian Sea basin. Environmental Monitoring and Assessment. 2010;171(1-4):395-410. doi:https://doi.org/10.1007/s10661-009-1286-x.

88. Al-Haidarey M, Hassan F, Al-Kubaisey A, Douabul A. The geoaccumulation index of some heavy metals in Al-Hawizeh Marsh, Iraq. Journal of Chemistry. 2010;7(S1):S157-S62.

89. Abdo M, El-Nasharty S. Physico-chemical evaluations and trace metals distribution in water-surficial sediment of Ismailia Canal, Egypt. Nature and Science. 2010;8(5):198-206.

90. Rifaat A. Major controls of some metals distribution in sediments off the Nile Delta, Egypt. Egyptian Journal of Aquatic Research. 2005;31:16-28.

91. Godwin AI. Assessment of heavy metals associated with bottom sediment of Asejire Reservoir, Southwest Nigeria. International Letters of Natural Sciences. 2016;55:9-16. doi:http://www.doi.org.10.18052/www.scipress.com/ILNS.55.9.

92. Ekeanyanwu C, Ogbuinyi C, Etienajirhevwe O. Trace metals distribution in fish tissues, bottom sediments and water from Okumeshi River in Delta State, Nigeria. Ethiopian Journal of Environmental Studies and Management. 2010;3(3). doi:https://doi.org/10.4314/ejesm.v3i3.63959.

93. Lalah J, Ochieng E, Wandiga S. Sources of heavy metal input into Winam Gulf, Kenya. Bulletin of Environmental Contamination and Toxicology. 2008;81(3):277-84. doi:http://www.10.1007/s00128-008-9452-3.

94. González AE, Rodríguez MT, Sá JJ, Espinosa AF, De La Rosa FB. Assessment of metals in sediments in a tributary of Guadalquiver River (Spain). Heavy metal partitioning and relation between the water and sediment system. Water, Air, and Soil Pollution. 2000;121(1-4):11-29. doi:https://doi.org/10.1023/A:1005203012514.

95. Mendil D, Ünal ÖF, Tüzen M, Soylak M. Determination of trace metals in different fish species and sediments from the River Yeşilırmak in Tokat, Turkey. Food and Chemical Toxicology. 2010;48(5):1383-92. doi:https://doi.org/10.1016/j.fct.2010.03.006.

96. Klavinš M, Briede A, Rodinov V, Kokorite I, Parele E, Klavina I. Heavy metals in rivers of Latvia. Science of the Total Environment. 2000;262(1-2):175-83. doi:https://doi.org/10.1016/S0048-9697(00)00597-0.

97. Karageorgis A, Nikolaidis N, Karamanos H, Skoulikidis N. Water and sediment quality assessment of the Axios River and its coastal environment. Continental Shelf Research. 2003;23(17-19):1929-44. doi:https://doi.org/10.1016/j.csr.2003.06.009.

98. Hudson-Edwards K, Macklin M, Taylor M. Historic metal mining inputs to Tees river sediment. Science of the Total Environment. 1997;194:437-45. doi:https://doi.org/10.1016/S0048-9697(96)05381-8.

99. Heiny JS, Tate C. Concentration, distribution, and comparison of selected trace elements in bed sediment and fish tissue in the South Platte River Basin, USA, 1992–1993. Archives of Environmental Contamination Toxicology. 1997;32(3):246-59.

100. Olivares-Rieumont S, De la Rosa D, Lima L, Graham DW, Katia D, Borroto J, et al. Assessment of heavy metal levels in Almendares River sediments-Havana City, Cuba. Water Research. 2005;39(16):3945-53.

101. Marrugo-Negrete J, Pinedo-Hernández J, Marrugo-Madrid S, Díez S. Assessment of trace element pollution and ecological risks in a river basin impacted by mining in Colombia. Environmental Science Pollution Research. 2021;28(1):201-10. doi:https://doi.org/10.1007/s11356-020-10356-4.

102. Ruiz-Fernández A, Hillaire-Marcel C, Páez-Osuna F, Ghaleb B, Soto-Jiménez M. Historical trends of metal pollution recorded in the sediments of the Culiacan River Estuary, Northwestern Mexico. Applied Geochemistry. 2003;18(4):577-88. doi:https://doi.org/10.1016/S0883-2927(02)00117-8.

