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ECOLOGICAL RISK AND ECONOMIC LOSS ESTIMATION OF HEAVY METALS POLLUTION IN THE BEIJIANG RIVER

OCENA RYZYKA EKOLOGICZNEGO I STRAT EKONOMICZNYCH WYNIKAJĄCYCH Z ZANIECZYSZCZENIA METALAMI CIĘŻKIMI RZEKI BEIJIANG

Abstract: The distribution and extent of heavy metal accumulation in the fluvial sediment of the Beijiang River are described. The potential toxicity of this pollution was quantified using a consensus based sediment quality guidelines (SQGs) method and the Hakanson potential ecological risk index. The concentrations of Hg, As, Cu, Zn, Pb, Ni and Cr were high enough to damage the sediment biota on a frequent basis. The potential ecological risk was much higher in the downstream, urbanized reaches of the river than in the upstream reaches which are still rural, but all sections of the river posed at least a moderate level of ecological risk. Estimates of the economic loss associated with these pollutions were appreciable, and were mainly due to Hg and Cu. The Beijiang River basin is heavily polluted, posing environmental risks for the downstream reaches of the Pearl River, and economic loss to the whole watershed.

Keywords: ecological risk assessment, economic loss estimation, heavy metals, sediment, ecosystem service, Beijiang River

Introduction

The pollution of aquatic ecosystems by heavy metals, driven by increasing urbanization and industrialization, is a growing global problem [1]. The accumulation of heavy metals in fluvial sediments has a major impact on riverine biota [2] and the health of local human populations [3], particularly as these pollutants are so readily released into the water in response to changes in environment [4]. River sediments act as a sink for various pollutants, and in so doing provide a record of anthropogenic emissions. An accurate assessment of

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water quality, alongside the environmental risk associated with the heavy metal contamination of the sediment, are prerequisites for proposing strategies aimed at environmental management and economic development, and the estimation of potential economic losses is a key consideration for any such strategy [5]. The assessment of the ecological risk of heavy metal pollution in sediments is currently based on various sediment quality standards [6-8], among which sediment quality guidelines (SQGs) have proven to be particularly suitable [9]. However, as yet, little attention has been paid to either the ecological risk or the extent of economic losses at the level of a whole watershed.

The Beijiang River, a tributary of the Pearl River in southern China, provides a source of drinking water for over a million people, but its water quality is being continuously degraded by the discharge of industrial and domestic waste water [10]. Here, we have applied a consensus-based SQG method and the Hakanson potential ecological risk index [11] to assess the extent of the ecological damage and the economic loss [12] caused by heavy metal pollution in the Beijiang River basin.

Materials and methods

Study area and sampling sites

The 468 km long Beijiang River flows to the north of Guangzhou City and joins the Pearl River at Foshan City. Its 38,832 km² watershed receives an annual volume of 4.82×10^{10} m³ runoff water [13].

