ELSEVIER

The Science of the Total Environment 206 (1997) 67–77

**the Science of the
Total Environment**

An International Journal for Scientific Research
into the Environment and its Relationship with Man

Spatial and temporal patterns of acidity and heavy metals in predicting the potential for ecological impact on the Le An river polluted by acid mine drainage

M. He, Z. Wang*, H. Tang

SKLEAC, Research Center for Eco-Environmental Sciences, PO Box 2871, Beijing 100085, Peoples' Republic of China

Received 30 May 1997; accepted 24 July 1997

Abstract

Integration and comparison of metal contamination from acid mine drainage and an assessment of the potential for ecological impact was conducted in the aquatic ecosystems of the Le An river. The results indicated low acidity, high levels of suspended solids containing a high content of copper in river water and sediment in the upstream region of the Le An river due to the pollution from the Dexing copper mine, and high concentrations of zinc and copper in surface water and sediments, high release potential and ready bioavailability of heavy metals in sediments downstream (after site A07) due to the pollution from the Jishui river. The pollution from acid mine drainage in the Le An river potentially effects an ecological impact on the aquatic ecosystem, mainly between sites A04 and A08. The management strategy should, therefore be mainly applied to acid mine drainage from the Dexing copper mine and heavy metal discharges from the Jishui river. © 1997 Elsevier Science B.V.

Keywords: Acid mine drainage; River; Heavy metal; Distribution; Ecological impacts

1. Introduction

A large quantity of acid mine drainage is produced due to the weathering of waste mines of metal sulfides, and is one of the major causes of

pollution in the surrounding environment. There is voluminous literature on the topic of pollution by acid mine drainage (Boult et al., 1994; Cabrera et al., 1984; Chapman et al., 1983; Foster et al., 1978).

China is rich in non-ferrous metal sulfide resources. The Dexing copper mine, located near the Gukou site in the upstream section of the Le

* Corresponding author. e-mail: wangzj@mail.rcees.ac.cn.

An river (279 km long), is the largest open-cast copper mine in Jiangxi Province, China. Its ore production in recent times is over 60 000 tons/day and will expand to 100 000 tons/day or more by the end of this century. The Dawu river, running through the Dexing copper mine, receives waste discharges from the mine and flows into the Le An river at Gukou (site A04). A small tributary, the Jishui river (J.R., 39 km long) is a further metal-polluted river along several small sulfide mines and smelters; it runs into the Le An river at Daicun (site A07) and finally flows into Poyang Lake, the largest fresh-water lake in China. Consequently, a large amount of various pollutants, mainly heavy metals, have been discharged into the Le An river where they cause significant ecological impact.

During 1987 and 1995, the Cooperative Ecological Research Project (CERP) was launched within the international Man and Biosphere (MAB) program, supported by the Federal Ministry for Re-

search and Technology (BMBF), Germany. The 'Ecological Effects of Heavy-metal Pollution in the Dexing Copper Mine Region' program, one of eight CERP sub-projects, was carried out to assess the impact of the mining operation (Tang et al., 1994; Muller and Tang, 1996).

A previous study of metal pollution by acid mine drainage in the Le An river was concerned mainly with the distribution (Yahya and Song, 1994; Ramezani, 1996; Lin et al., 1992; Lin and Li, 1992), absorption (Du et al., 1994), transport (Lin and Li, 1994), speciation (Mao, 1996; Mao et al., 1992), toxicity (Wang et al., 1994; Wang and Tang, 1994), as well as ecological investigation (Xu et al., 1994; Zhu et al., 1994). No attention has been paid to the integration and comparison of the physico-chemical data and the assessment of the potential for ecological effect.

The major objective of this paper, by integrating the data obtained from the CERP program and using the approach of principal components

Fig. 1. Research area and sampling scheme.

analysis and linear regression analysis, is to present a description of the spatial and temporal distribution of heavy metals in surface water and sediments and to describe the stability and bioavailability of heavy metals in sediments. An evaluation of the potential for ecological impact is also illustrated.