103. Aguilar Pesantes A, Peña Carpio E, Vitvar T, María Mahamud López M, Menéndez-Aguado JM. A Multi-Index Analysis Approach to Heavy Metal

Pollution Assessment in River Sediments in the Ponce Enríquez Area, Ecuador. Water. 2019;11(3):590. doi:https://doi.org/10.3390/w11030590.

104. Martin J-M, Meybeck M. Elemental mass-balance of material carried by major world rivers. Marine Chemistry. 1979;7(3):173-206. doi:https://doi.org/10.1016/0304-4203(79)90039-2.

105. Simex S, Helz G. Regional geochemistry of trace elements in Chesapeake Bay. Environmental Geology. 1981;3(6):315-23.

List of Tables

Table 1. Heavy metal contamination in (a) surface water and (b) sediments of global rivers

a)

Region	Heavy metal concentration in surface water (mg L^{-1})	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg	References
Asia	Yangtze River, China	0.00097	0.0004	0.0013	0.0028	0.002	-	0.031	0.00004	[32]
	Wen-Rui Tang River, China	-	0.00098	0.00532	0.0209	0.00423	-	0.0721	0.00003	[63]
	Beijiang River, China	0.01953	0.00043	-	0.003	0.00224	-	0.01636	0.00002	[33]
	Gomti River, India	-	0.1	-	0.02	0.02	0.04	0.07	-	[36]
	Beas River, India	-	0.005	0.031	0.004	0.081	-	0.22	-	[67]
	Kali River, India	-	0.06	0.06	-	0.13	-	21.71	-	[37]
	Ganga, India	-	0.02141	0.0502	0.03128	0.09578	0.04052	0.05041	-	[68]
	Buriganga River, Bangladesh	-	0.059	0.114	0.239	0.119	0.015	0.33	-	[34]
	Bangshi River, Bangladesh	0.024	0.007	0.093	1.05	0.108	0.035	3.32	-	[35]
	To Lich River, Vietnam	-	-	0.0029	0.0045	0.0081	-	0.0511	-	[25]
	Soan River, Pakistan	-	-	0.01	0.02	0.65	-	0.015	-	[69]
	Haraz River, Iran	0.05535	0.00265	-	0.01325	0.0044	-	0.05275	-	[70]
	Asia rivers and lakes (1970 – 2017)	-	0.01071	0.12804	0.03759	0.03605	0.09162	0.20805	-	[31••]
Africa	Ismailia Canal, Egypt	-	0.00045	-	0.007	0.018	-	0.015	-	[71]
	Nile River, Egypt	-	0.0045	-	0.007	0.018	0.01	0.015	-	[71]
	Challawa River, Nigeria	-	-	0.924	0.39	0.84	0.21	2.227	-	[38]
	Nairobi River, Kenya	-	-	1.11	0.05	7.5	-	0.48	-	[39]
	Mkuju River, Tanzania	0.009785	0.00008	0.01008	0.0095	0.03935	0.00495	0.03247	-	[72]
	Nil River, Algeria	-	0.00032	-	0.000061	0.00058	-	0.00038	-	[73]
	Africa rivers and lakes (1970 – 2017)	-	0.003	0.03694	0.03417	0.03405	0.02973	0.05918	-	[31••]
Europe	Mala Welna River, Poland	-	0.003	0.009	0.089	0.04	0.015	0.115	-	[74]
	Guadalquivir River, Spain	-	0.000015	-	0.00264	0.000178	-	0.00158	-	[75]
	Odiel River, Spain	4.686	0.589	0.18	122	1.985	4.429	466	-	[76]