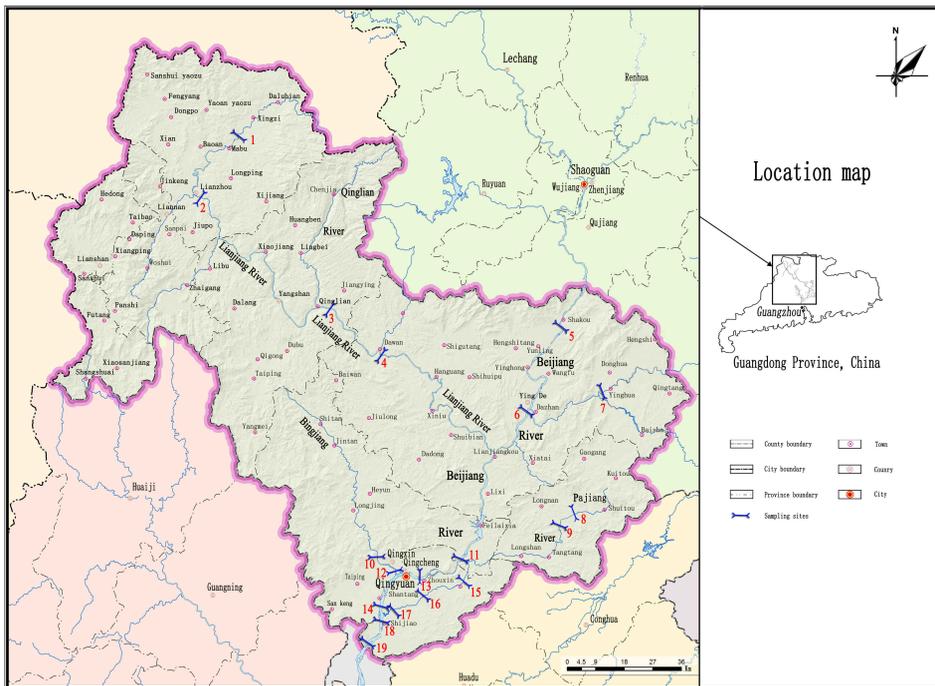


Fig. 1. Map of study area and sampling stations

More than 80% of the total flow takes place between April and September, with the maximum to minimum discharge ratio varying from three to six fold [14]. The development of mining and industry, accompanied by rapid urbanization, has given rise to a growing water pollution problem in the river basin [10]. The study involved the monitoring of 19 sites, the locations of which are given in Figure 1. Sites #1-#10 are located in the upstream reaches of the river, and are surrounded by agricultural land, involving the cultivation of rice and vegetables. The area is composed mostly of Cretaceous chalk. Sites #11-#19 are located within the urbanized part of the catchment, in which industrial activity is dominated by electronics, metallurgy, building materials and the working of non-ferrous metals.

Chemical analysis

The top 2 cm of the river sediment was sampled using a customized device. The samples were initially frozen, and later analysed for the presence of eight heavy metals. The quantification of Cu, Zn, Pb, Cd, Ni and Cr content was conducted by first treating the sample with HF-HClO₄, and then subjecting the extract to atomic absorption spectrophotometry. The content of Hg and As was determined by extraction in, respectively, H₂SO₄-HNO₃-K₂CrO₇ and H₂SO₄-HNO₃ followed by atomic fluorescence. In order to check and control the probably pollution by samples during testing process, each sample analyzed by two blank whole-process. For the sake of ensure the validity of data and the accuracy and precision of analysis methods, the reference materials were adopted (Hg: GBW (E) 080392; As: GBW (E) 080390; Cd: GBW (E) 080401; Pb: GBW (E) 080399; Zn: GBW (E) 080400) Cu: GBW (E) 080396; Ni: GBW (E) 080392; Cr: GBW (E) 080403 [15]. The quality control gave good precision with a relative standard deviation better than 5% for all the duplicate samples.

Analysis methods

Sediment quality assessment

The extent of the pollution set against two threshold values, namely the “lowest effect screening level” (LEL) and the “severe effect screening level” (SEL). An LEL sediment is considered to be clean to marginally polluted, and is not expected to be deleterious to the majority of sediment-dwelling biota [16], whereas in SEL sediment, the level of pollution is high enough to compromise the survival of aquatic biota on a frequent basis [17]. Levels between LEL and SEL have a moderate impact on biota health, while levels above SEL are expected to severely impact upon biota health [18].

Potential ecological risk assessment

The ecological risk assessment proposed by Hakanson [11] is based on the assumption that the sensitivity of an aquatic system depends on its productivity [8]. It is based on the following expressions [19]:

$$E_r^i = T_r^i \times C_f^i \quad (1)$$

$$C_f^i = C_s^i / C_n^i \quad (2)$$

$$RI = \sum E_r^i = \sum T_r^i \times C_f^i \quad (3)$$

Here T_r^i represents a toxic response factor for each given pollutant, C_f^i the contamination factor for each heavy metal, C_s^i the measured level of each heavy metal in the sediment, C_n^i the background level of each heavy metal and E_r^i the potential ecological risk index. RI is the sum of all risk factors. The sediments' heavy metal toxicity coefficient and geochemical background values are shown in Table 1. Grading standard of the heavy metal pollution ecological risk coefficient and index are detailed Table 2.