2. Methods

2.1. Field sites, sampling and analysis

The research area and sampling location is shown in Fig. 1. Site A01 is in upstream section of the river and is situated 20 km from the major mines. Site A04 is 20 km downstream from A01, where the acid mine drainage flows into the Le An river where it converges with the Dawu river (DWR). Site A05 is 20 km downstream from site A04. Site A07 is 50 km downstream and converges with the Jishui river. Sites A08–A13 are between 84 and 159 km downstream. Site A16 is 230 km downstream and in the delta area of the Poyang lake, the largest fresh water lake in China.

During 1987 and 1994, samples for water and sediments were collected on seven occasions in the rainy or dry season. During August 1993 and July 1994, annual hydrological and chemical monitoring at site A08 was carried out. The pH value was measured with a portable pH meter in situ. Surface water samples were collected with a plastic water sampler and filtered through a 0.45- μm Millipore membrane in situ and acidified immediately. Conventional methods were employed for

determining the physico-chemical characteristics of the water. Sediment samples were taken using a Veen grab sampler and were wet-digested after being dried at room temperature. The sediment samples when brought back to the laboratory were centrifuged at 4000 rev/min for 30 min to obtain the interstitial water (Backman J21 freezing centrifugation). The organic carbon and sulfur in sediments were analyzed using a LECO Corporation (USA) carbon and sulfur determination model CS-225, controlled by a microprocessor. Grain size separation was carried out using nylon sieves and a settling procedure (Muller, 1967), separating the sand ($> 63 \mu\text{m}$), silt ($63\text{--}2 \mu\text{m}$), and clay ($< 2 \mu\text{m}$) fractions of the sediments. Ten grams of each sample for granulometric analysis were suspended in distilled water, and dispersed by ultrasonic treatment (three times for 30 s). The medium silt ($20\text{--}6.3 \mu\text{m}$), fine silt ($6.3\text{--}2 \mu\text{m}$) and clay fraction ($< 2 \mu\text{m}$) were separated using an 'ATTERBERG-cylinder' through repeated suspension (in distilled water) and settlement cycles. The determination of the elements Cu, Pb and Zn in a standard reference sediment sample (CRM 280, COMEURE) and in a standard reference water sample (produced by the Chinese Academy of Environmental Science) was achieved by first digesting the samples in a microwave oven equipped with PFA advanced composition vessels, followed by a Perkin-Elmer Enhanced Data System 3100 GF-AAS measurement. The detection limits for Cu, Pb and Zn are 0.02, 0.05 and 0.001 $\mu\text{g/l}$, respectively.

Table 1

Physical-chemical characteristics for surface water in Le An river (in dry the season, October 1994)

Sites	TC (mg/l)	IC (mg/l)	Conductivity ($\mu\text{S/cm}$)	Turbidity (SiO_2 , mg/l)	Mineral (mg/l)	Hardness (CaCO_3 , mg/l)	Alkalinity (CaO, mg/l)
A01	11.0	10.0	86.0	3.12	36.0	102.34	20.88
A03	9.0	9.0	131.0	31.47	176.0	148.39	17.90
A04	7.0	4.0	390.0	24.31	530.0	317.25	0.00
A05	11.0	9.0	164.0	40.12	172.0	189.33	20.88
A06	12.0	11.0	151.0	254.45	228.0	199.56	29.84
A07	8.0	8.0	196.0	23.45	164.0	143.28	19.09
A08	7.0	7.0	133.0	116.10	124.0	179.10	16.11
A13	10.0	9.0	121.0	8.47	118.0	133.04	24.26
A14	11.0	9.0	107.0	11.58	78.0	97.22	17.90

Samples of crustacean, rotifer, algae for qualitative analysis were collected using a photoplankton net with a mesh size of 50 μm from the surface water. Polyurethane foam cut into identical units ($\text{PFU-}5 \times 7 \times 8 \text{ cm}$) was used as an artificial substrate for colonization of the protozoan communities (Xu et al., 1994). Benthonic macroinvertebrates were collected with a 0.05- m^2 Peterson grab at each of the sampling sites (Zhu et al., 1994).

The rainy season in this area begins in April and finishes in September, in which 60–75% of annual rainfall and most of the storm floods are concentrated. From October to March, less rainfall could be observed and the flow rate in the Le An river is relatively lower (dry season).