	Tigris River, Turkey	0.0024	0.0014	< 0.005	0.1650	0.0003	0.0720	0.0370	-	[24]
	Bogacayi River, Turkey	0.00043	0.00023	0.0032	0.00092	0.00048	0.00347	-	-	[61]
	Gironde Estuary, France	-	0.00005	-	0.001403	0.000242	-	0.0061	-	[77]
	Estuary of Marche, Italy	-	0.000045	-	-	0.000315	-	0.002183	-	[78]
	Uglješnica River, Serbia	0.0002	0.01473	-	0.00408	0.04855	-	0.00998	0.00022	[62]
	Erenik River, Kosovo	-	0.007	0.029	0.044	0.014	-	0.042	-	[79]
	Europe rivers and lakes (1970 – 2017)	-	0.00062	0.00725	0.00848	0.00757	0.00395	0.09607	-	[31••]
South America	Pardo River, Brazil	0.00214	0.00005	0.00188	0.00328	0.0018	0.00975	0.0133	-	[64]
	South American rivers and lakes (1970 – 2017)	-	0.00271	0.01248	0.01535	0.0325	0.01087	0.08347	-	[31••]
North America	Mississippi River, US	-	0.00057	0.0002	0.0021	0.00031	-	0.0016	-	[80]
	Illinois River, US	-	0.0006	0.021	0.001	0.002	0.002	0.031	-	[81]
	North American rivers and lakes (1970 – 2017)	-	0.00361	0.02664	0.03813	0.02483	0.00584	0.19693	-	[31••]
Latin America and Caribbean	San Pedro River, Mexico	0.16	0.014	0.212	0.2	-	0.3	-	-	[43]
	Chanchas River, Peru	0.0143	-	-	0.00257	0.00101	-	0.000375		[44]
	Puyango River Basin, Ecuador	0.015465	-	-	-	0.0274	-	-	0.0000046	[42]
World average		0.00062	0.00008	-	0.00168	0.000079	-	0.0006	-	[82]
Standards	Fresh toxicity reference values	0.15	0.002	0.011	0.009	0.003	0.052	0.018	-	[45]
	Human health ambient water quality criteria of US EPA	0.000018	-	-	1.3	-	0.61	7.4	-	[40]
	WHO's drinking water quality guidelines	0.01	0.003	0.05	2	0.01	0.07	-	0.006	[41]

b)

Region	Heavy metal concentration in the sediments (mg kg^{-1} dry wt.)	As	Cd	Cr	Cu	Pb	Ni	Zn	Hg	References
Asia	Yangtze River, China	25.8567	0.4200	58.4667	46.4733	37.7533	-	148.8100	0.1933	[32]
	Jialu River, China	-	2.93	60.8	39.22	29.35	42.44	107.58	-	[83]
	Yongding River, China	-	-	47.61	24.71	35.47	40.45	94.75	-	[26]
	Yellow River, China	31	-	84.5	-	52	-	-	31	[84]
	Lianshan River, China	-	53.18	-	116.50	112.28	57.41	633.85	-	[85]

	Gomti River, India	-	5.0	16.2	23.2	46.2	23.9	76.3	-	[36]
	Subarnarekha River, India	-		111	69	75	42	100	-	[86]
	Swarnamukhi River Basin, India	-	0.2	85.25	100.9	21.39	2.43	63.4	-	[56•]
	Ganga, India	-	79.07	190.4	43.0	210.615	57.74	231.88	-	[68]
	Buriganga River, Bangladesh	15.54	7.74	530	62.1	65.16	47	52.975	-	[34]
	Korotoa River, Bangladesh	27.00	2.8	118	82	63	103	-	-	[23]
	Bangshi River, Bangladesh	1.93	0.61	98	-	60	-	-	-	[35]
	To Lich River, Vietnam	83.90	4.4	107.9	87.7	67.1	64.8	477.9	-	[25]
	Soan River, Pakistan	-	1.37	10.73	17.64	27.86	28.00	45.18	-	[69]
	Haraz River, Iran	33.55	3.50	28.05	32.10	26.35	43.55	73.80	-	[87]
	Al-Hawizeh Marsh, Iraq	3939.6	42.5	419.1	145.1	1602.4	-	-	-	[88]
Africa	Ismailia Canal, Egypt	232.50	5.40	-	44.70	26.60	38.40	110.60	-	[89]
	Nile River, Egypt	-	-	274	81	23.2	112	221	-	[90]
	Asejire Reservoir, Nigeria	-	-	0.03	43.68	72.02	0.05	20.86	-	[91]
	Qua Iboe River, Nigeria	-	5.67	28.52	43.72	231.52	2.6	-	-	[14••]
	Okumeshi River, Nigeria	-	1.32	0.87	-	0.45	-	-	-	[92]
	Winam Gulf, Kenya	-	4.8	46.1	71.5	82.5	-	170.0	-	[93]
	Nil River, Algeria	-	2.34	-	38.38	61.50	96.20	-	-	[73]
Europe	Odra River, Poland	95.33	8.47	64.67	99.33	113.33	51.00	1054.67	-	[46]
	Guadaira River, Spain	2	3	38	25	20	37	51	-	[94]
	Tinto River, Spain	-	12	151	2700	13,400	36	5280	-	[48]
	Tigris River, Turkey	12.44	7.90	158.35	2860.25	660.11	534.58	1061.54	-	[24]
	Yeşilırmak River, Turkey	-	0.55	-	38.7	17.3	79.2	45.5	-	[95]
	Gironde Estuary, France	-	1.11	-	36.62	58.99		235.08	-	[77]
	Rivers of Latvia, Latvia	-	0.99	-	14.08	21.10	21.96		-	[96]
	River Po, Italy	-	3.7	-	90.1	98.5	161	645	-	[30]
	Lambro River, Italy	-	2.1	-	90.1	98.5	161.0	305.0	-	[30]
	Uglješnica River, Serbia	-	-	-	-	-	-	-	-	[62]
	Pasvik River, N. Fennoscandia	-	3.84	-	6495	62	6490	439	-	[12]
	Danube River, Central and western Europe	388	32.9	556.5	8088	541.8	173.3	2010	-	[47]
	Erenik River, Kosovo	-	-	625.0	62.3	14.8	-	157.0	-	[79]