Table 1

C_n^i and T_r^i of the heavy metals of the sediments

	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr
Background value* C_n^i [mg·kg ⁻¹]	0.06	13.2	16.4	55	36.6	0.72	19.11	35
Toxicity coefficient T_r^i	40	10	5	1	5	30	5	2

* The geochemical background value refers to the highest background of the heavy metal content in normal soil particles before modern industrialization [1]

Table 2

Grading of Hakanson potential ecological risk index

	Low	Moderate	Considerable	High	Significantly high
E_r^i	< 40	≤ 80	≤ 160	≤ 320	> 320
RI	< 150	≤ 300	≤ 600	> 600	
R_i	0	0.125	0.25	0.5	1

Economic Loss Estimation

The economic loss caused by heavy metal pollution in the water was estimated from the following relationships:

$$H_i = \alpha \times \gamma_i \times R_i \quad (4)$$

$$H = \sum H_i \quad (5)$$

$$\gamma_i = E_r^i / RI \quad (6)$$

Here H represents the total economic loss caused by the heavy metal pollution; α the monetary loss coefficient (\$8,498 per hm²·a) [20], γ_i the proportion of the potential ecological risk index accounted for by a specific heavy metal, and R_i the weighting of ecological risk (Table 2). Inorganic pollutants in the river derive mainly from heavy metals, so the economic loss caused by heavy metal pollution represents 40% of the total loss [21]. As a result value of α was adjusted to \$3,399.20 hm²·a.

Result and discussion

Distribution of heavy metals and the extent of pollution

The measured heavy metal concentrations are detailed in Table 3. The mean sediment concentrations of Hg, As, Cu, Zn, Pb, Cd, Ni and Cr were, respectively 0.28, 21.83, 115.72, 188.64, 188.62, 0.41, 36.67 and 199.67 mg·kg⁻¹. The upstream sediments were considerably less polluted than the downstream ones, reflecting the effect of industrialization and urbanization in and around Qingyuan City.

Table 3

Concentrations of heavy metals in sediments of the Beijiang River [$\text{mg}\cdot\text{kg}^{-1}$]

Site		Hg	As	Cu	Zn	Pb	Cd	Ni	Cr
Upper stream (Site 1-10)	Average	0.15	17.31	49.20	142.52	128.18	0.48	31.46	122.38
	Stdev	0.04	2.37	21.78	37.87	17.83	0.84	8.10	44.79
	Max	0.18	19.50	110.00	176.00	145.00	2.86	38.20	161.00
	Min	0.04	11.50	36.60	41.20	81.80	0.18	10.00	14.80
Downstream (Site 11-19)	Average	0.41	26.84	189.63	239.89	255.78	0.34	42.46	285.56
	Stdev	0.12	4.83	60.20	48.33	64.57	0.09	4.44	68.20
	Max	0.55	36.80	243.00	289.00	341.00	0.50	49.50	348.00
	Min	0.17	18.00	41.70	129.00	120.00	0.21	36.10	120.00
Average	Average	0.28	21.83	115.72	188.64	188.62	0.41	36.67	199.67
	Stdev	0.16	6.09	83.89	65.19	79.35	0.60	8.57	100.39
	Max	0.55	36.80	243.00	289.00	341.00	2.86	49.50	348.00
	Min	0.04	11.50	36.60	41.20	81.80	0.18	10.00	14.80

Table 4

Sediment quality guidelines of heavy metals in sediments of the Beijiang River [$\text{mg}\cdot\text{kg}^{-1}$], [%]

Site	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr
LEL	0.15	8.20	16.00	120.00	16.00	1.20	16.00	26.00
SEL	1.30	70.00	110.00	270.00	50.00	9.60	50.00	110.00
% of samples < LEL	10.50	0.00	0.00	5.30	0.00	94.70	5.30	5.30
Between LEL-SEL	89.50	100.00	52.60	78.90	0.00	5.30	94.70	10.50
% of samples > SEL	0.00	0.00	47.40	15.80	100.00	0.00	0.00	84.20