2.2. Data collection and statistical analyses

All of the data for this paper were collected from the CERP database and relevant publications (Muller and Tang, 1996; Tang et al., 1994).

An ecological risk index (RI) has been used as a diagnostic tool for the potential sediment pollution of heavy metals (Lars, 1980).

Diversity indices for crustacean, rotifer, algae and protozoan communities were calculated using the Margalef diversity index (Margalef, 1957). Diversity indices for benthonic macroinvertebrates were calculated using the Shannon–Weaver diversity index (Shannon, 1949).

Principal component analysis (PCA) was used in this study to explain the interrelation of the concentrations of heavy metals and geochemical data in the sediments. The linear regression analyses were applied to evaluate both the relationship between the ecological risk index of sediments and the biological diversity index. Statisti-

cal analyses were performed using the SPSS statistical software package.

3. Results and discussion

3.1. Physical and chemical properties of the surface water

The physical and chemical properties of the surface water in the dry season (October, 1994) are shown in Table 1. The contents of total carbon (TC) and inorganic carbon (IC) are 7.0–12.0 mg/l and 4.0–11.0 mg/l, respectively, and the lowest values are at Gukou (site A04). High electrical conductivity, total hardness and contents of mineral matter are also observed at site A04. The results show that the pollution by acid mine drainage from the Dexing Copper Mine had a significant impact on the water quality of the Le An river. Additionally, at Daicun (site A07), due to the pollution from the Jishui river, a slight variation in water quality is also observed.

Table 2 shows the average, maximum and minimum pH values in surface water along the Le An river during 1987 and 1994. The pH values at site A04 were very low due to the acid mine drainage. Generally, at site A05, the pH values recover to normal levels due to the strong buffer capacity of the Le An river water. In the rainy season, a large quantity of acid mine drainage flowed into the Le An river, and the river water in all sampling sites was acidic ($\text{pH} = 3.24\text{--}6.5$). At site A07, due to pollution from the Jishui river, the pH values were slightly lower than that of upstream sections. Additionally, at site A12, the pH values were a little lower due to the pollution of discharges of wastes from a nearby small gold mine.

Table 2
The pH variation of surface water in the Le An river (1987–1994)

Sites	A01	A04	A05	A06	A07	A08	A09	A11	A12	A13
Average	7.05	5.18	6.74	7.08	6.86	7.01	7.06	7.08	6.95	7.09
Minimum	6.55	3.24	6.30	5.75	6.30	6.50	6.40	6.42	6.30	6.30
Maximum	7.65	7.20	7.30	7.60	7.20	7.30	7.32	7.40	7.35	7.42

Table 3

Range of pollution index (*I*) values (pollution site/water quality criteria) and frequency exceeding water quality criteria*

Sites	Sampling numbers	Copper		Lead		Zinc	
		Range (<i>I</i>)	Times	Range (<i>I</i>)	Times	Range (<i>I</i>)	Times
A01	7	1.4–2.9	2	1.1–2.7	4	1.1–1.3	2
A04	7	2.9–194	6	1.1–3.5	4	1.4	1
A05	6	1.3–10	4	1.4–3.1	2	< 1	0
A06	5	1.8–19	4	1.3–3.0	3	< 1	0
A07	7	1.8–8.9	4	1.1–2.6	3	3.1–3.5	3
A08	3	1.5–1.9	2	< 1	0	< 1	0
A09	5	1.3–4.2	4	2.6	1	< 1	0
A11	3	1.4–2.1	2	< 1	0	< 1	0
A12	3	2.0–2.8	2	< 1	0	< 1	0
A13	6	1.3–3.5	4	1.2–3.1	2	< 1	0

* National water quality criteria (NS-SW-88 for type II water, GB 3838 or water quality criteria for aquatic culture, TJ-35-79); Cu, 0.01 mg/l; Pb, 0.05 mg/l; Zn, 0.1 mg/l.