	Axios River, Greece	40	11	180	93	140	188	271	-	[97]
	Tees River, UK	-	5.95	-	76.9	6880	-	1920	-	[98]
South America	Pardo River, Brazil	0.68	0.045	24.525	17.735	8.27	6.75	34.86	-	[64]
North America	Illinois River, US	-	2	-	19	28	-	81	-	[81]
	South Platte River, US	31	22	71	480	270	-	3700	-	[99]
Latin America and Caribbean	Rimac River, Peru	1543	31	71	796	2281	23	8076	-	[27]
	Almendares River, Cuba	-	4.3	23.4	420.8	189	-	708.8	-	[100]
	San Jorge River, Colombia	1.8	1159	-	6656	7.2	105	1064	0.31	[101]
	Culiacan River Estuary, Mexico	-	0.55	-	27.95	29.2	45.85	115.5	-	[102]
	Siete River, Ecuador	842.8	0.73	-	483.7	20.3	5960.9	132.5	1	[103]
World sediment river average		-	1	100	100	150	90	350	-	[104]
Surface rock average		-	0.13	97	32	20	49	129	-	
Standards	NOAA ERL[a]	8.2	1.2	81	34	46.7	20.9	150	0.15	[49]
	NOAA ERM[a]	70	9.6	370	270	218	51.6	410	0.71	[49]
	TRV[b]	6	0.6	26	16	31	16	110	-	[45]

"-" Not available; [a] National Oceanic and Atmospheric Administration (NOAA)'s effects range low (ERL) and effects range median (ERM); [b] Freshwater sediment toxicity reference value

Table 2. Classifications of heavy metal contamination and adverse effect levels on ecosystem based on assessment indexes

Index	Classification	Contamination degree	References
I_{geo}	$I_{geo} < 0$	Uncontaminated	[9]
	$0 \leq I_{geo} < 1$	Uncontaminated to moderately contaminated	
	$1 \leq I_{geo} < 2$	Moderately contaminated	
	$2 \leq I_{geo} < 3$	Moderately to heavily contaminated	
	$3 \leq I_{geo} < 4$	Heavily contaminated	
	$4 \leq I_{geo} < 5$	Heavily to extremely contaminated	
	$I_{geo} \geq 5$	Extremely contaminated	
CF	$CF < 1$	Low degree	[7]
	$1 \leq CF < 3$	Moderate degree	
	$3 \leq CF < 6$	Considerable degree	
	$CF \geq 6$	Very high degree	
EF	$EF < 2$	No enrichment	[105]
	$2 \leq EF < 5$	Moderate enrichment	
	$5 \leq EF < 20$	Significant enrichment	
	$20 \leq EF < 40$	Very high enrichment	
	$EF \geq 40$	Extremely high enrichment	
PCI	$PCI < 1$	Low contamination	[12]
	$1 \leq PCI < 3$	Moderate contamination	
	$PCI \geq 3$	Severe or very severe contamination	
HQ	$HQ < 0.1$	No adverse effects	[13]
	$0.1 \leq HQ < 1$	Potential hazards	
	$1 \leq HQ < 10$	Moderate hazards	
	$HQ \geq 10$	High hazards	
mHQ	$mHQ < 0.5$	Nil to very low severity of contamination	[14●●]
	$0.5 < mHQ < 1$	Very low severity of contamination	
	$1 < mHQ < 1.5$	Low severity of contamination	
	$1.5 < mHQ < 2$	Moderate severity of contamination	
	$2 < mHQ < 2.5$	Considerable severity of contamination	
	$2.5 < mHQ < 3$	High severity of contamination	
	$3 < mHQ < 3.5$	Very high severity of contamination	
	$mHQ > 3.5$	Extreme severity of contamination	
DC	$DC < 8$	Low degree	[7]
	$8 \leq DC < 16$	Moderate degree	
	$16 \leq DC < 24$	Considerable degree	
	$DC \geq 24$	Very high degree	
mCd	$mCd < 1.5$	Uncontaminated	[16]
	$1.5 \leq mCd < 2$	Slightly contaminated	
	$2 \leq mCd < 4$	Moderately contaminated	
	$4 \leq mCd < 8$	Moderately to heavily contaminated	
	$8 \leq mCd < 16$	Heavily contaminated	
	$16 \leq mCd < 32$	Severely contaminated	
	$mCd \geq 32$	Extremely contaminated	
PLI	$PLI = 0$	Perfection	[17]
	$PLI < 1$	Baseline level	
	$PLI > 1$	Contaminated	
$PI_{Nemerow}$	$PI < 0.7$	Unpolluted	[54]
	$0.7 \leq PI < 1$	Slightly polluted	
	$1 \leq PI < 2$	Moderately polluted	
	$2 \leq PI < 3$	Heavily polluted	
	$PI \geq 3$	Severely polluted	
MPI	$MPI < 1$	Unpolluted	[55]
	$1 \leq MPI < 2$	Slightly polluted	
	$2 \leq MPI < 3$	Moderately polluted	
	$3 \leq MPI <5$	Moderately-heavily polluted	
	$5 \leq MPI < 10$	Heavily polluted	
	$MPI \geq 10$	Severely polluted	