Table 5

Arsenic and heavy metal concentrations in sediment samples from the Beijiang River and other selected rivers from the literature [$\text{mg}\cdot\text{kg}^{-1}$]

River	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr	Reference
Upper stream of Beijiang	0.04-0.18	11.5-19.5	36.6-110.0	41.2-176.0	81.80-145.0	0.18-0.24*	10.0-38.2	14.8-161.0	This study
Downstream of Beijiang	0.17-0.55	18.0-36.8	41.7-243.0	129.0-289.0	120.0-341.0	0.21-0.50	36.1-49.5	120.0-348.0	This study
Pearl River, China	--	--	101.8-829.4	172.6-560.7	43.8-219.6	0.21-4.15	--	6.7-215.5	[24]
Huaihe River, China	--	--	16.0-46.30	53.0-93.0	17.6-29.5	0.13-0.24	--	45.8-71.5	[25]
Yangtze River, China	0.04-1.43	7.9-29.9	26.0-129.0	71.0-1142.0	20.0-98.0	0.20-3.40	26.0-57.0	57.0-205.0	[26]
Yellow River, China	--	--	11.0-34.9	51.1-133.8	17.4-55.1	0.07-1.41	14.4-59.1	30.9-102.7	[27]
Luan River, China	0.01-1.39	2.1-12.9	6.5-178.6	21.1-25.7	8.7-38.3	0.03-0.37	--	28.7-152.7	[15]
River Yeşilirmak, Turkey	--	--	13.1-38.7	24.7-45.5	3.3-17.3	0.12-0.55	15.4-79.2	--	[25]
Tigris River, Turkey	--	2.0-18.0	11.2-5075.6	60.1-2396.0	62.3-566.6	0.70-4.90	74.0-288.0	28.4-151.7	[23]
Guadiana, SW Iberian	0.16-4.43	8.8-55.6	7.5-71.9	102.0-483.0	22.9-47.9	0.10-1.40	20.8-38.1	14.0-49.0	[22]