3.2. Evolution of heavy metal concentrations in the surface water

During May 1987 and October 1994, a total of seven sampling times were carried out in different seasons. Table 3 shows the range of pollution index (*I*) values (pollution site/water quality criteria) and the frequency exceeding water quality criteria in all sampling numbers. At site A01 upstream of the river and away from the copper mine areas, the average dissolved Cu concentration was low. Only in June 1993 did the concentration exceed the allowable water quality criterion of the Peoples' Republic of China for surface water (GB 3838-88) and the pollution index of Cu was 2.9. The highest Cu concentration was observed at A04 ($I = 3.8$ –194), while it was relatively lower at other sampling sites. In the slightly-polluted years, after site A04, the Cu concentration significantly decreased along the Le An river. In heavily-polluted seasons, from site A04 to site 13, the Cu concentration exceeded the water quality criterion, hence copper is transported downstream along the Le An river. The Pb concentration was higher upstream than downstream due to the pollution of acid mine drainage. The highest Zn concentration was observed at A07 ($I = 3.1$ –3.5).

The frequency of heavy metal concentrations for the annual hydrological and chemical moni-

toring at site A08 during August 1993 and July 1994 are given in Fig. 2. The average values for Cu, Zn and Pb in surface water (filtered through a 0.45- μ m Millipore filter) are 0.043, 0.171 and 0.025 mg/l, respectively, showing that the major pollutants are Cu and Zn in surface water at site A08, which is situated 34 km downstream for site A07 and at the confluence of pollutants from the Le An river and the Jishui river.

3.3. Distribution of heavy metals in suspended solids

The Le An river is heavily polluted by acid mine drainage and contains a large amount of ore-tailing particles from Dexing copper mine. A large amount of fine-grained ore tailing and iron/aluminum oxyhydroxides constitute the majority of the suspended particles (Luan et al., 1994). Fig. 3 shows changes in the suspended solids (SS) content and distribution of metals in suspended solids in the water of the Le An river. The result shows that the content of suspended solids was relatively low in the dry season (September, 1989) compared to rainy season (June, 1993). The highest content of suspended solids, observed at site A04 and site A07 are due to the input of pollutants from the Dawu river and Jishui river, respectively. The suspended particulates accumulated a large quantity of heavy metals, mainly copper at site A04 and zinc at site A07.

Fig. 2. Frequency of heavy metal concentration in water at Hushan (1993,8–1994,7).

3.4. Distribution of heavy metals in sediments

The regional background values of heavy metals in the Le An river were 45, 34 and 117 mg/kg for Cu, Pb and Zn, respectively. Accordingly, the

sediments of the Le An river were heavily polluted by heavy metals. Table 4 shows the average, minimum, maximum and medium metal concentrations in sediments sampling during 1987 and 1994. Metals that had sediment concentrations significantly above their background values were Zn, Pb and especially Cu. At site A01, the concentrations of copper were 36 (24–45) mg/kg near the background level. At site A04, due to an input of acid mine drainage, the sediments were heavily polluted. The average concentration of copper was 2878 mg/kg and the highest value reached 4100 mg/kg. From site A04 to site A06, the Cu concentration gradually decreased due to dilution and precipitation effects, etc. At site A07, due to further pollution from Jishui river, the Cu concentration was relatively high. From site A08 to site A16, the Cu concentration still exceeded the regional background level. From site A01 to site A06, the average Pb concentrations were 29–44 mg/kg. At site A07, high Pb concentrations (average 208 mg/kg) were observed, especially in 1993 (309.7 mg/kg) and in 1994 (583.8 mg/kg). From site A08 to site A16, average Pb concentrations were 49–81 mg/kg. At site A01, high Zn concentrations (316 mg/kg) were observed due to discharges from an active-carbon factory. The highest Zn concentrations were observed (average 878 mg/kg, max. 1118 mg/kg) at site A07 due to pollution from Jishui river, where there are several small copper sulfide mines, a medium sized Pb–Zn mine and a lead smelter.