MI	$MI < 0.3$	Very pure	[18]
	$0.3 \leq MI < 1$	Pure	
	$1 \leq MI < 2$	Slightly affected	
	$2 \leq MI < 4$	Moderately affected	
	$4 \leq MI < 6$	Strongly affected	
	$MI \geq 6$	Seriously affected	
HPI	$HPI < 100$	Safe for human consumption	[8]
	$HPI \geq 100$	Not safe for human consumption	
CSI	$CSI < 0.5$	Uncontaminated	[19]
	$0.5 \leq CSI < 1$	Very low severity of contamination	
	$1 \leq CSI < 1.5$	Low severity of contamination	
	$1.5 \leq CSI < 2$	Low to moderate severity of contamination	
	$2 \leq CSI < 2.5$	Moderate severity of contamination	
	$2.5 \leq CSI < 3$	Moderate to high severity of contamination	
	$3 \leq CSI < 4$	High severity of contamination	
	$4 \leq CSI < 5$	Very high severity of contamination	
	$CSI \geq 5$	Ultra-high severity of contamination	
ECI	$ECI < 2$	Uncontaminated	[14●●]
	$2 < ECI < 3$	Uncontaminated to slightly contaminated	
	$3 < ECI < 4$	Slightly to moderately contaminated	
	$4 < ECI < 5$	Moderately to considerably contaminated	
	$5 < ECI < 6$	Considerably to highly contaminated	
	$6 < ECI < 7$	Highly contaminated	
	$ECI > 7$	Extremely contaminated	
$PERI$	$PERI < 110$	Low risk	[7]
	$110 \leq PERI < 220$	Moderate risk	
	$220 \leq PERI < 440$	High risk	
	$PERI \geq 440$	Significantly high risk	
$mRAC$	$mRAC < 1\%$	No potential adverse effect	[57]
	$1\% \leq mRAC < 9\%$	Low potential adverse effect	
	$10\% \leq mRAC < 29\%$	Medium potential adverse effect	
	$30\% \leq mRAC < 49\%$	High potential adverse effect	
	$mRAC \geq 50\%$	Very high adverse effect	
$mPEL_Q$	$mPEL_Q \leq 0.1$	Low degree of contamination	[58]
	$0.1 < mPEL_Q \leq 1.5$	Medium-low degree of contamination	
	$1.5 < mPEL_Q \leq 2.3$	High-medium degree of contamination	
	$mPEL_Q > 2.3$	High degree of contamination	
$mERM_Q$	$mERM_Q \leq 0.1$	Low priority site	[59]
	$0.1 < mERM_Q \leq 0.5$	Medium-low priority site	
	$0.5 < mERM_Q \leq 1.5$	High-medium priority site	
	$mERM_Q > 1.5$	High priority site	