* We dismissed the site 7 of Cd, which may be caused by sampling error

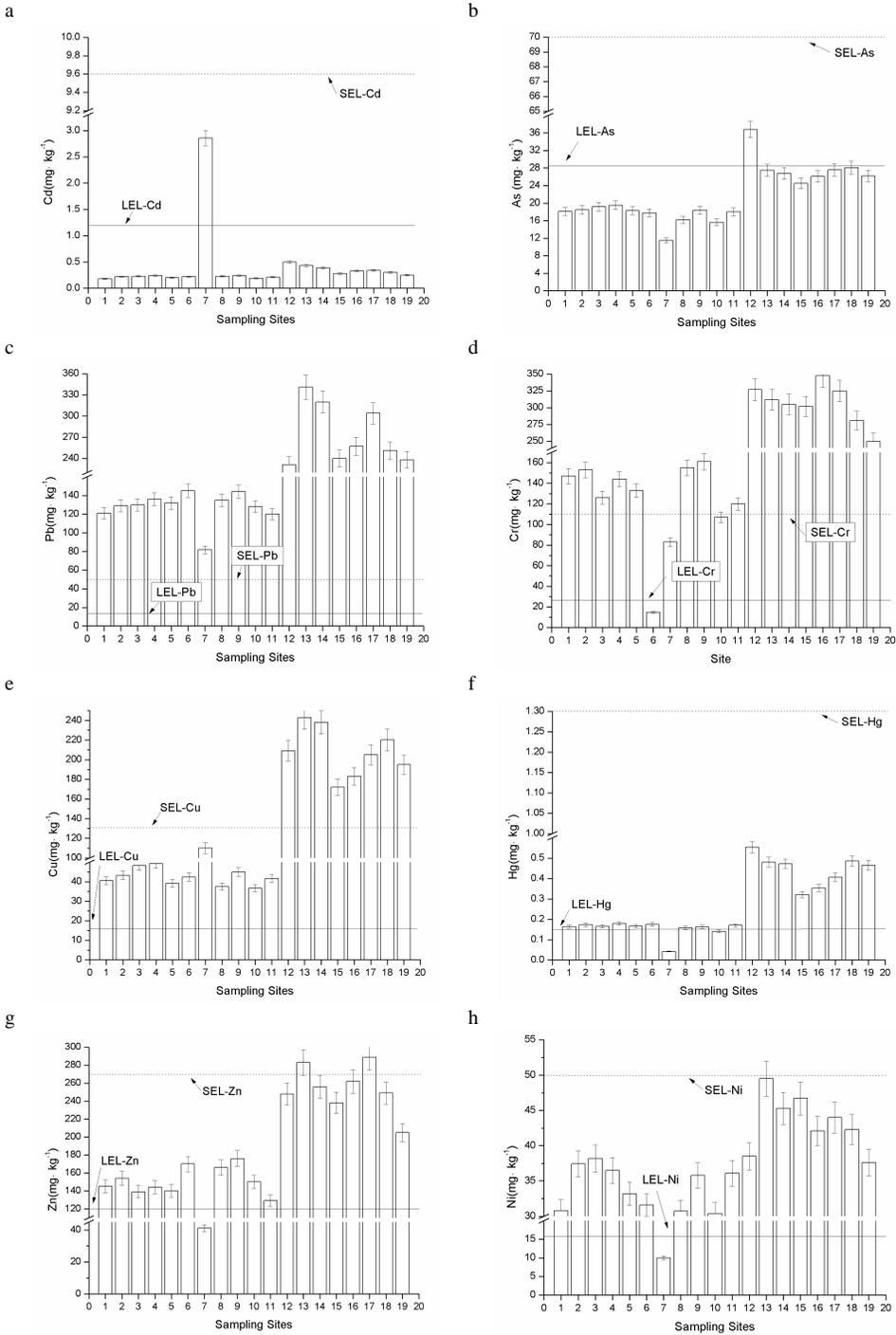


Fig. 2. Heavy metal concentrations of each sampling transects

According to the SQG methodology, the measured heavy metal concentrations in the river sediment samples were compared to consensus-based SEL and LEL values (Table 4). All of the pollutants, except for Cd (the concentration of Cd exceeded its LEL only at site #7, located downstream of a sewage treatment plant) and As (the concentration of Cd exceeded its LEL only at site #12, located downstream of Qingxin County), exceeded their respective LEL (Fig. 2a, 2b); those for Pb and Cr even exceeded their SEL (Fig. 2c, 2d). For Cu, the latter was the case for eight of the 19 samples (Fig. 2e). The concentrations of Hg, Zn and Ni exceeded their LELs in respectively 16, 17 and 18 of the 19 samples (Fig 2f-2h). The levels of Hg, As, Zn and Ni lay between their LEL and SEL at only a few sites. The concentration of Hg, Zn and Ni at site #7 was below the respective LEL, while the Zn concentration exceeded its LEL at sites #13, #14 and #17. Except at sites #6, #7 and #10, the concentration of Cr was uniformly higher than its SEL. For Cu, this also applied to sites #12 through #19, while at the remaining sites, the level was >LEL. Similarly for Pb, all sites sampled were polluted at a level >SEL (Fig. 2).

A comparison between the heavy metal concentrations in the sediment of the Beijiing River with those in other river sediments is shown in Table 5. This shows that in the upstream reaches of the Beijiing river, pollution levels were similar to that present in most rivers, but in its downstream reaches, Cr pollution was particularly severe, while that of both As and Pb was only exceeded in the Guadiana [22] and Tigris [23].