3.5. Principal components analysis of sediment properties

The principal component analyses for the concentrations of iron, manganese, phosphorus, copper, lead, zinc, cadmium, chromium, nickel and cobalt, as well as the proportion of carbon, sulfur and particles of various grain sizes (sand: > 63 μm ; silt: 2–6.3 μm , 6.3–20 μm , < 20 μm , 20–63 μm ; and clay: < 2 μm) were conducted. A total of four significant principal components (PC) were extracted from these data. PC 1 accounts for 37.1% of the total variance. PC 2, PC 3 and PC 4 explained 25.4%, 16.9% and 5.9% of the total variance, respectively. Thus, 85.2% of the total

Fig. 3. Contents of suspended solids and distribution of Cu, Pb and Zn in the suspended solids in the Le An river (1989,9: dry season; 1993,6: rainy season).

information could be explained by these four factors. The ordination model is presented in Fig. 4. PC 1 is the weight sum of six main parameters for particles of various grain sizes; PC 2 represents the concentrations of copper, sulfur, iron and P_2O_5 . Since principal components are orthog-

onal, the processes governing PC 2 are independent of PC 1. Hence, the information contained in PC 2 is more representative of pollutants from acid mine drainage. PC 3 represents the following factors: lead, zinc, cadmium and manganese. The carbon content is represented by PC 4.

Table 4
Distribution of Cu, Pb and Zn in sediments in Le An river (1987–1994)

Sites	A01	A04	A05	A06	A07	A08	A09	A11	A12	A13	A14	A15	A16
Cu													
Average	36	2878	2173	1788	1012	733	523	439	660	464	247	206	215
Median	34	2891	1790	1648	914	950	439	568	674	506	290	251	310
Minimum	24	1405	1134	1177	406	100	90	241	472	172	80	124	131
Maximum	45	4100	4185	2285	1906	1055	1257	657	851	614	350	287	333
Pb													
Average	44	42	44	29	208	94	68	77	79	75	67	49	81
Median	35	33	43	33	179	103	74	68	67	79	72	59	82
Minimum	15	7	13	15	32	44	68	41	72	32	34	39	66
Maximum	95	100	121	38	584	150	116	141	126	113	112	98	96
Zn													
Average	316	221	201	202	878	664	451	830	624	505	304	353	226
Median	245	65	161	157	1006	600	449	608	616	521	298	314	253
Minimum	170	62	66	93	113	391	177	190	502	164	125	179	59
Maximum	1040	1497	532	568	1501	1159	787	1618	814	670	692	548	402

Units, mg/kg.

Fig. 4. Sediment PCA ordination model: PC1, 37.1%; PC2, 25.4%; PC3, 16.9%. (a, < 2 μ m; b, 2–6.3 μ m; c, 6.3–20 μ m; d, < 20 μ m; e, silt; f, > 63 μ m; g, C(%); h, S(%); i, P_2O_5 ; j, Cu; k, Zn; l, Pb; m, Cd; n, Fe; o, Mn; p, Cr; q, Ni; r, Co).

3.6. Stabilization and bioavailability of heavy metals in sediments

Fig. 5 shows the concentration of heavy metals in interstitial water. The results indicate that the major pollutants are copper in the interstitial water of sediments along the Le An river and a

high zinc concentration was observed at site A12 due to pollution by wastes from a nearby gold mine. High contents of sulphate, hydroxide, iron, manganese and a low content of organic matter were generated by the pollution of acid mine drainage in sediments upstream in the river, especially at site A04 (Dai et al., 1994).

According to the speciation analysis (Mao, 1996), studied by sequential selective chemical extraction following the method of Tessier et al. (1979), the background (site A01) copper was in the carbonate-binding fraction; the copper discharged from the Dexing copper mine mainly bound to the residual fractions; the copper content downstream (after site A07) was mainly in the pyrite/organic binding fraction and the residual fractions. The copper content of the sediment is relatively more stable at site A01 and upstream (site A04–A06) rather than downstream, especially at site A07 (Mao, 1996). The highest contents of heavy metals in water extracts (Wang and Tang, 1994) and in the interstitial water of sediments were also at site A07. Additionally, the potential release of sediment-bound heavy metals were higher at site A07 than in the upstream site A05 (Wen and Herbert, 1997a). The measure-

Fig. 5. Metal content of interstitial water in the sediments of the Le An river.

ment of acid volatile sulfide (AVS) and simultaneously extracted metals (SEM) showed that the major binding component for metals were most likely to be iron and magnesium oxide at site A07 (Wen and Herbert, 1997b). The result of the toxicity bioassay proved that the interstitial water and extracts of sediments at site A07 exhibited strong toxicity than that of upstream waters. Hence the sediments in the downstream (after site A07) sector represent a strong risk for pollution and are readily bioavailable.