Potential ecological risk assessment

The calculated potential ecological risk and potential toxicity response indices are given in Table 6. In the upstream sites #1-#10, the RI value lay between 150 and 300 (mean of 185.2), while the mean RI in the downstream sites #11-#19 was 433.7. Both the up and downstream reaches of the river were associated with potential ecological risk, but the level of risk in the downstream reaches was considerable. The mean ecological risk factors (E_r^i) of As, Zn, Pb, Ni and Cr were all < 40 (low ecological risk), but that for Hg in the upstream reaches was 101.7, a value lying in the range associated with considerable risk. The downstream mean Hg E_r^i was 274.8 (reaching 369.3 at one site), representing a high to very high ecological risk. Similarly the concentration of Cd at site #7 was high enough to give an E_r^i of >80 (medium risk level).

Table 6
Ecological risk factor (E_{ri}) and the potential ecological risk index (RI) of heavy metals in surface sediments of the Beijiing river

Site	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr	RI
1	109.33	13.71	12.35	2.64	16.53	7.50	8.06	8.40	178.52
2	115.33	14.02	13.20	2.80	17.62	9.17	9.79	8.74	190.67
3	110.00	14.55	14.70	2.53	17.76	9.58	9.99	7.20	186.31
4	119.33	14.77	15.03	2.62	18.58	10.00	9.55	8.23	198.11
5	110.67	13.86	11.95	2.55	18.03	8.33	8.69	7.60	181.68
6	116.67	13.48	12.93	3.09	19.81	9.17	8.27	0.85	184.27
7	28.00	8.71	33.54	0.75	11.17	119.17	2.62	4.74	208.70
8	105.33	12.27	11.43	3.02	18.44	9.58	8.03	8.86	176.96
9	108.67	13.94	13.72	3.20	19.67	10.00	9.37	9.20	187.77
10	93.33	11.82	11.16	2.73	17.49	7.92	7.95	6.11	158.51
Average of upper stream	101.67	13.11	15.00	2.59	17.51	20.04	8.23	6.99	185.15
Stdev of upper stream	26.86	1.80	6.64	0.69	2.44	34.84	2.12	2.56	13.31

Site	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr	RI
11	113.33	13.64	12.71	2.35	16.39	8.75	9.45	6.86	183.48
12	369.33	27.88	63.72	4.51	31.56	20.83	10.07	18.69	546.59
13	320.67	20.83	74.09	5.15	46.58	17.92	12.95	17.83	516.02
14	314.67	20.30	72.56	4.65	43.72	16.25	11.85	17.43	501.43
15	214.00	18.56	52.44	4.33	32.79	11.67	12.22	17.26	363.27
16	236.00	19.77	55.79	4.76	35.11	13.75	11.02	19.89	396.09
17	271.33	20.91	62.50	5.25	41.53	14.17	11.51	18.57	445.77
18	324.00	21.29	67.07	4.53	34.29	12.50	11.07	16.06	490.81
19	310.00	19.85	59.45	3.73	32.51	10.42	9.84	14.29	460.09
Average of downstream	274.81	20.34	57.81	4.36	34.94	14.03	11.11	16.32	433.73
Stdev of downstream	77.12	3.66	18.35	0.88	8.82	3.80	1.16	3.90	110.23

The analysis suggested that the severity of the ecological risk among the heavy metals can be ranked Hg>Cd>Cu>Pb>As>Cr>Ni>Zn. Hg is the most hazardous of these pollutants not because of its high concentration so much as because of its high toxicity. Based on RI values, it appeared that the upstream reaches of the Beijiang River were still relatively unpolluted, but that the heavily urbanized downstream reaches were seriously polluted.

Economic loss calculation

The estimated economic losses due to polluted sediment are detailed in Table 7. The global loss for the upstream reaches of the river was estimated as \$466.63 per hm²·a while that for the downstream reaches was \$1,133.52 per hm²·a. Even though the lower concentration of Hg and Cd, economic loss caused by them were higher than other heavy metals because of the highest toxicity coefficient.

Sediment plays an important role in maintaining the fluvial environment, and the diversity of ecosystem services is dependent on the sediment's quantity [28]. The sediment is a major determinant of both economic efficiency, environmental protection and ecosystem sustainability. The estimated economic loss due to heavy metal pollution in the Beijiang River varied from about \$500 per hm²·a in its upstream reaches to > \$1,100 per hm²·a in its downstream reaches. These figures represent an appreciable (around 5.5% and 13.3%, respectively) loss to the economic value of the upstream and downstream ecosystem services. As a result of anthropogenic activity, pollution of the fluvial sediment has become an environmental problem [29], since heavy metals such as Hg, As, Cu, Zn, Pb, Cd, Ni and Cr are very persistent in the sediment and are known to be detrimental to aquatic ecosystems, fisheries and water quality [30]. They have a tendency to accumulate in the food chain, and also compromise the soil ecosystem [31].

Table 7
Heavy metals economic loss [\$ per hm²·a]

Hi	Hg	As	Cu	Zn	Pb	Cd	Ni	Cr	H
upper stream	466.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	466.63
downstream	1076.88	0.00	56.64	0.00	0.00	0.00	0.00	0.00	1133.52

A whole suite of human activity, including mining, industry, agriculture, fuel consumption and waste disposal, has been responsible for the growing accumulation of heavy metals and other pollutants in fluvial sediments [28, 32]. Heavy polluters, such as the electronics and electroplating industries, routinely discharge waste water containing

a substantial load of heavy metals [33]. Counter-measures against sediment pollution will therefore require adjustments to industrial practices and the siting of industrial plants, particularly where the waste products include Hg, Cr and/or Cd. The consequence of economic loss from heavy metals would be contribute to the government make decision scientific. The present estimates of the economic loss caused by heavy metal pollution are likely to be on the conservative side as a result of the location of the sampling sites. Further more, the loss of environment pollution time effect not taken into account, so, it is necessary to have a further study on higher accuracy, more economical and practical and consider comprehensive method to control the losses which caused by environmental pollution.

Conclusions

Nearly all of the heavy metal concentrations were elevated in the Beijiang River sediments, although the upstream sediments were clearly less polluted than were the downstream ones. The upstream reaches of the river presented a moderate ecological risk, but the risk in the downstream reaches was relatively high. The economic loss associated with heavy metal pollution was predominantly caused by the presence of Hg; it represented about 5.5% (upstream reaches) and 13.3% (downstream reaches) of the value of the river ecosystem services. A significant reduction in the discharge of industrial effluent and domestic sewage will be necessary to improve the quality of the river water.

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OCENA RYZYKA EKOLOGICZNEGO I STRAT EKONOMICZNYCH WYNIKAJĄCYCH Z ZANIECZYSZCZENIA METALAMI CIĘŻKIMI RZEKI BEIJIANG

Abstrakt: W artykule opisano dystrybucję i stopień akumulacji metali ciężkich w rzecznych osadach rzeki Beijiang. Potencjalną toksyczność tych zanieczyszczeń obliczono za pomocą metody wytycznych jakości osadów (SQGs) opartej na konsensusie i za pomocą potencjalnego wskaźnika ryzyka ekologicznego Håkansona. Stężenia Hg, As, Cu, Zn, Pb, Ni i Cr były na tyle wysokie, aby uszkodzić biocenozę osadu. Potencjalne ryzyko ekologiczne było znacznie większe w dalszych, zurbanizowanych odcinkach rzeki niż na wcześniejszych odcinkach, które nadal są wiejskie, ale wszystkie odcinki rzeki reprezentowały co najmniej umiarkowany poziom ryzyka ekologicznego. Szacunki strat ekonomicznych związanych z tymi zanieczyszczeniami były znaczne, a to głównie ze względu na obecność Hg i Cu. Dorzecze rzeki Beijiang jest mocno zanieczyszczone, stwarzając zagrożenie dla środowiska w dalszym biegu rzeki Perłowej i możliwość strat ekonomicznych dla całej zlewni.

Słowa kluczowe: ocena ryzyka ekologicznego, oszacowanie strat ekonomicznych, metale ciężkie, osady, odnowa ekosystemu, rzeka Beijiang