3.7. Prediction of the potential for ecological effects

A total of 123 species of algae, 32 species of crustacean, 19 species of rotifer, 58 species of protozoa and 26 species of benthos were collected at six sampling sites along the Le An river and the diversity indices were calculated (Xu et al., 1994; Zhu et al., 1994). The ecological risk indices of sediments were calculated for assessing the multiple metal pollution (He et al., 1997). The variation of flow rate, water depth and temperature along the Le An river was small (Lin and Li,

1994). Xu et al. (1994) and Zhu et al. (1994) confirmed that the main factors of impact on aquatic ecosystems were heavy metals and pH, and the impact on the diversity index was not related to other environmental conditions. In this study, we conducted the linear regression analysis between the diversity index and risk index (RI). The results (Fig. 6) show that a notable correlation exists between the diversity index for algae, zooplankton (crustacean and rotifer), protozoa and benthonic macroinvertebrae and the ecological risk index (RI). The coefficient of determination for the relationship between diversity index and risk index were 0.9499, 0.8591, 0.8976 and 0.9176 for algae, zooplankton, benthos and protozoa, respectively. According to the regression equations, on the basis of the RI values of sediments, we calculated the diversity index and the average ratio of the diversity index (pollution site/control site) for algae, zooplankton, benthos and protozoa at all sampling sites. The ecological effect of sediments for the Le An river were predicted, based on the values of the average ratio of the diversity index (pollution site/control

Fig. 6. Linear regression analysis of diversity index vs. risk index (RI) of sediments.

Fig. 7. The predicting diversity index ratio (pollution site/control site) and the ecological effects.

site), using the hierarchical model (He et al., 1997): class I: 1.0, no-effect; class II: 0.75–1.0, slightly affected; class III: 0.5–0.75, moderately affected; class IV: 0.25–0.5, strongly affected; class V: < 0.25, seriously affected. The results (Fig. 7) show that the aquatic ecosystem was seriously affected at site A04, strongly affected at site A05, moderately affected from site A06 to site A08, and slightly affected after site A08.

4. Conclusions

By integration and comparison of several years' data, the results clearly show that the discharges from Dexing copper mine and mines along Jishui river has resulted in a significant increase in the concentration of copper, zinc and lead in water and sediments along the Le An river. At site A04, the low acidity, high contents of suspended solids and high concentration of copper in river water and sediment are the main pollution problems. At site A07, high concentrations of zinc and copper in surface water and sediment are observed. At other sites downstream, high concentrations of copper and zinc are observed. The spatial variation of geochemical data in sediments could be explained using PCA analysis. The ecological ef-

fects of acid mine drainage can be predicted based on the risk index (RI) of sediments. The river water and sediment pollution in the Le An river have strongly affected the aquatic ecosystem, mainly between sites A04 and A08. The management priority should be addressed mainly to acid mine drainage from Dexing copper mine and heavy metals discharges from Jishui river.

Acknowledgements

The author would like to thank the participants in the project, who also provided the data for this paper. We cannot list their names because more than 20 scientists contributed to the work (including scientists from Germany). Special thanks are due to German BMBF and Chinese CAS for providing funding support and to Dr Thomas Schaaf in Paris office of UNESCO and Prof. Zhao Xiangyin from Chinese MAB for coordinating the project.

References

- Boult S, Collins DN, White KN, Curtis CD. Metal transport in a stream polluted by acid mine drainage—The Afon Goch, Anglesey, UK. *Environ Poll* 1994;84:279–284.

- Cabrera F, Toca CG, Diaz E, Arambarri PDE. Acid mine-water and agricultural pollution in a river skirting the Donana National Park (Guadamar river, South West Spain). *Water Res* 1984;18:1469–1482.
- Chapman BM, Jones DR, Jung RF. Processes controlling metal ion attention in acid mine drainage streams. *Geochem Cosmochim Acta* 1983;47:1957–1973.
- Dai Z, Starke R, Kleeberg R, Wang X, Liu Y. Physico-chemical properties of Le An river sediments. *China Environ Sci* 1994;5:129–134.
- Du Q, Wen X, Tang H. Surface complexation model for the adsorption of heavy metals on the river sediment nearby Poyang Lake. *China Environ Sci* 1994;5:140–148.
- Foster P, Hunt TE, Morris AW. Metals in acid mine stream and estuary. *Sci Tot Environ* 1978;9:75–86.
- He M, Wang Z, Tang H. The chemical, toxicological and ecological studies in assessing the heavy metal pollution in Le An river, China. *Water Res* 1997;in press.
- Lars H. An ecological risk index for aquatic pollution control: A sedimentological approach. *Wat Res* 1980;14:975–1001.
- Lin Y, Li Q. Study on the heavy metal speciation modeling in aquatic system of Le An river. *J Environ Sci (China)* 1992;4:100–108.
- Lin Y, Li Q. The present change of heavy metal pollution in Le An river—Poyang Lake. *China Environ Sci* 1994;5:110–115.
- Lin Y, Li Q, Zou G, Shi S. Impacts of acid mine drainage on water quality of Le An river and Poyang Lake area. *J Environ Sci (China)* 1992;4:4–13.
- Luan Z, Klute R, Hahn H, Tang H. The stability and aggregation of fine-grained ore tailing, hydrous Fe/Al oxides and their binary mixtures in natural water. *China Environ Sci* 1994;5:149–158.
- Mao M. Speciation of metals in sediments along the Le An river. in the Final report of the Co-operative Ecological Research Project (CERP). Published in 1996 by the United Nations Educational, Scientific and Cultural Organization, 1996:1–57.
- Mao M, Liu Z, Dong H. Distribution and speciation of metals in sediments along Le An river. *J Environ Sci (China)* 1992;4:72–81.
- Margalef R. Information theory in ecology. *Mem. real acad.* 3rd ser. Barcelona 1957;32:374–449.
- Muller G. Methods in sedimentary petrology Part one. *Schweizerbart Stuttgart* 1967:283.
- Muller G, Tang H. Ecological effects of heavy-metal pollution in the Dexing Copper Mine region in Jiang Xi Province, China. Final report of the Co-operative Ecological Research Project (CERP). Published in 1996 by the United Nations Educational, Scientific and Cultural Organization, 1996.
- Ramezani N. Heavy-metal concentrations in sediment from the Le An river to Poyang lake. Final report of the Co-operative Ecological Research Project (CERP). Published in 1996 by the United Nations Educational, Scientific and Cultural Organization, 1996.
- Shannon C. The Mathematical Theory of Communication. Urbana: Univ. Illinois Press, 1949:49–73.
- Tang H, Wang Z, Liu J, Muller G. Ecological impacts of heavy metal pollution from Dexing Copper Mine to Poyang Lake—Recent research progress in CERP-continual phase. *China Environ Sci* 1994;5:97–101.
- Tessier A, Campbell PGC, Bisson M. Sequential extraction procedure for the speciation of particulate trace metals. *Anal Chem* 1979;51:844.
- Wang H, Tang H. Toxic effects of the polluted sediments in Le An river on *Hydrobios*. *China Environ Sci* 1994;5:165–168.
- Wang Z, Ma M, Du Q, Wen X. Toxic assessment by *Photobacterium phosphoreum*. *China Environ Sci* 1994;5:159–164.
- Wen X, Herbert E.A. The acid and base properties of Le An river sediment and their influence on the release of heavy metals contained in sediment samples. *Environ Chem (in Chinese)*, 1997a;in press.
- Wen X, Herbert E.A. Acid-volatile-sulfide(AVS) in Le An river sediment and the effect of oxygen on the release of heavy metals in the sediment. *Environ Sci (in Chinese)*, 1997b;in press.
- Xu M, Gao Y, Ma M, Wang Z. The relationship between the changes of plankton community structure and the metal pollution in Le An river. *China Environ Sci* 1994;5:172–176.
- Yahya A, Song Y. Distributions of heavy metals in sediments and pore waters of Le An river at Caijiawan. *China Environ Sci* 1994;5:105–109.
- Zhu J, Ren S, Lin Z, Lin Y. Preliminary study on the benthic macroinvertebrate community relating to the metal pollution in Le An river. *China Environ Sci* 1994;5:177–181.